Development of a Custom Data Acquisition System for the Study of Vehicle Dynamics in Longer Combination Vehicles

by

Jameson Colbert

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Approved by

David Bevly, Chair, Albert J. Smith Jr. Professor of Mechanical Engineering
David Beale, Professor of Mechanical Engineering
Song-yul Choe, Associate Professor of Mechanical Engineering
Thaddeus Roppel, Associate Professor of Electrical and Computer Engineering

Abstract

This thesis details the development, deployment, and verification of a custom data acquisition system for the purpose of studying vehicle dynamics in a triple trailer Longer Combination Vehicle (LCV). In addition to the data acquisition the thesis details the simulation efforts that were undertaken to both verify the experimental data as well as assess the stability of the vehicle itself. The research was part of an effort to assess the viability of widening the available roadways that are currently accessible to LCV trailers. This project undertook the task of fully instrumenting a triple trailer LCV with a package of more than 35 sensors and implementation of a custom Data Acquisition System (DAQ) to log over 200 channels coming from the aforementioned sensors. Once outfitted with the sensor package, the LCV was put through a variety of dynamic tests including lane changes and constant radius turns in an attempt to capture various dynamic characteristics of the vehicle.

A series of simulations were run to match the maneuvers undertaken during the experimental phase. That data was then compared to ensure that the simulation did indeed agree with the experimental data. Once in agreement the simulations were expanded to speeds that were not able to be achieved experimentally due to safety concerns. The last element of the simulation was a comparison between the LCV triple and a standard double trailer heavy truck as seen on the highways today.

The LCV under test behaved as expected given the prior research into LCV dynamics. Additionally the simulation and the experimental data were shown to agree. The simulation exposed the instability of the vehicle at speeds easily expected on the highways. When comparing the triple LCV to the double it was shown that at lower speeds the first four units behaved similarly, but as the speeds increased the effects of the third trailer were shown in the responses of the second. Finally this thesis shows that there is a need for heavy

precautions before allowing triple LCV to traverse the highway roads. At lower speeds the vehicle is safe but increasing that speed to that of the standard highway speed shows that the vehicle will respond with undesirable outputs.

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Chapter 1

Introduction & Background

Highway safety has been and for the foreseeable future will always be a topic of great concern and research. The most prominent reason for that are auto accident fatalities. In 2011 alone, a total of 32,367 people died as a result of a car accident[7]. Most individuals find themselves weary of driving next to or in the vicinity of large trucks as they fear being involved in an accident with one. of the 32,367 fatalities, 3,373 people where killed in accidents in 2011 involving large trucks. Of those 3,373 people, only 16% (553) of those where occupants of the large truck; the rest being either occupants of another vehicle or pedestrians[7]. So when discussing the safety and stability of large vehicles the people most affected by these results are the individuals driving in the vicinity the large trucks and not actually the occupants of the large trucks itself. To that effect there needs to be a good amount of certainty that a large vehicle is stable before it is permitted on highway systems in all states. Currently the only large trucks allowed to operate on all highways in the 50 states are single semi-trailer and smaller double trailer units.

Tractor trailers are everywhere, single tractors pulling a single trailer are as common as a family sedan on today's highways and interstates. To some degree the same can be said for a tractor pulling a pair of 'pup trailers' (28 ft semitrailers); this configuration is referred to as as a double. Both of those combinations are used to transport low-density freight across the nation as both are permitted on the highways in all 50 states. The topic of concern and the focus of this thesis will be the assessment of stability of triple-trailer LCVs, and a comparison of the triple-trailer configuration to the double-trailer configuration using computer simulations. The term 'LCV' is an acronym for Longer Combination Vehicle and is used to describe a combination of two or more trailers with a gross weight in excess of

80,000 lb. The most common LCV combinations are two trailers where one is longer than 28 ft or a series of three pup trailers. The test vehicle used in this project is that of a single tractor pulling three pup trailers, it can be seen in Figure 1.1.

Figure 1.1: LCV Triple Test Vehicle Maneuvering Highway Corner

The research done on this project included both experimental results involving the triple-trailer and computer simulations of the same vehicle. The experimental data was obtained by instrumenting the vehicle shown in Figure 1.1; which is one of the vehicles used at the National Center for Asphalt Technologies (NCAT) for asphalt life cycle testing. The vehicle was then put through a variety of standard dynamic maneuvers during which the vehicle's response was recorded. The methodology and results of the experimental phase is described in Chapter 3. The simulated data was obtained by running numerous simulations in TrukSim, which is a software package developed by Mechanical Simulation Corporation specifically for simulating the response of large vehicles. This data was then to be compared with the results of the computer simulations in Chapter 4. The research for this thesis was done in conjunction with a larger effort to characterize and study LCV dynamics, sponsored by the National Transportation Research Center Incorporated (NTRCI) and was a collaborative effort including both universities and private companies. The report generated from that effort can be found in [6].

1.1 Background

As mentioned above, both single trailers and combinations of two small trailers are permitted on all highways throughout the nation. The end goal of this research is to assess the stability of the triple-trailer LCV in an effort to help determine whether or not they should also be allowed throughout this nation's highway system. Currently only a handful of states permit LCVs to operate on their highways, and each of those states have different restrictions in place on what type of LCV can be used. The current highways on which LCVs can operate on in the United States is shown in Figure 1.2; as illustrated the options are limited for the triple trailer LCV of 100' or greater in length combination. This is of note since this is the type of LCV that was used in this study and is the form that has the most push to become legal.
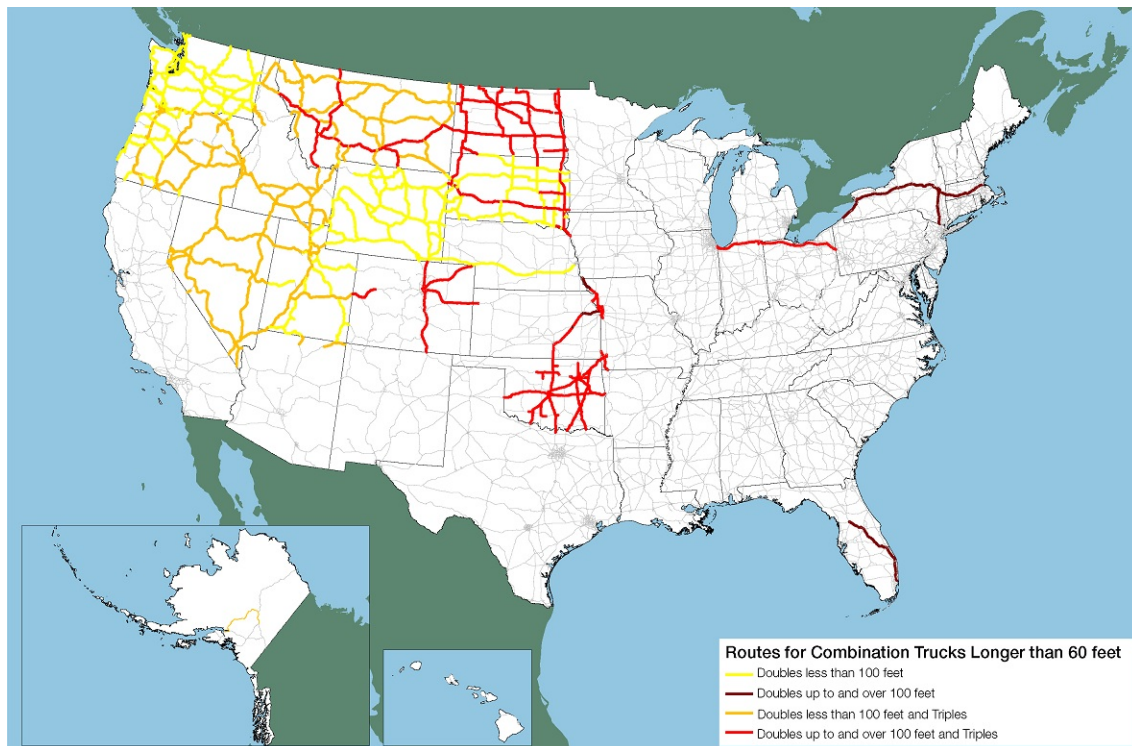
Figure 1.2: Map of Approved Highway Routes for LCVs [1]

One of the driving forces for this research is the push to expand the network of highways and roads that are accessible to LCV's. The reasoning for this is to increase the efficiency of the commercial vehicles. For instance, examine the case of a single semitrailer versus a LCV configured with three pup trailers. The increased efficiency can be seen in Table 1.1; for this example the trip length was 15,000 miles and both trucks are assumed to have the same fuel efficiency of 6.5 mpg and using the average cost of one gallon of diesel being $3.951. This represents a fuel cost of $9,117.70 for this simulated trip. This cost savings is significant when you think about this on a national scale and not just a single trip, so it is easy to see why there would be a push to permit the use of LCV on most of the highways in the nation.

Table 1.1: Efficiency Comparison Single Trailer vs. LCV Triple

Vehicle Type	Height	Width	Length	# of Trailers	ft^3	Cost per ft^3
Single Trailer	10	8	40	1	3,200	$2.85
LCV Triple	10	8	25	3	6,000	$1.52
				Differences:	2,800	$1.34

1.2   Literature Review

There are several different classifications of LCVs, each of them having their own unique advantages and disadvantages. Though the LCV has been around for some time there has been little experimental research performed on this family of vehicles. Most of the experimental research to date has been aimed at characterizing the simple single semitrailer configuration, which makes sense do to the ubiquitous nature of that vehicle. This section will go into what has been done in the past to study the LCV as well as establish a fundamental understanding of what components go into an LCV as well as how they go together to form the vehicle.

While there was no research found where a triple LCV was instrumented and then underwent experimental testing liken to that described in this thesis there were other efforts put forth in the characterization of Longer Combination Vehicles. One of the most helpful

pieces found was 'An Overview of the Dynamic Performance Properties of Long Truck Combinations' [3]. This paper went through and outlined what was to be expected from vehicles with multiple trailers in combination. it formed a general understanding of the dynamics using simulation and gathering of current literature at the time of publication. This paper served as the foundation for what this thesis expanded upon. When searching for a general understanding of the components found in LCV units 'A Factbook of the Mechanical Properties of the Components for Single-Unit and Articulated Heavy Trucks' [8] by Paul Francher et al described each component and what role it played in the dynamics. In addition to the study of how the LCV's behave there have been several efforts into exploring how to control them. One such effort is described in 'Performance Characteristics for Automated Driving of Long Heavy Combinations Evaluated in Motion Simulator' [9]. In that publication the authors describe the efforts of formulating multiple control methods for autonomous driving of LCV's. They achieve this by studying the inputs of numerous experienced LCV drivers given the same vehicle path to drive. This is the path of the future, commercial vehicles are being explored as one of the leading areas for autonomous driving on the highway systems both stateside and internationally.

As mentioned the research done for this thesis was done in conjunction with a larger project put on by the National Transportation Research Center Inc. as such there are several prior efforts put on by the center that all lead up to the project for which this thesis is indebted to. The report for the research project that supported this thesis is found in 'U32: Vehicle Stability and Dynamics Longer Combination Vehicles Final Report' [6]. The aforementioned prior efforts are detailed in [10], [11], and [12]. Those projects performed similar experimental and simulation testing that was undertaken for this research on other heavy articulation vehicles. Those efforts lead directly to current research.

1.2.1 LCV Overview

The basic components for an LCV are a tractor and an assortment of semitrailers. The formal definition of a semitrailer is a trailer that cannot stand on it's own and has to be supported by the vehicle which it follows. The most common occurrence of semitrailers is where only one trailer is being supported by a tractor, this is the typical '18 Wheeler' or 'semi-truck' illustrated in Figure 1.3.
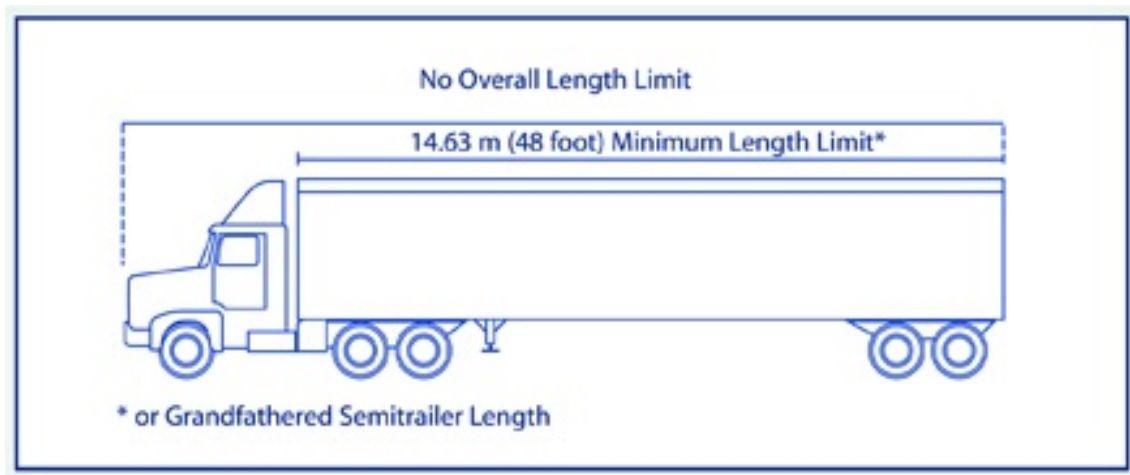
Figure 1.3: Typical Tractor & Single Semi-Trailer Combination [2]

The other common occurrence is that of two semi-trailers towed by one tractor. The first trailer is supported by the tractor exactly like it would be if it were the only semi-trailer attached. The difference here is the second semi-trailer is supported via a converter dolly, that is also attached to the first trailer. The converter dolly is what connects a semi-trailer to another semi-trailer or anything other than the tractor for that matter. The name converter dolly comes from the fact that the dolly 'converts' the semi-trailer into a full stand alone trailer that can then be towed via the pintle hitch at the front of the dolly. An illustration of the double trailer configuration can be seen in Figure 1.4 and an illustration of a typical converter dolly is shown in Figure 1.5.

Figure 1.4: Typical LCV Double Trailer Configuration
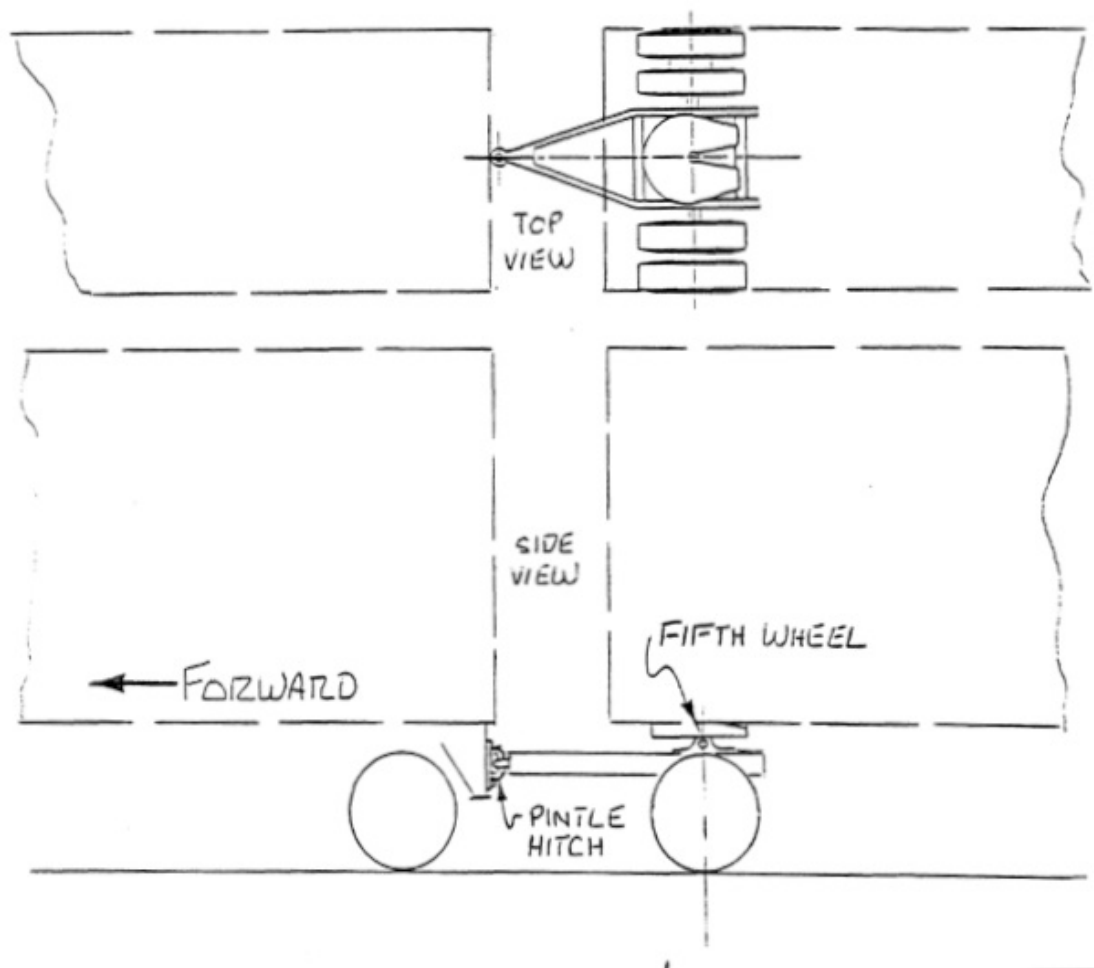
Figure 1.5: Converter Dolly with Pintle Hitch [3]

As those two combinations are the most prominent throughout the nation they are the only combinations most people think possible. There are however five other conventional combinations. These, along with the two most popular are pictured in Figure 1.6. As mentioned earlier the triple trailer combination is the focus of this research but much of the same dynamic properties apply to all of these vehicles and are either amplified or dampened depending on the configuration.
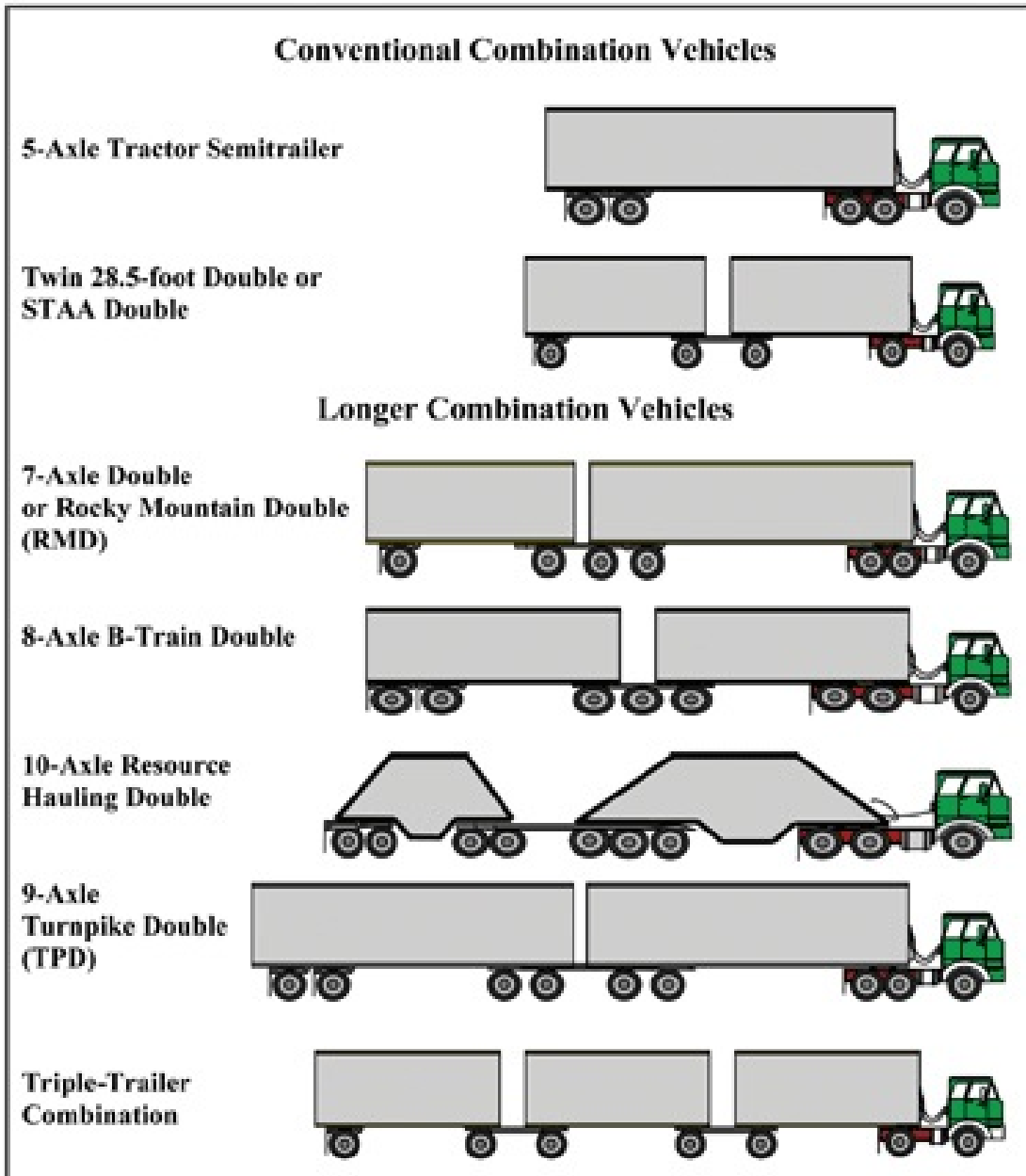
Figure 1.6: Possible LCV Configurations [4]

1.2.2 LCV Dynamics

When dealing with any vehicle dynamics project there are always certain behaviors that are identified as crucial. Those behaviors then become the center of attention when

outfitting the vehicle with a sensor package. With the goal being to capture the behaviors that have been identified the selection and implementation of the sensor package can be found in Chapter 2. In the case of the triple trailer LCV there are four key areas of concern. Those are, in no particular order; Rearward Amplification, Vehicle Off-Tracking, Vehicle Rollover, and Vehicle Understeer/Oversteer propensity. The two that pose the greatest complexities in dealing with LCV stability are Vehicle Off-Tracking and Rearward Amplification. The rollover phenomena is very similar to that of any other vehicle and as such there are numerous approaches to limit the rollover propensity of a vehicle, or in this case a trailer. The same can be said for Oversteer/Understeer; each unit can be examined as a single vehicle typically would.

Rearward Amplification is the act of dynamic responses growing in magnitude the further from the the steer axle you are. This is easily visualized with the cracking of a whip; small rapid inputs results in large outputs at the end of the whip. The formal definition of rearward amplification is the ratio of a unit's maximum amplitude in a trailing unit to its amplitude in the tractor [13]. The most common calculation when considering rearward amplification is the lateral accelerations but in theory, any quantity would work. Vehicle off-tracking is defined as the lateral deviation between the path of the center of the front axle and the path of the centerline of another part of the vehicle [13]. Essentially it is when a following axle fails to follow the path set by the lead axle, this is not only seen in heavy vehicles but most individuals who drive light trucks experience it on a daily basis.

Both rearward amplification and off-tracking are directly related to trailer length, and both are large factors is the perceived stability of the LCV. The difficult part is that they are inversely proportionate to trailer length. So the longer the trailer the less rearward amplification but the more off-tracking and vis versa. When traveling through urban environments, shorter trailers are desired as they would give you a smaller turning radius with less off-tracking. However, longer trailers are desired on the highways to reduce rearward amplification as off-tracking is of little concern on the highways.

Rearward Amplification

One of the of the most common causes of vehicle crashes is lane departure. In 2011 there were 15,307 fatal roadway departure crashes resulting in 16,948 fatalities, which was 51 percent of the fatal crashes in the United States for that year [14]. When a vehicle begins to depart a lane the most common reaction from the driver is to rapidly correct in an attempt to return to the lane. This results in a sudden, high magnitude change in steer angle. This of course initiates a dynamic maneuver; referred to as an impulse steer response. Additionally another leading cause of vehicle crashes is obstacle avoidance. This maneuver is simulated by either a single or double lane change. The vehicle purposefully leaves the lane it was traveling in and in the case of the double lane change return to the original lane after the obstacle. All three of these maneuvers result in a rapid change in steering input and at high speeds the response of the vehicle can become rather violent.

Speed is particularly important when dealing with such maneuvers on LCVs, once the speed is in excess of 50 mph the phenomena of rearward amplification plays a large roll in the overall dynamics of the LCV [15]. At such speeds mundane and subtle maneuvers experienced at the tractor can result in a rather large dynamic response towards the end of the vehicle train. This can lead to very dangerous outcomes including rollover and lane departure of subsequent units depending on the lateral acceleration and steering input from the leading vehicle.

Rearward Amplification Influences

The largest factor on rearward amplification is the length of the trailer. The longer the trailer, the less susceptible it is to rearward amplification. Additionally as the number of trailers increase, so does the rearward amplification with the added trailer. For example, a triple trailer LCV with trailers measuring 48 ft in length will experience less rearward amplification than a triple with 28 ft trailers. Similarly the triple will have less rearward amplification than a double with 28 ft trailers [3]. If the trailers are of the same length then

simply the more trailers that are added the more rearward amplification can be expected. Additionally the magnitude of rearward amplification can be influenced by the frequency of steering input, location of pintle hitch connections between trailers, and the ratio between lateral stiffness on the vehicle tires to the weight of the vehicle [3].

As mentioned the frequency of the steering input plays a significant role in the rearward amplification characteristics of a vehicle. This correlation is illustrated in Figure 1.7. This graph was produced using data generated by a double tank trailer simulation. As can be seen at low frequencies the amplitudes of the three units is identical, i.e. there is no rearward amplification. As the frequency increases there begins to be some separation between the responses of the three units. As the frequency crosses 1 rad/s (0.16 Hz) the first two units (tractor & first trailer) begin to separate themselves from the last two units (dolly & second trailer). It is at this point that the lateral acceleration of the second trailer is greater than that of the tractor. Then, at approx 3 rad/s (0.48 Hz) the maximum separation between the response of the tractor and second trailer is experienced. At this frequency the magnitude of the lateral acceleration experienced by the second trailer is nearly double that of the tractor.
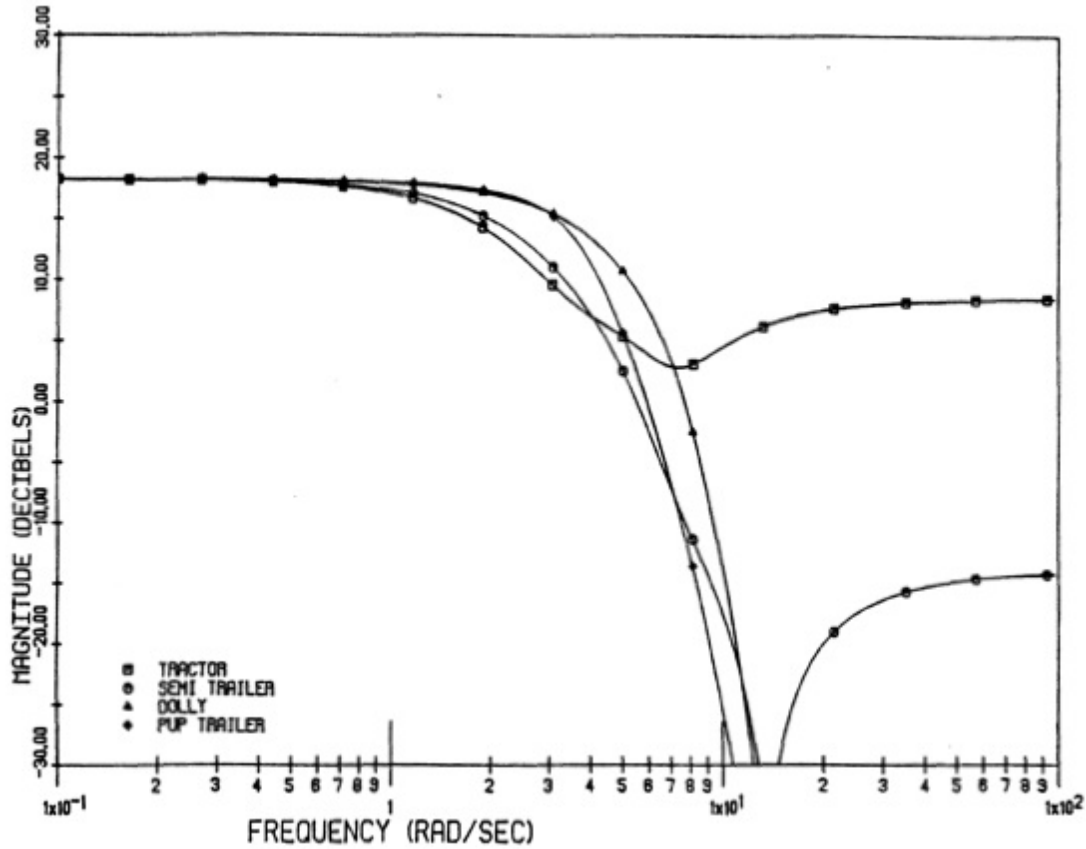
Figure 1.7: Rearward Amplification Response of Double Tank Trailer [5]

Though the figure shows that the lateral acceleration is less that what is generated at lower steering frequencies, the trend as it pertains to rearward amplification remains similar in more severe maneuvers and raises great concern as a potential cause for rollover. The danger is that since the driver of the tractor is limited to feeling only the lateral accelerations of the tractor, he/she may find themselves unaware of a potential rollover about to occur. So it is easy to see the danger in rearward amplification since the lateral accelerations experienced by the tractor may be well within its limits while the last trailing vehicle may experience lateral accelerations too great for it to handle, causing rollover.

Taking these results and exploring the outcome of several different configurations yields Figure 1.8. This plot looks at the amplification gain (the ratio of lateral acceleration between

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the last and first vehicle in a LCV) as a function of the same steering input frequency. As previously illustrated, the amplification is minimal at low frequencies and begins to separate at approximately 1 rad/s (0.16 Hz) with a maximum separation experienced at approximately 3 rad/s (0.48 Hz). Note that the largest gain is experienced by the triple trailer with 28 ft trailers, which is very similar to the vehicle used in testing for this research. The description of each configuration in the study can be found in Table 1.3.
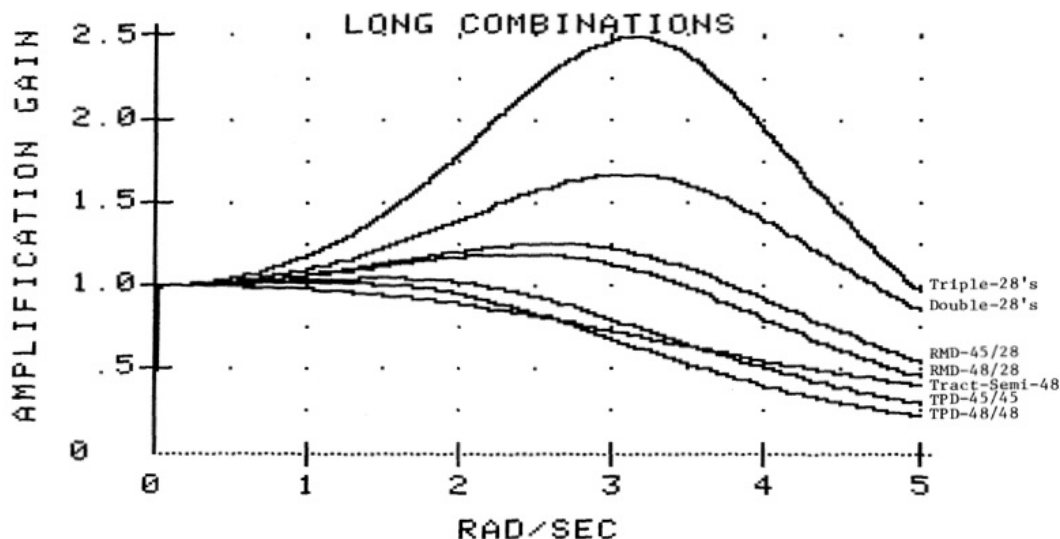
Figure 1.8: Rearward Amplification Response of Various Vehicle Combinations [3]

Rearward Amplification Outcomes

The most severe result of rearward amplification is vehicle rollover. This is due to the increased lateral acceleration in each successive unit which at some point will exceed the vehicle's static rollover threshold (SRT). The SRT is defined as the maximum angle which a vehicle can withstand before it or any of the successive units experience rollover. As with any vehicle though, the rollover threshold is effected by a variety of parameters including

but not limited to CG height, suspension components, tire stiffness, track width, and load distribution.

Vehicle Off-Tracking

During low-speed turns, the trailing axle follows a path inside the one set by the lead axle. The lateral offset from the front axle path is proportionate to the wheelbase of the vehicle. This same trait is exhibited in LCVs in that the axles of each unit of the combination track to the inside of the path followed by the preceding axle. This phenomena is what leads to drivers of semi-trucks to have to 'square the corner' when making turns in low speed urban environments. An illustration of low speed off-tracking is shown in Figure 1.9. As previously stated as speed is increased the trailing axle tracks closer to the centerline of the lead axle and will eventually, at high enough speeds track to the outside of the lead axle path. This behavior is illustrated in Figure 1.10.
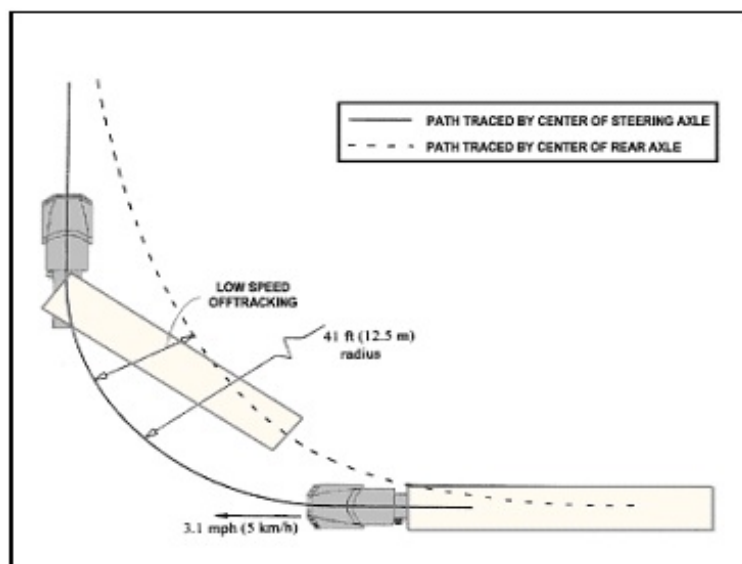
Figure 1.9: Low Speed LCV Off-Tracking [4]
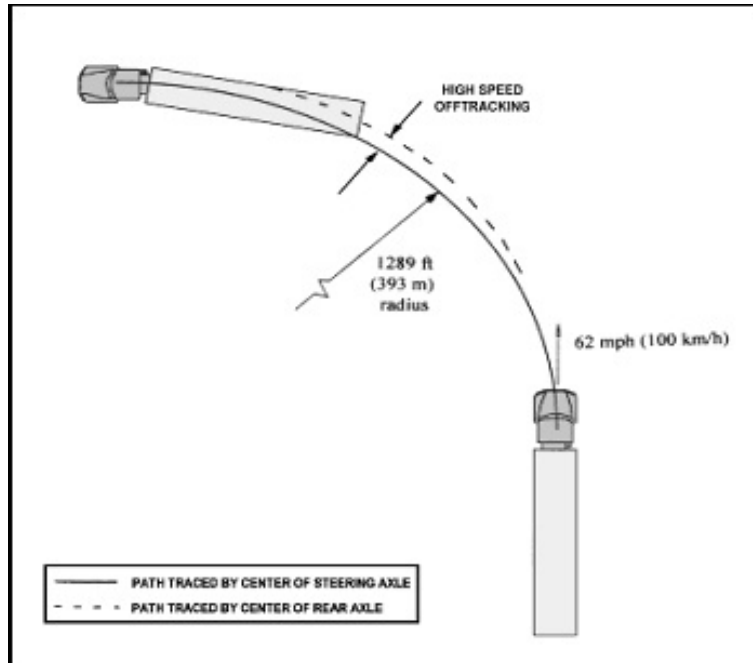
Figure 1.10: High Speed LCV Off-Tracking [4]

The level of off-tracking is effected by the length between each axle and the number of articulation points between the units of the vehicle also influences off-tracking [3]. One of the key areas of concern is that of on ramps and exit ramps of highways and interstates. With enough off-tracking the trailing vehicle can end up traveling off the inside edge of the ramp [3]. In order to better characterize off-tracking a simulation was run with seven different configurations at low speeds around an exit ramp with a constant radius of 300 ft. Those results are shown in Table 1.2. The abbreviations for the configurations are detailed in Table 1.3.

The 'Swept Path' is the width needed to pass the entire vehicle, assuming a common width of 102 inches [3]. As discussed above, if a vehicle increases speed through the turn the amount of off-tracking diminishes to a point where the trailers will actually begin to track outside of the path set by the lead vehicle. The same simulation was run as above but with a radius of 600 ft and at a speed of 55 mph, those results are shown in Table 1.4. Again, refer to Table 1.3 for abbreviation explanations. In the high speed simulation, all of

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Table 1.2: Low Speed Off-Tracking Results [3]

		Off-Tracking		Maximum Swept Path	
		m	ft	m	ft
1	Double-28	0.61	3.20	2.0	10.5
2	Triple-28	0.88	3.47	2.9	11.4
3	Tr/Semi 48	0.98	3.57	3.2	11.7
4	RMD-45/28	1.04	3.63	3.4	11.9
5	RMD-48/28	1.16	3.75	3.8	12.3
6	TPD-45/45	1.49	4.08	4.9	13.4
7	TPD-48/48	1.71	4.30	5.6	14.1

Table 1.3: Legend for Table 1.2, Table 1.4, and Figure 1.8 [3]

Short Name	Full Name	Semitrailer Lengths (ft)		Semitrailer Lengths (m)	
Tr/Semi-48	Tractor with 48 ft Semitrailer	48.0	-	14.6	-
Double-28	STAA Double	28.0	28.0	8.5	8.5
RMD 48/28	Rocky Mountain Double	48.0	28.0	14.6	14.6
RMD45/28	Rocky Mountain Double	45.0	28.0	13.7	13.7
TPD 48/48	Turnpike Double	48.0	48.0	14.6	14.6
TPD 45/45	Turnpike Double	45.0	45.0	13.7	13.7
Triple-28	Triple	28.0	28.0	8.5	8.5

the configurations saw a decrease in off-tracking. Additionally all of the LCV configurations saw more off-tracking than the typical trailer/semitrailer combination. While interesting, there shouldn't be much weight put on this as the potential for the high speed off-tracking phenomenon to cause a collision is considered minimal [3].

Table 1.4: High Speed Off-Tracking Results [3]

		Off-Tracking	
		m	ft
1	Tr/Semi 48	0.16	0.52
2	TPD-48/48	0.34	1.10
3	TPD-45/45	0.38	1.25
4	RMD-48/28	0.41	1.33
5	Double-28	0.44	1.43
6	RMD-45/28	0.44	1.45
7	Triple-28	0.65	2.13

Vehicle Rollover

When a vehicle undergoes a dynamic maneuver, weight is transferred from the inside wheel to the outside wheel. If the vehicle has a suspension system then the phenomena of roll is experienced. The aforementioned weight transfer creates a moment about the roll center of the vehicle that is referred to as the roll moment. To counteract this moment, force is transferred from the inner wheels to the outer wheels. This is illustrated in Figure 1.11. Summing the moment about the center of the outer tire contact patch yields Equation (1.1). This is using the small angle approximation of $\sin \varphi = \varphi, \cos \varphi = 1$.
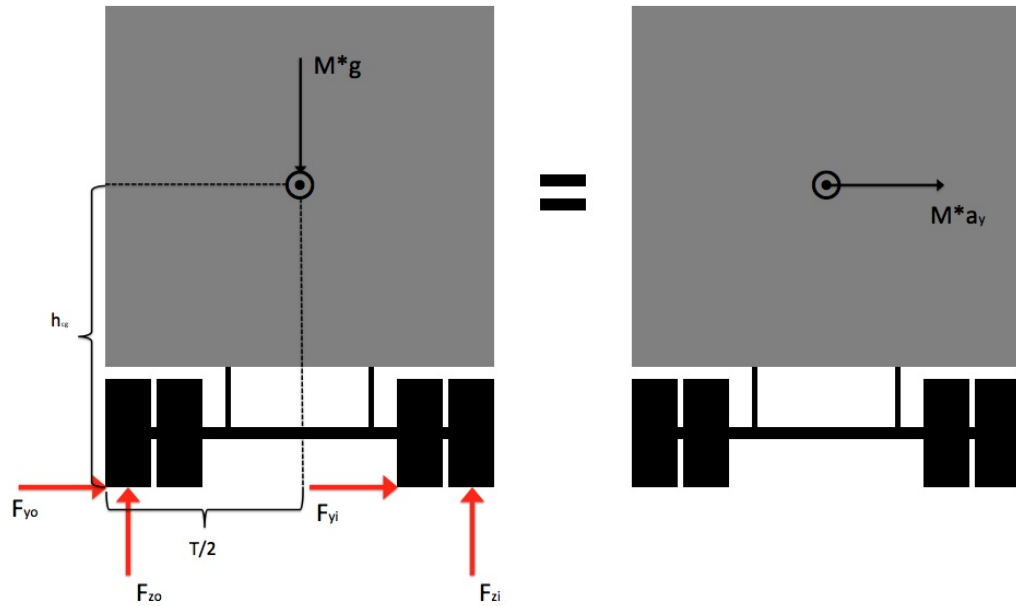
Figure 1.11: Rollover Moment Diagram

$$Ma_yh_{cg} - M\varphi h_{cg} + F_{zi}t - Mg\frac{t}{2} = 0 \qquad (1.1)$$

where

F_{zi} = Inner Vertical Tire Force

t = Track Width

M = Vehicle Mass

a_y = Lateral Acceleration

h_{cg} = Vertical Height of Center of Gravity (CG)

φ = Transverse Slope

It is important to note that there were some assumptions made when deriving Equation (1.1), those being that you can neglect the effect of the vehicle frame and suspension compliance. These neglections are made because rigid chassis behavior is much easier to

calculate as you do not need more precise information about the vehicle i.e. suspension stiffness and roll center. As long as the vehicle stays within its rollover threshold, the effect of this assumption is minimal [6].

The phenomena of roll happens in several stages. First the vertical load on the vehicle is transferred from the inner tires to the outer tires and continues until the vertical load on the inner tires is equal to zero. This point is refereed to as the stability limit of the vehicle. The vehicle will not rollover until one of two things happen. One, the location of the center of gravity (CG) passes outside of the outer tires. Or the stabilizing moment described above is less than the roll inertia generated by the maneuver. This rarely happens in passenger vehicle as they experience what is called yaw divergence typically long before rollover. Yaw divergence is when the tires cannot provide enough lateral force to maintain the maneuver and the tires begin to slide on the road.

Vehicle Understeer/Oversteer

One of the most common metrics to measure a vehicle's steering characteristic is by calculating the understeer gradient. As defined in Equation (1.2), the understeer gradient is the ratio of the deviation from the Ackerman steering angle to the lateral acceleration [16].

$$K = \frac{\left(\delta - \left(\frac{L}{R}\right) * 57.3\right)}{a_y} \tag{1.2}$$

where

δ = Road Wheel Angle (deg)

L = Tractor Wheel Base Length (steer axle to drive axle center-line)

R = Turn Radius

$\frac{v^2}{Rg}$ = Lateral Acceleration a_y

K = Understeer Gradient (deg/g)

The factor 57.3 converts from radians to degrees

However, when you look to analyze a heavy vehicle with many axles it become much more complicated; but can be expressed as an equivalent two-axle vehicle [17].

The yaw stability of a vehicle is dependent on whether the understeer gradient, K for that vehicle is greater than zero, less than zero, or exactly zero. In the case where K is less than zero the vehicle is said to be understeer. Whereas a positive K characterizes the vehicle as oversteer; if K is zero then the vehicle is said to exhibit neutral steer characteristics [16]. Passenger cars in today's market avoid making a vehicle that is oversteer as that is a more dangerous case for the everyday driver. In the oversteer case it would take less steer angle to perform a constant radius turn if the driver were to increase speed. It is obvious to see how that would not be the desired condition for even the most experienced drivers to deal with on a daily basis.

When dealing with LCV's, Equation (1.2) can be applied to each unit of the combination in order to determine each unit's understeer gradient. This is achieved by using the road wheel angle of the steer axle to calculate K for the tractor. The articulation angle between the subsequent trailers and the dolly or tractor to which they are connected is used to calculate K for the other vehicles in the combination [5]. When studying LCV dynamics it is important to remember that since each unit has an independent value for K there can be units that are oversteer at the same time as there are other ones that are understeer and/or neutral steer. Furthermore, as each unit in the combination is unique in that they are loaded and constructed differently; the effects of vehicle speed and lateral acceleration on the unit's understeer gradient are going to be different [18, 19].

Being that there are instances where there will be a mixture of understeer and oversteer units in a LCV, it is important to understand what each combination will mean for the dynamics of the vehicle. Since it is very rare to see any vehicle exhibit neutral steer we will only consider the resulting four possible combinations of understeer and oversteer. The dynamics of each combination is described in Table 1.5.

Table 1.5: Resulting Dynamics from Understeer/Oversteer Combinations [6]

		Leading Vehicle	
		Oversteer	Understeer
Trailing Vehicle	Understeer	As speed increases toward the critical speed, the articulation gain approaches infinity. This results in a jackknife. System is unstable at high speed.	The vehicle is stable. As speed increases, the articulation angle gain (increase in articulation relative to steering input increase) will approach the ratio of the two units' understeer gradients.
	Oversteer	Response depends on whether the ratio of the understeer gradients is greater or less than the ratio of the wheelbases, and the articulation gain will go to negative or positive infinity. This results in a jackknife or a swing out, though the difference will be hard to tell from the driving perspective. The vehicle is unstable at high speed.	The articulation gain is initially positive but becomes negative and the trailer swings out. This is an unstable arrangement at high speed. However, at low speeds, the articulation gain is positive, making the vehicle drivable.

Chapter 2

Test Vehicle Instrumentation

The aim of this chapter is to detail the process of developing and implementing the data acquisition system (DAQ) for use on the LCV triple test vehicle. The goal of the DAQ was to capture those responses outlined earlier in section 1.2.2 at high data rates and store the data in a manner conducive to analysis. Each section will discuss the process of selecting the sensor(s) as well as integrating the sensor into the DAQ. The resulting data files containing the dynamic measurements will facilitate the analysis and comparison of the response of the actual vehicle to that of the simulated vehicle. Through a collaborative effort with other research partners the following list of responses were chosen to be targeted for measuring:

1. Roll Angle per Lateral Acceleration

2. Yaw Rate per Lateral Acceleration of Tractor and Trailers

3. Path Deviation Error per Trailer Referenced to the Tractor

4. Lateral Acceleration per Steer Angle

5. Yaw Rate per Steer Angle

6. Lateral Acceleration per Trailer

7. Lateral Acceleration of the Tractor

8. Yaw Rate per Trailer

9. Yaw Rate of the Tractor

10. Understeer Gradient of the Tractor and Trailers

11. Trailer Motion Damping Time and Distance

The above characteristics can be separated into three measurement groups

1. Position Measurements

2. Inertial Measurements

3. Displacement Measurements

2.1   Sensors

Sensor selection was a critical part of this project. With such a large vehicle it required a large amount of sensors; luckily this research involved several other research team members outside of Auburn University that were able to help provide the additional sensors needed to instrument the triple. This process included many discussions on not only what needed to be captured but how to capture what was identified as the critical responses. In the end a total of 37 individual sensors were installed on the triple-trailer. These sensors produced a total of 206 individual channels of data that were to be recorded by the DAQ. That process is outlined below in Section 2.2. The measurements that were recorded are shown below in tabular form in Table 2.1 as well as in picture form in Figures 2.1. Note that in Table 2.1 a sensor bracketed by '()' means that the measurement was attempted but for some reason not captured.

The channels that are key to characterizing vehicle dynamics were to be recorded at a nominal sampling rate of 100 Hz. Supplementary channels were sampled at lower rates, as indicated in the table. Section 2.2 explains how each sensor's data was transmitted to a central computer and every single data point was given a time stamp. While the sampling rate was not exactly 100 Hz and not all channels were sampled simultaneously, an experiment prior to data collection showed that the method reliably provided data at the time indicated in each time stamp.

Table 2.1: Summary of Measurements and Sensors

Unit	Quantity	Vehicle CAN	String Pot	GPS	IMU	GPS & IMU
Tractor	Horizontal and Vertical Displacement of the Steer Axle		SP1-25			
	Horizontal and Vertical Displacement of the Second Drive Axle		SP1-25			
	Steer Input at the Steer Column		SP1-25			
	Steer Input, Steer Kingpin		SP1-25			
	Engine Parameters	(X)				
	Three-Axis Accelerations and Angular Rates				MemSense	
	Position			Novatel		
Trailer 1	Horizontal and Vertical Displacement of the Axle		SP1-25			
	Three-Axis Accelerations and Angular Rates				CrossBow	
	Position			Novatel		
Trailer 2	Articulation Angle to Leading Converter Dolly		SR1A-62			
	Horizontal and Vertical Displacement of the Axle		SP1-25			
	Three-Axis Accelerations and Angular Rates					(RT2500)
	Position			Novatel		
Trailer 3	Articulation Angle to Leading Converter Dolly		SR1A-62			
	Horizontal and Vertical Displacement of the Axle		SP1-25			
	Three-Axis Accelerations and Angular Rates					(RT3200)
	Position			Novatel		

Each unit of the vehicle had two GPS receivers one for the measurement and one for redundancy. Additionally each unit had an IMU to record accelerations and angular rates, and string potentiometers to measure displacements within the vehicle. The two GPS and

Color	Item Description	Connection Type	Data Rate (Hz)		Color	Item Description	Connection Type	Data Rate (Hz)
	Sting Pot	CAN	100			MemSense	USB	150
	Engine CAN	CAN	100			Crossbow	RS-232	20
	Novatel	RS-232	5			RT-2500	TCP-IP	100
	U-Blox	USB	1			RT-3100	TCP-IP	100
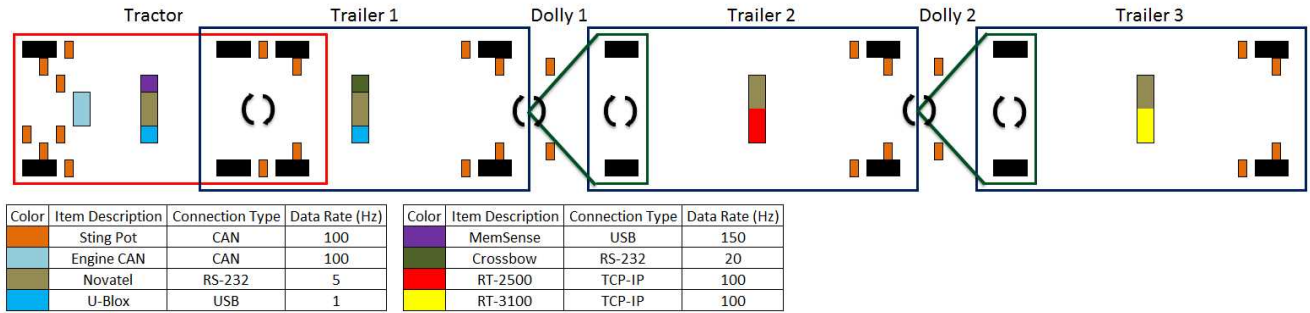
Figure 2.1: Sensor Placement on LCV Triple

IMUs were separate sensors on the Tractor and Trailer 1; whereas the GPS units and the IMU were integrated on Trailers 2 and 3.

2.1.1 Displacement Measurements

String potentiometers or 'string pots' were used to measure dolly-to-trailer articulation angles, lateral and vertical displacement of axles, and steering input. Several of the desired characteristics have to do with vehicle roll and understeer tendencies. In order to fully capture those characteristics it is necessary to understand what the axle of the vehicle is doing at the time of the maneuver. To achieve this, the decision was made to use string pots to measure the linear displacement of each axle in three dimensions. A diagram to show how this was to be achieved is shown below in Figure 2.2. Combining the string pot measurements with the IMUs and GPS measurements the desired characteristic values can be obtained. A total of 27 string pots were used along the vehicle; four were model SR1A-62 shown to the left in Figure 2.3 used to measure the dolly-to-trailer articulation. These weatherproof units have a stroke length of 62 inches. All other string pots on the vehicle were model SP1-25, shown in Figure 2.3 to the right, with a stroke length of 25 inches. They were installed to measure axle displacement on the test vehicle. The steering input was also measured with a SP1-25 string pot.
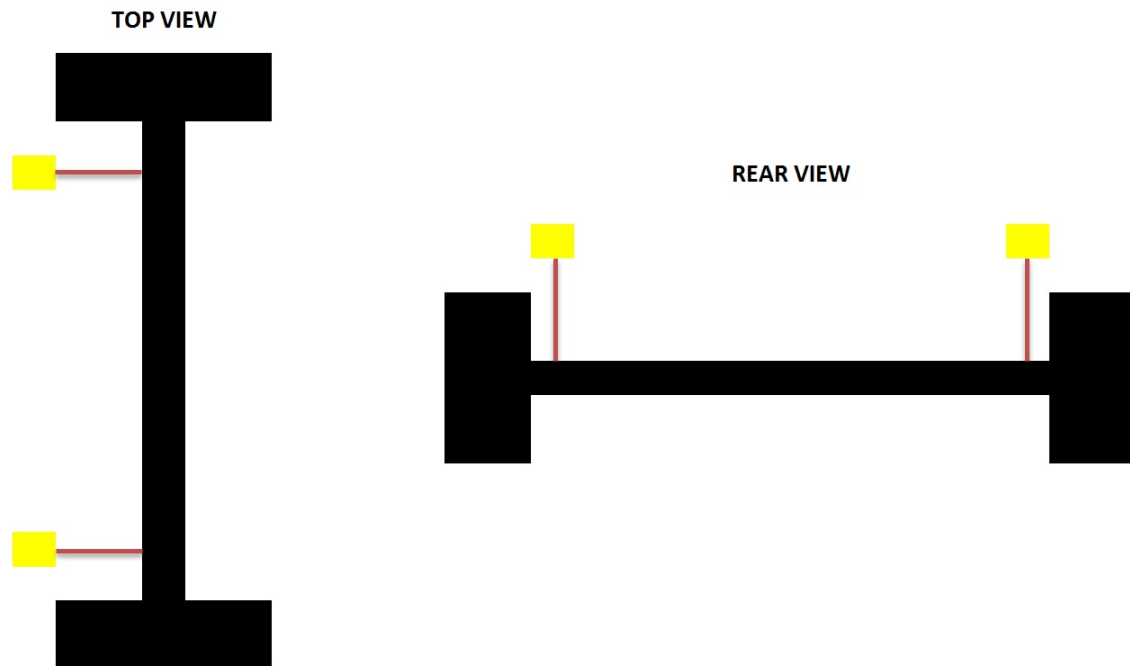
Figure 2.2: Sketch of Axle Deflection Measurements

Figure 2.3: Celesco String Potentiometers, SR1A-62 (left) and SP1-25 (right)

2.1.2 Positioning Measurements

One of the most crucial measurements for this project is position. If the position measurement is not accurate then the entire analysis can be effected greatly. GPS receivers range

wildly in performance as well as cost. The most costly units being the ones used in missile guidance and other various high precision environments. The cheapest being the ones placed in consumer electronics such as cell phones. In an attempt to minimize the error all four of the units were outfitted with a Novatel ProPak GPS receiver that provides acceptable performance for such a project. In addition the the Novatel receivers, the tractor and the first trailer had a u-Blox GPS receiver for redundancy. The second and third trailer used the OxfordRT units for redundancy. A picture of the Novatel receiver as well as the u-Blox receiver can be seen in Figure 2.4, an image of the OxfordRT units is shown below in Section 2.1.3.

Novatel ProPak   **uBlox EVK-6H**
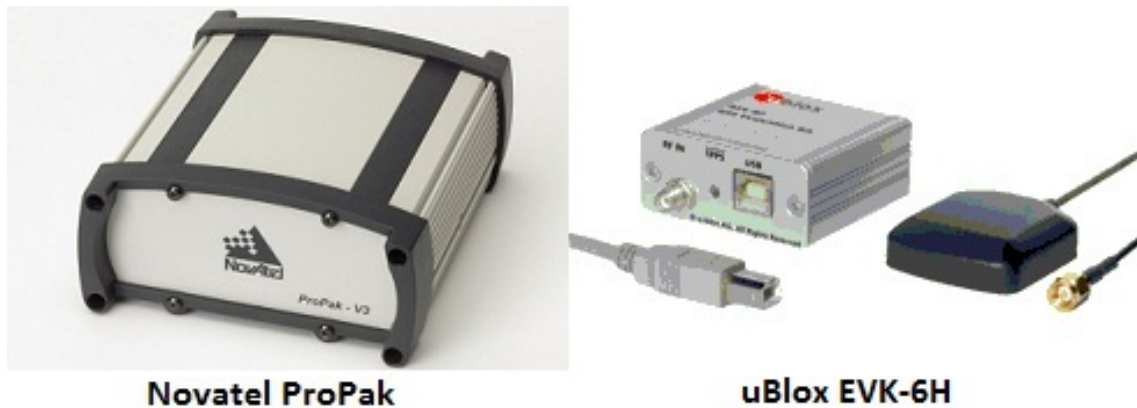
Figure 2.4: GPS Receivers Novatel ProPak (left) u-Blox Receiver (right)

2.1.3 Accelerations & Rates Measurements

Inertial measurements use accelerometers and gyroscopes to measure the rate of change bot laterally and rotationally in anywhere from one to six axes. Inertial Measurement Units (IMUs) contain three accelerometers and three gyroscopes internally aligned in such a fashion to measure both the acceleration and rotational rate along three axes. The IMU is referred to as a six axes since there are two measurements on each axes. When placed near the center of gravity of a vehicle, the output from the IMU can be translated into the yaw, pitch, and

roll of the vehicle. Figure 2.5 shows the three axes that are measured by the IMU and which axes translates to yaw, pitch, and roll.
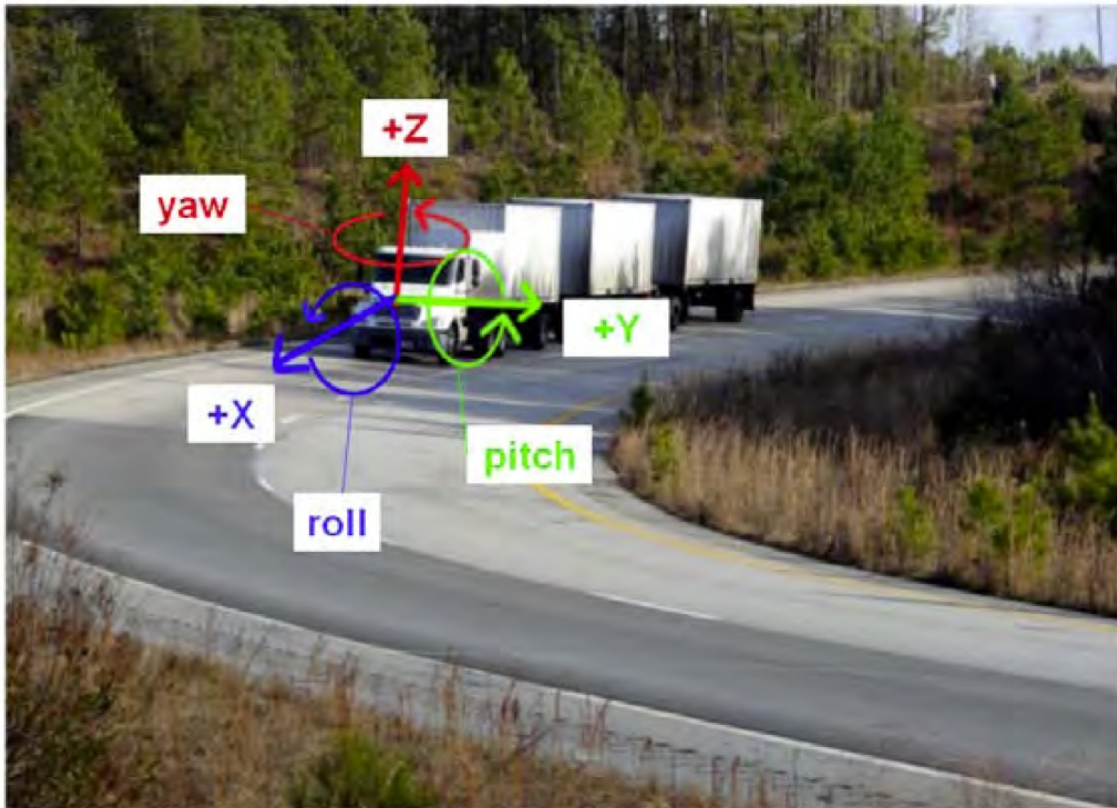
Figure 2.5: Illustration of Triple-Trailer Frame of Reference

IMU grades range from tactical, which is used in missiles and other very high precision environments all the way to hobby level where the sensors are very cheap and precision is not of the highest priority. Several quality IMUs were borrowed for this project from various sources. An IMU was mounted on each of the units in the combination. A MemSense IMU was obtained to be mounted on the tractor. Being much lower in price than the other sensors, the MemSense offers exceptional quality for its price. The MemSense is shown in Figure 2.6 along with its technical specifications in Table 2.2.

Table 2.2: MemSense Performance Statistics

Acceleration	NA02	NA05	NA10			
Dynamic Range	± 2	± 5	± 10	g		
Offset	±30	± 30	± 30	mg	0 to 70 °C Maximum
Nonlinearity	± 0.4 (± 1.0)	± 0.4 (± 1.0)	± 0.4 (± 1.0)	% of FS	Typical (Maximum)
Noise	0.6 (0.8)	1.1 (1.3)	2.1 (2.8)	mg	Typical (Maximum), 1 σ
Digital Sensitivity	9.1553×10^{-5}	2.2888×10^{-4}	4.5776×10^{-4}	g/bit	See Equation 1 on page 9
Bandwidth [1]	50	50	50	Hz	-3dB point
Angular Rate	-0150F050	-0300F050	-0600F050	-1200F050	°/s	
Dynamic Range	± 150	± 300	± 600	± 1200	°/s	
Offset	+/-1.5	+/-1.5	+/-1.5	+/-1.5	°/s	0 to 70 °C Maximum
Cross-Axis Sensitivity	+/-1	+/-1	+/-1	+/-1	%	Maximum
Nonlinearity	0.1	0.1	0.1	0.1	% of FS	Best fit straight line
Noise	0.36 (0.95)	0.56 (0.95)	0.56 (0.95)	0.56 (0.95)	°/s	Typical (Maximum), 1 σ
Digital Sensitivity	6.8664×10^{-3}	1.3733×10^{-2}	2.7465×10^{-2}	5.4932×10^{-2}	°/s/bit	See Equation 1 on page 9
Bandwidth [1]	50	50	50	50	Hz	-3dB point

Figure 2.6: MemSense Inertial Measurement Unit

The Crossbow NAV 440, shown in Figure 2.7 is a higher-grade IMU. Table 2.3 shows its technical specifications.

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Table 2.3: CrossBow Nav 440 Performance Statistics

PERFORMANCE

Position/Velocity

Position Accuracy	<3.0 m CEP
1PPS Accuracy	±50 ns

Heading

Accuracy	<1.0° rms (magnetic)
	<0.75° rms (with GPS aiding)

Attitude

Range: Roll, Pitch	±180°, ±90°
Accuracy	<0.4°

Angular Rate

Range: Roll, Pitch, Yaw	±200°
Bias Stability in run	<10°/hr
Bias Stability over temp	<0.02°/sec

Acceleration

Input Range	±4 g or ±10 g
Bias Stability in run	<1 mg
Bias Stability over temp	<4 mg

Figure 2.7: MemSense Inertial Measurement Unit

Table 2.4: Oxford RT2500/3100 Performance Statistics

Quantity	unit	RT2500	RT3100
Positioning Accuracy (SBAS)	m	2.0 SBAS	0.6
Positioning Accuracy (DGPS)	m	--	0.4
Velocity Accuracy	km/h rms	0.2	0.1
Heading	deg standard deviation	0.3	0.1
Roll and Pitch	deg standard deviation	0.15	0.05
Acceleration Linearity	% standard deviation	0.01	0.01
Angular Rate Bias	deg/s standard deviation	0.02	0.01

The Oxford RT-2500 Inertial and GPS Navigation System, shown in Figure 2.8, to the left includes three angular rate sensors (gyroscopes), three servo-grade accelerometers, the GPS receiver and all the required processing in one very compact box. The internal processing includes the strap-down algorithms (using a WGS-84 earth model), Kalman filtering and in-flight alignment algorithms. The internal Pentium-class processor runs the QNX real-time operating system to ensure that the outputs are always delivered on time the technical specifications can be seen in Table 2.4. The Oxford RT-3100, shown in Figure 2.8, to the right is similar to the Oxford RT-2500 model; but promises a little better accuracy in its measurements. Its technical specifications can be seen in Table 2.4 as well.

Figure 2.8: Oxford RT Units RT2500 (left) and RT3100 (right)

2.2 Data Acquisition

The test vehicle was equipped with numerous sensors that needed to be interfaced with various communication methods. To facilitate this complex data collection with the maximum control over the process, a custom data collection system was developed. The system consisted of an industrial computer with Ubuntu Linux operating system and a wireless (WiFi) router. The Industrial computer ran without a monitor, keyboard, or mouse and connected to the Oxford RT units via the router on an Ethernet network connection. The wireless router allows the data collection process to be monitored and controlled via a laptop computer in the truck cab. It should be noted that no data was sent over the wireless link it was only to monitor and control the data acquisition. All data was recorded directly to the industrial PC and the data acquisition process, and once started was not interrupted by a loss of communication from the laptop in the cab. The location of the PC can be seen in Figure 2.9.
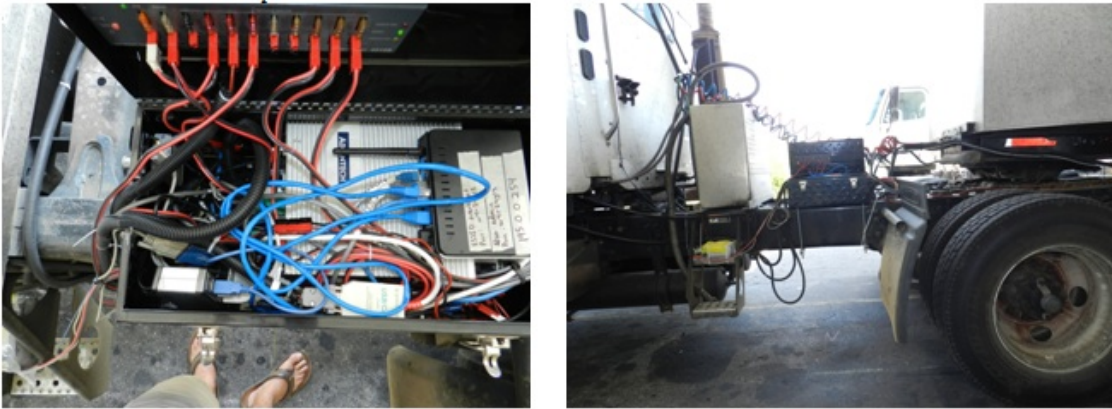
Figure 2.9: Placement of Advantech Industrial PC

The Advantech PC was wired to each of the sensors either directly or through an onboard network i.e. CAN bus. The interfaces of the Advantech are detailed as follows.

- Direct UDP/IP communication with the OxfordRT units over CAT6 Ethernet

- Four Serial (RS-232) ports:

    - Three Novatel GPS Units for Tractor and Trailer 1&2

    - Trailer 1 IMU (Crossbow 440)

- Six USB Connections

    - MemSense IMU

    - RS-232 to USB Converter for Novatel GPS Receiver on Tractor

    - Two u-Blox GPS Receivers

    - Two USB-CAN Converters for the Two CAN Buses

The wiring between the sensors and the computer is shown in Figure 2.10.
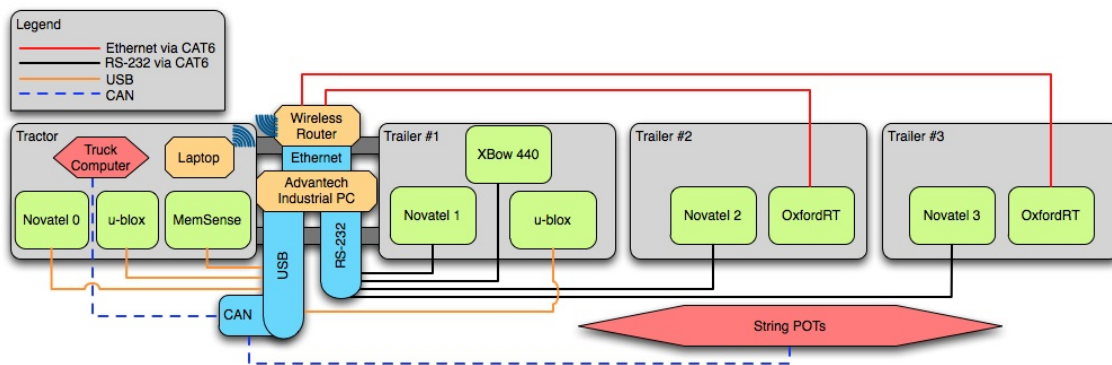
Figure 2.10: Wiring Diagram Illustrating the Connections Between the Sensors and the DAQ

2.2.1 CAN Bus

Most of the sensors in this project had internal signal conditioning and output a digital signal. Part of this research required the need to build signal conditioning, including an analog-to-digital (A/D) converter, for the string pots. The string pots needed to be connected to an A/D converter, which would convert the signal to digital and then send the message over a Controller Area Network (CAN) network similar to that which is found on most

production vehicles. The main driving force behind this decision as opposed to purchasing and using a commercial DAQ with A/D converters attached was controllability. Since the entire system was to be designed and implemented in house, all of the inner workings will be known making any possible troubleshooting easily accomplished. A diagram of the system is in Figure 2.11.

Color	Description	Color	Description
	CAN Terminator		Message Line
	CAN Cable		Power
	String Pot		Ground
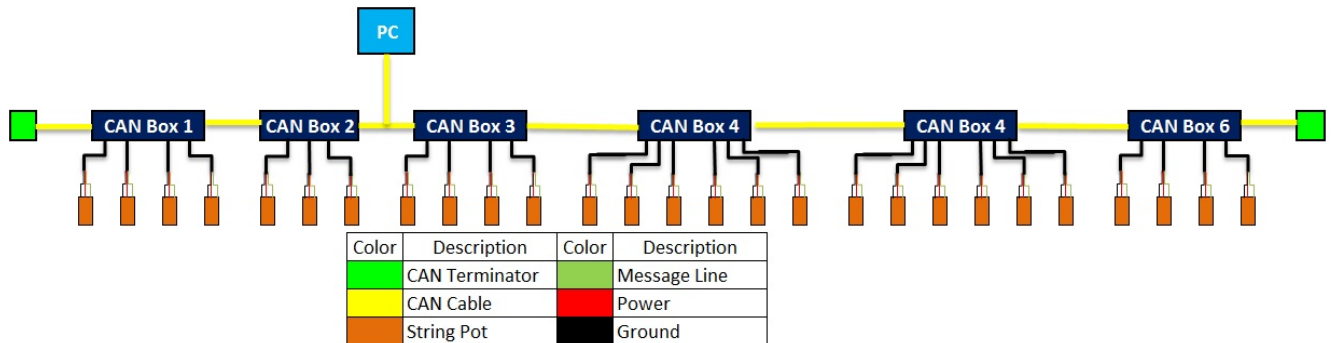
Figure 2.11: Diagram of CAN Bus

As mentioned, the CAN network is the same network that is standard on vehicles today in order for microcontrollers and devices to communicate with each other within a vehicle without a host computer. The LCV contained two separate CAN buses, one that is already there from the factory and one that was created for the string pots. The factory installed CAN network is in accordance with the SAE J1939 standard. Using the SAE J1939 message list, the vehicle codes were translated and the values were able to be read by the DAQ and subsequently logged.

The second network created was for use with the string pots and their associated A/D converters. This path was chosen for multiple reasons; the main two being complete control over design as well as lowering line noise on the string pots by placing the A/D converter close to the string pots themselves. The idea of having complete control over the network is the most critical part of the whole process. This allowed for the creation of a proprietary message set that could not interfere with any other CAN network. An added benefit is that it provided extensive knowledge of the system so that in the event something went wrong

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it took less time to diagnose and resolve the issue. There were a total of six CAN boxes created, each containing the A/D converter, CAN chip, and circuit board. One of these boxes can be seen in Figure 2.12.
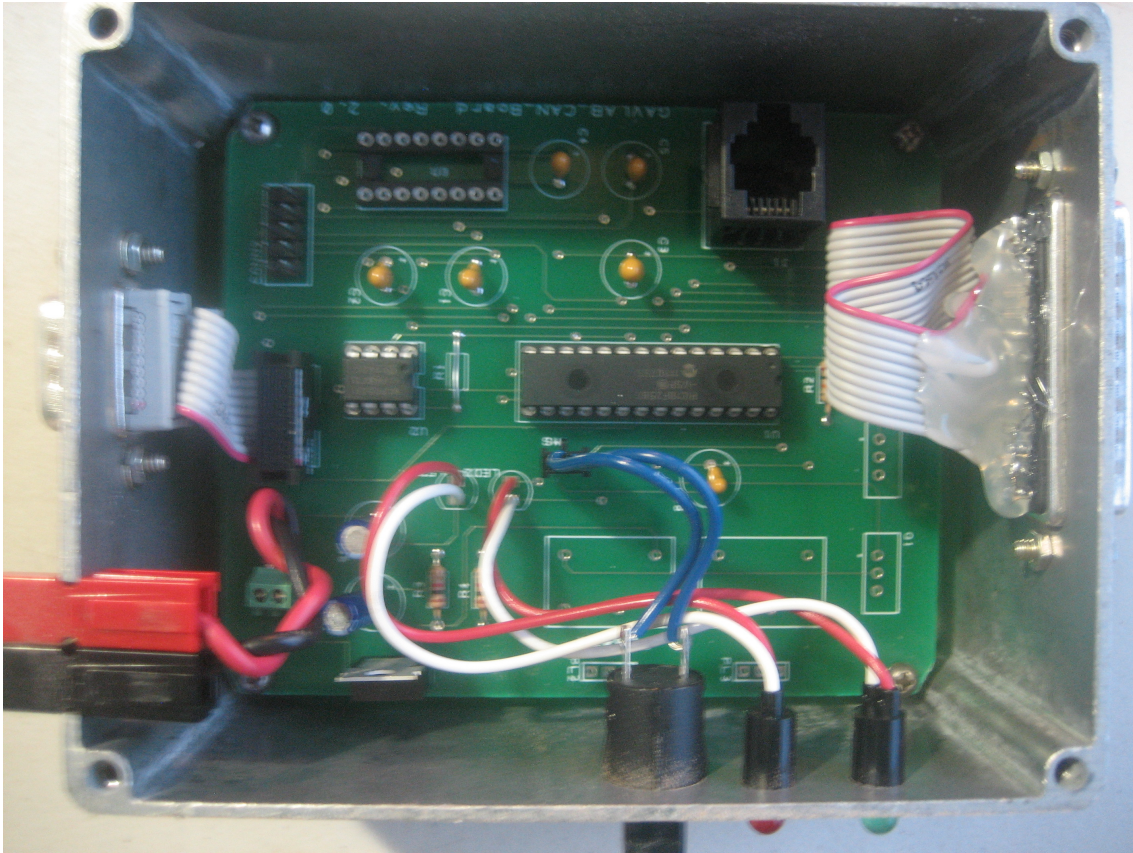
Figure 2.12: Inside of a CAN Box

Each string pot was connected to the CAN box by a custom DB25 connector that was wired to provide power and ground to each string pot as well as a line for the message. In order to collect the measurements from the string pots, each A/D had to be polled over the network. This was achieved by setting up one of the CAN boxes to send out a message on the CAN bus at 100 Hz that would trigger each of the A/D converters to poll all of the connected string pots. The message set used for the string pots is relatively straightforward; each A/D will send out a status message every second to alert the computer if something is not working. The message structure for the String Pot CAN-bus can be seen in Figure 2.13.
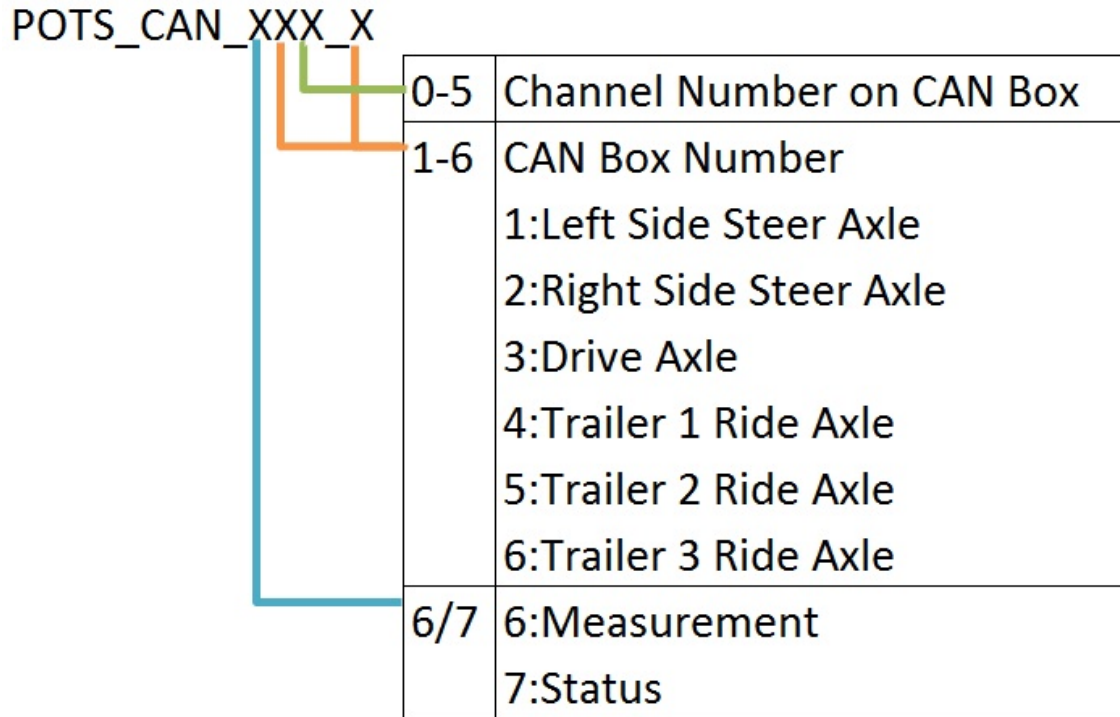
Figure 2.13: CAN Message Structure

2.2.2 Sensor Interfacing

Code had to be written to receive and interpret the data from each sensor. Some of the code already existed and was used again for this research. The new sensors that had to be interfaced were the MemSense IMU, the u-blox GPS units, and the Oxford RT units. The code for all of the sensor interfaces was written in C++ and ran on the embedded Linux computer on the tractor. The middleware used to communicate all of the sensor data between processes is called Mission Oriented Operating Suite (MOOS) [20]. This middleware uses client-server architecture with a centralized database and provides basic tools for Inter-Process Communication via sockets. This allows for viewing the raw data in real time, and logging the data in a standard format. Each sensor had a corresponding process running that interfaced with that sensor, formated its data, and published it as separate channels to the MOOS database. The MOOS database holds the latest value from each channel on

each sensor and allows other processes to access this data. An illustration of this interface process can be seen in Figure 2.14.
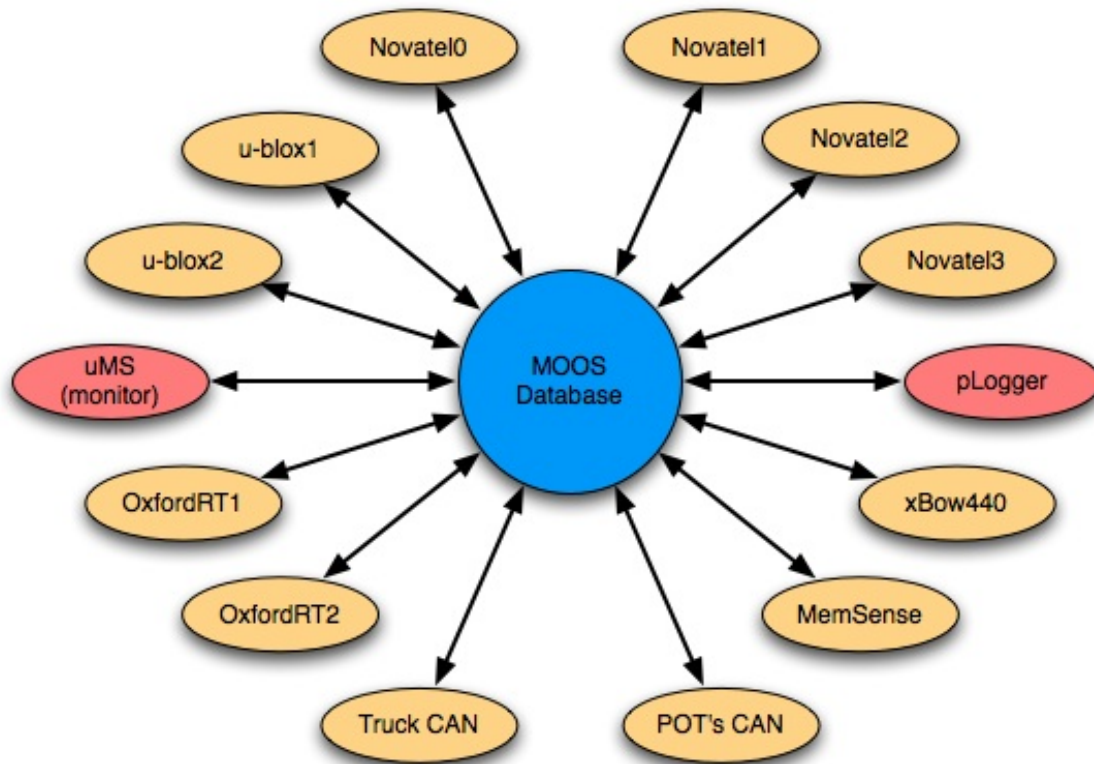
Figure 2.14: Illustration of the MOOS Architecture

2.2.3   Data Logging

Using the laptop in the cab of the truck, the logging was started and stopped via Secure Shell (SSH). Additionally, the data was monitored using MOOSs uMS utility which shows the latest values for each of the sensors in a table. The MOOS utility pLogger connects to the MOOS database and records all changes to all channels to an asynchronous log format. This preserves the data in its raw form with its original timestamps taken by the sensor interface process. This is more difficult to process than synchronous data logs, but provides more accurate timing information. An example of the file format can be seen in Figure 2.15.

```
2212  1.16        zAngularRateZ_38        gOXTS-RT                      0.0006
2213  1.16        zAngularRateY_38        gOXTS-RT                      -0.0011
2214  1.16        zAngularRateX_38        gOXTS-RT                      0.0023
2215  1.16        zAccelZ_38              gOXTS-RT                      0.1471
2216  1.16        zAccelY_38              gOXTS-RT                      9.8181
2217  1.16        zAccelX_38              gOXTS-RT                      -0.101
2218  1.16        zTime_38                gOXTS-RT                      -25.106
2219  1.161       POTS_CAN_613_1          gTruckCanSuspensionPots_pots  43
2220  1.161       POTS_CAN_622_2          gTruckCanSuspensionPots_pots  265
2221  1.161       POTS_CAN_612_1          gTruckCanSuspensionPots_pots  170
2222  1.161       POTS_CAN_621_2          gTruckCanSuspensionPots_pots  204
2223  1.161       POTS_CAN_611_1          gTruckCanSuspensionPots_pots  375
2224  1.161       POTS_CAN_610_1          gTruckCanSuspensionPots_pots  43
2225  1.161       POTS_CAN_620_2          gTruckCanSuspensionPots_pots  265
2226  1.161       POTS_CAN_630_3          gTruckCanSuspensionPots_pots  839
2227  1.162       zGPSSeconds_gNovatel2   gNovatel2                     25618140
2228  1.162       zGPSWeek_gNovatel2      gNovatel2                     163
2229  1.162       zHgtStdDev_gNovatel2    gNovatel2                     4.6626
2230  1.162       zLongStdDev_gNovatel2   gNovatel2                     2.4053
2231  1.162       zLatStdDev_gNovatel2    gNovatel2                     1.6299
2232  1.162       zHeight_gNovatel2       gNovatel2                     185.4075
2233  1.162       zLong_gNovatel2         gNovatel2                     -85.2961
2234  1.162       zLat_gNovatel2          gNovatel2                     32.598
2235  1.162       zSampleTimer_gMemSense  gMemSense                     16931
2236  1.162       zMagZ_gMemSense         gMemSense                     -0.7923
```

Figure 2.15: Screen Shot of Asynchronous Log File

2.3 Hardware Installation

With the three trailers being nearly identical, the mounting boxes and brackets required
were fairly similar. Several sensors needed to be mounted in the tractor's engine compart-
ment. This included one string pot set up on the steer axle, along with two string pots for
vertical and horizontal displacement of the kingpin, and lastly a string pot for the angular
rotation of the steering shaft. Behind the tractor cab a toolbox with the main CPU was
mounted. This box is where the two CAN buses were connected to the industrial computer
for data acquisition and processing. Figure 2.9 shows the actual toolbox that was on the
tractor along with the location. This box contained the industrial computer, which handled
all of the data acquisition as well as various networking devices used for communication
throughout the vehicle.

As previously stated, string pots were used to measure the vertical and horizontal dis-
placement of the axles. One pair of string pots were mounted directly above the axle and

another mounted directly horizontal to the axle. This was done to maximize the displacements and maximize signal to noise. Figure 2.16 shows these brackets mounted on the LCV with the string pots attached. Note the cable for the string pots is highlighted in red for all of the following pictures.

Figure 2.16: String Pots Mounted for Axle Deflection

Similar to the toolbox mounted directly behind the cab of the tractor. Another toolbox was mounted under each of the trailers. Figure 2.17 shows how they were mounted; a close-up shows the power and serial cables going into and coming out of the box.

Figure 2.17: Example of Toolboxes Mounted Underneath Trailers for Sensor Mounting

As described above, each of the string pots were connected to a CAN-box that contained the A/D converter. These A/D converters could handle six string pot inputs, and they output

their data into the CAN bus that run alongside the trailer combination. Figure 2.18 below shows one of these A/D converter boxes mounted under a trailer.

Figure 2.18: Mounted CAN Box

To calculate the articulation angle, the longer string pots were mounted on the dolly and attached to the successive trailer. They were crisscrossed in an attempt to get as linear of a measurement as possible and to maximize the displacement. Figure 2.19 shows the actual mounting on the LCV.
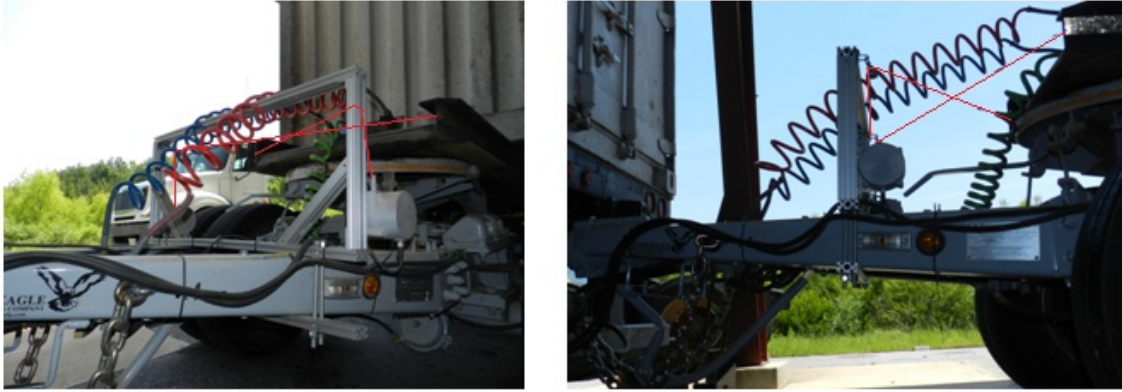
Figure 2.19: String Pots Mounted for Articulation Angle

The tractor's engine compartment was not only less conducive to taking measurements, but it also required more of them. The displacement of the kingpin on both sides required two more string pots to be mounted on the axle. Additionally, measuring the angular displacement of the steering shaft required a string pot be mounted perpendicular to the shaft. The axle deflection string pots can be seen in Figure 2.20 and the steering shaft in Figure 2.21.
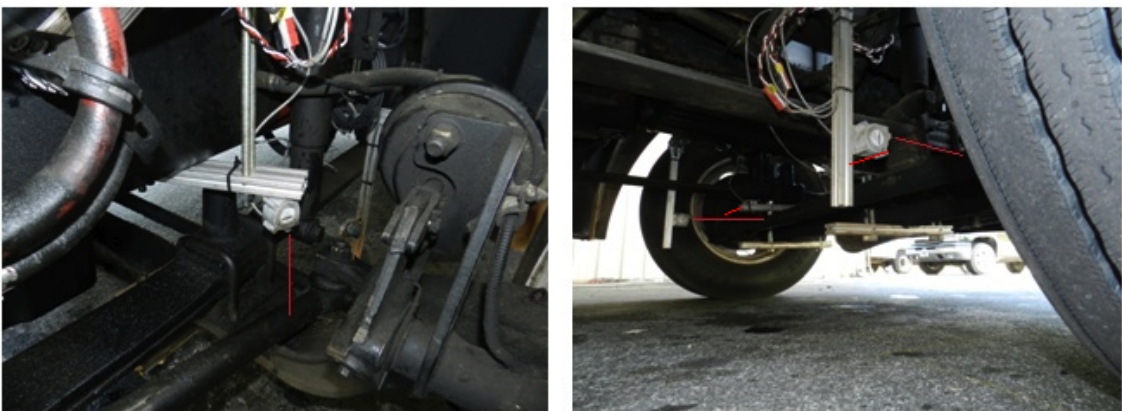
Figure 2.20: Steer Axle String Pots
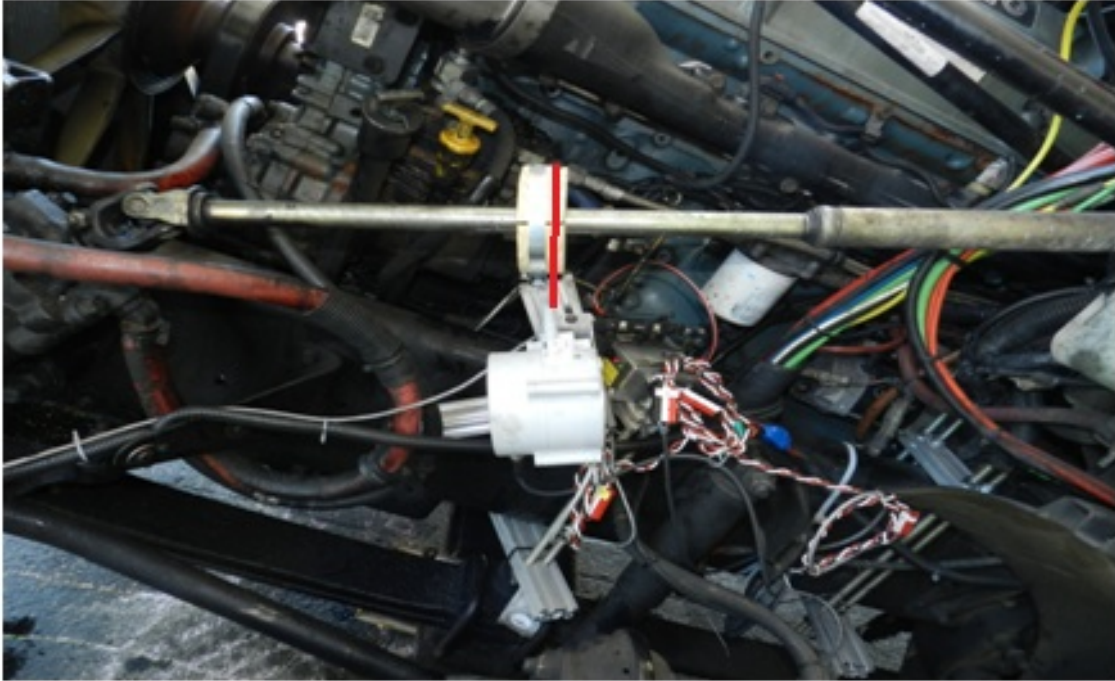
Figure 2.21: String Pot Mounted for Steer Angle

Each of the GPS receivers requires antennas to be mounted on top of its respective trailer. Shown in Figure 2.22 are the patch antenna on the center of the trailer roof for the u-blox, and the larger antenna on the side of the trailer roof for the Novatel.

Figure 2.22: GPS Antenna Mounted on the Trailer Roof

Chapter 3

Experimental Results

The scope of this chapter is to outline and describe the experimental testing undertaken with the LCV triple at the NCAT test track. The goal of the test plan was to expose the test vehicle to various maneuvers that are designed to incite certain dynamic responses. The dynamic responses of interest were outlined earlier in Section 1.2.2. The responses to these maneuvers were to be captured by use of a custom designed data acquisition system (DAQ) that was detailed in Chapter 2.

3.1   Test Track

All of the experimental testing was conducted at NCAT in Opelika, AL. This facility is used for advanced asphalt wear testing and uses a fleet of tractor trailer combinations to wear sections of asphalt at accelerated rates. The track located at the facility is one of a kind and offers a very unique platform for both heavy truck research as well as other automotive research goals that could not be conducted on normal roads and highways. The track is a 1.7 mile long oval comprised of 46 different 200-ft. test sections. The two curves the track has an 8° banking and use a spiral-curve-spiral configuration. An aerial view of the track can be seen in Figure 3.1.

3.2   Test Vehicle

As mentioned, NCAT operates a fleet of tractor trailer combinations, the majority of which consist of a lead tractor pulling three sleds loaded with steel plates. However, one of the vehicles was perfectly suited for this research project. It consists of a Freightliner tractor pulling three standard shipping containers; which are loaded down with concrete barriers.

Figure 3.1: Aerial View of NCAT Test Track

The containers are loaded to greater than the legal limit in order to increase the wear rate of the asphalt. Each container measures 20 ft in length and is riding on a Cheetah container chassis. The first trailer is obviously connected to the tractor with the second and third trailers being connected via identical silver eagle converter dollies.

3.3   Testing Maneuvers

As mentioned above, the vehicle underwent several different maneuvers as a part of this testing. This section will describe in detail each of those maneuvers as well as what the maneuver is aimed at achieving with regards to the LCV triple.

3.3.1   Constant Radius Turn

Object of Maneuver

The object of the constant radius maneuver is to asses several of the vehicle's steady-state handling characteristics. The main two being the understeer gradient of each trailer as well as the roll steer of the converter dollies. The maneuver was to be repeated at various speeds ranging from 20 to 45 mph. The driver was to have final say on whether or not each

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attempt was to be completed. Each speed was to be repeated 10 times to ensure that not only adequate but complete data was recorded. In order for this maneuver to be successful in characterizing the vehicle characteristics the conditions of the maneuver needed to meet most if not all of the following.

- Consistent Road Wheel Steer Angle

- Consistent Vehicle Speed

- Consistent Lateral Acceleration *for runs of the same speed*

Maneuver Path

The maneuver is to be performed exactly as it sounds. The vehicle is to travel in a constant radius turn while attempting as best as possible to maintain the conditions listed above. As mentioned earlier in Section 3.1 the curves at the NCAT test track are not true curves except for in the middle of the curve. For this reason, the GPS position data that is recorded during the maneuver will serve to both establish the correct course that the maneuver is performed on but also will define the radius that the vehicle travels.

3.3.2 Single Lane Change

Object of Maneuver

The goal of this test is to capture the response of the vehicle due to obstacle avoidance style maneuver. The target of the test is to show the transient response of the vehicle due to the step change in position. The output from this test will allow for the study of path deviation for all of the units in the vehicle train as well as the settling distances of the subsequent units due to steering inputs at the tractor. Similarly it will allow for the study of rearward amplification of the units. The critical parameters for the test are each unit's lateral acceleration and relative position of each unit to the original path of the tractor.

Maneuver Path

The path that the vehicle is to follow is exactly like the name of the maneuver suggests. The goal is to begin the test with the vehicle in a steady velocity driving straight so that the transient responses are minimal at the start. Additionally it is desired that the vehicle be in zero-yaw attitude, meaning that the vehicle is driving straight. The driver is to maneuver the vehicle through the first gate and then steer the vehicle into the targeted lane and through the second gate within the determined distance. This maneuver had to be attempted in a portion of road that is as straight and flat as possible as to mitigate any non-accounted for effects. The driver's ability to negotiate the maneuver consistently will help insure that sufficient data will be collected during the test series. The layout of the Single Lane Change is illustrated below in Figure 3.2.
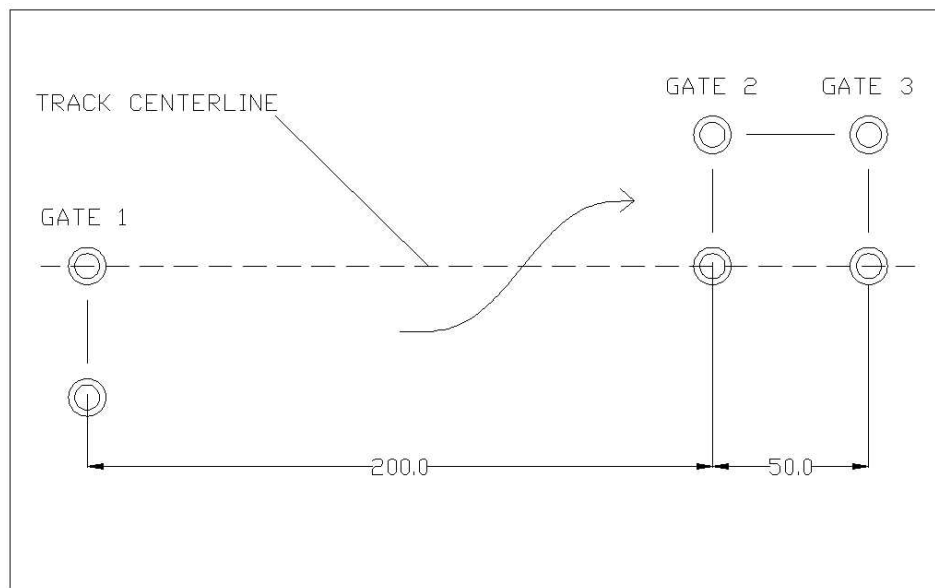

Figure 3.2: Single Lane Change Maneuver Diagram

3.3.3 Double Lane Change

Object of Maneuver

The double lane change is designed to capture the response of the vehicle in an obstacle avoidance maneuver, much like the single lane change. The main difference in the two is that when executing the double lane change, the maneuver is not complete until the vehicle has returned to the lane that it was originally traveling in. This test is the most dangerous of the three as it incites the most lateral acceleration of them all and therefor leads to the most dangerous conditions for large, high center-of-gravity vehicles. The same measurements are of interest in the double lane change that were critical in the single lane change (path deviation, lateral acceleration, and settling distances) for each of the units. This maneuver stands to give the most data towards characterizing the rearward amplification as it is not just a single step change response nor a response in steady state, but instead a response to consecutive lane changes.

Maneuver Path

The path of the vehicle is approximately two consecutive single lane changes maneuvers. The vehicle is to start out in the outer lane and once it passes through the first gate location. Change course and move to the inner lane before the next gate location. Once through the second gate location, there is a brief stretch of distance to be traveled in the inner lane, the end of this segment is marked by the third gate location. Once through the third gate location, the vehicle is to maneuver back into the outer lane once again before the fourth and final gate location. Once the entire vehicle has passed through the fourth gate and has returned to a steady state operation the maneuver is complete. An illustration of the maneuver can be seen in Figure 3.3.
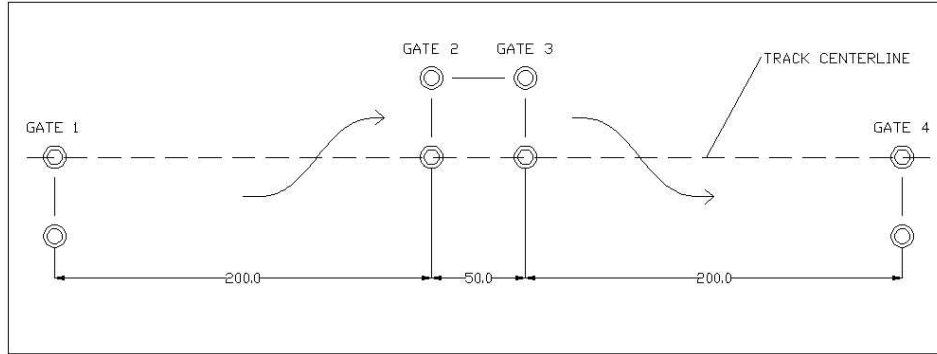
Figure 3.3: Double Lane Change Maneuver Diagram

3.4 Data Processing

Once all data was collected, the raw data files were downloaded from the DAQ system and needed to be cleaned up and prepared for analysis. This process was broken down into a three step process: data handling (3.4.1), data formatting (3.4.2)), and real-time kinematic (RTK) corrections (3.4.3)).

3.4.1 Data Handling

The computer that was mounted on the test vehicle recorded every run and stored the data internally. Following testing, all of the data sets were downloaded from the vehicle computer to a more powerful computer for the post-process work. A backup copy was left on the vehicle computer and another raw backup was stored in another location for redundancy.

3.4.2 Data Formatting

Data recording was more efficient when the recorder ran continuously as the vehicle went around the track, with maneuvers on both the north and south straight segments. Data for each maneuver on the straight or curve were extracted from the larger file following the tests. This was accomplished by defining zones around the track using known GPS coordinates for the track, as shown in Figure 3.4.

50
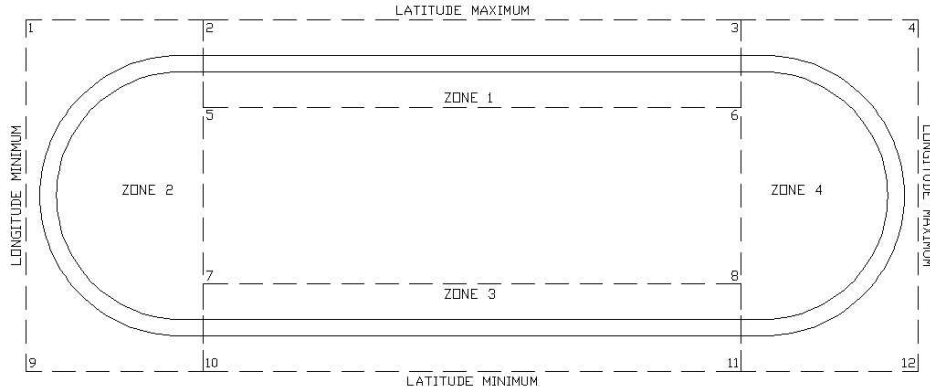
Figure 3.4: Zones for separating data recorded on the curves from data recorded on the straights.

A MATLAB program was written to step through the large files line-by-line to determine the zone, and then to write all of the corresponding data for each zone to a new file. This program was also run against the individual recordings to ensure that all of the files representing a certain maneuver started and stopped at the same geographic point. The speed and maneuver were coded in the individual file names. An example of this is: 'NTRCI_35mph_Dbl_Ln_Chng_R2' which corresponds to the second running of a 56 km/h (35 mph) double lane change.

The next step was coordinate transformations and unit conversions. The analysts chose to use the ISO vehicle coordinate system with positive z direction up, as indicated in Figure 3.5.

Another MATLAB program was written to bring in the data from specific runs and create an overlay plot so the accelerations of the tractor and three trailers could be compared. Figure 3.6 is the specific case of angular rate about the z-axis in a double lane change. The four IMUs are listed in their order from front to rear in the combination vehicle. The upper graph is the raw data prior to the coordinate transformation, and the lower is after the transformation. The lower graph shows the four units of the vehicle yawing in their proper sequence . The data shown is after being put through a 10th order Butter-worth filter with a cut-off frequency of 3 Hz.

51

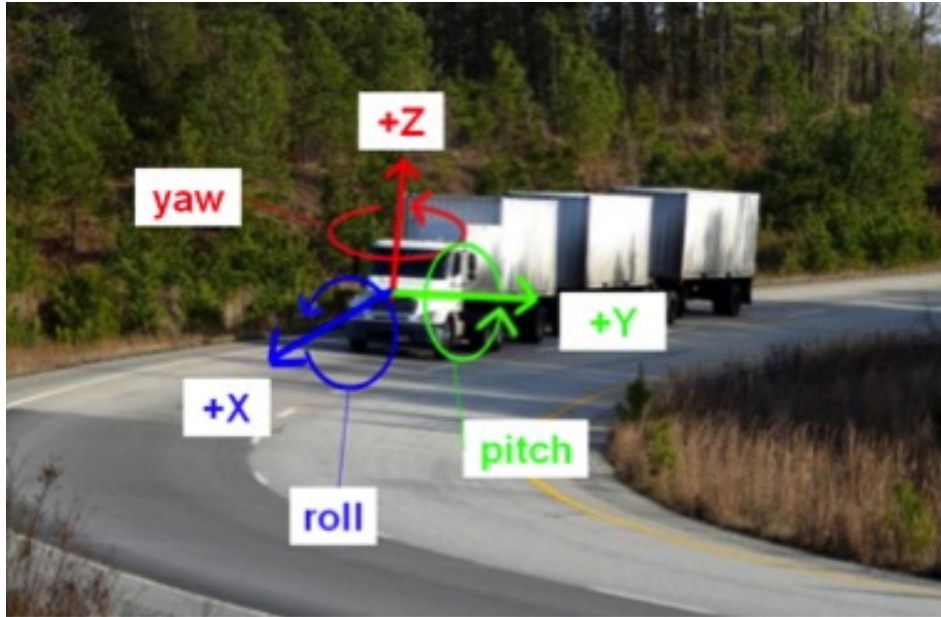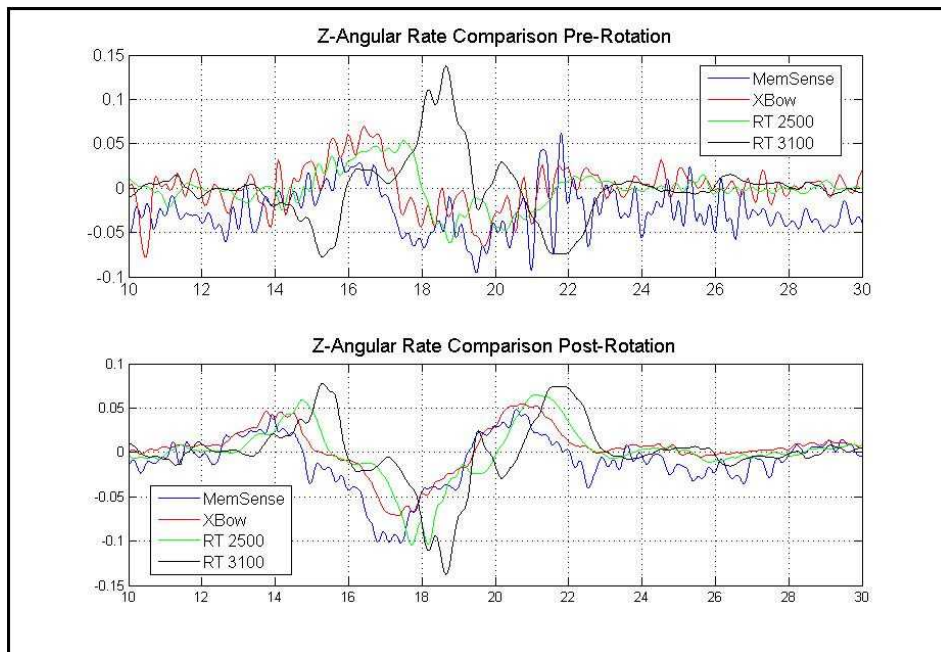Figure 3.5: ISO standard frame-of-reference with Y to the left and Z up.

Figure 3.6: Raw vs. Post Processed Angular Rates.

After the necessary transforms were confirmed, a program was written in Python to iterate through each file automatically and perform the rotations on the desired channels. The

program additionally converted the latitude and longitude coordinates to Universal Transverse Mercator (UTM) coordinates. This gave a set of rectilinear positioning coordinates of the tractor and trailers relative to an origin point close to the track. This simplified visualization of the data.

3.4.3 RTK Corrections

In order to obtain global positioning coordinates, two GPS receivers were placed on each of the units in the combination. Novatel GPS receivers were on each of the units, while the lower cost alternatives, the u-blox GPS receivers, were on the tractor and first trailer. The second and third trailer both carried an Oxford RT unit, but they did not function as discussed in Section 3.6.

The accuracy (1σ) of the standard GPS positions that the receivers report are usually on the order of 1 or 2 meters (3 to 6 ft). This error comes from several factors, including atmospheric conditions, which is the largest contributor, as well as satellite and receiver clock biases, and noise in the measurements inside the GPS receiver. As the satellite's signal propagates through the ionosphere and troposphere that surround the Earth, the electron dispersion and humidity can affect the GPS signal.

When several GPS receivers are operating within close proximity (several kilometers), these signal errors become highly correlated. Differential GPS (DGPS) techniques take advantage of this fact and compensate for the correlated errors. DGPS methods can use the pseudorange, the carrier noise measurement, or a combination of both. Real-Time Kinematic (RTK) systems can take a precise carrier phase measurement and calculate global positions that are equally precise. The RTK system at NCAT uses a static base station with known coordinates near the track and compares its GPS measurements to those of a roving GPS receiver in close proximity.

3.5 Analysis of Experimental Data

The experimental data was analyzed in order to look at the understeer characteristics of the LCV along with the body roll of each unit and axle steer. As described below in Section 3.6, there were some data collection issues that prohibited the accurate collection of acceleration data for the second and third trailers. However the second and third trailers there was adequate data collected on position, speed, and suspension deflections. This data was then compared to the results of the simulation which is described in Chapter 4. The vehicle characterization parameters mentioned above were obtained in conjunction with Western Michigan University as part of the collaborative effort for the NTRCI project for LCV vehicle dynamics. That report can be found in the appendices of [6].

3.5.1 Understeer Characteristics

As described in Section 1.2.2 the understeer gradient effects the vehicle's ability to follow the path defined by the steer angle of the steer axle tires or road wheel angle. The portion of the data that will contribute to the analysis of this characteristic is the data obtained during the constant radius maneuvers in the banked corners of the track. An overlay of two separate runs at separate speeds in shown below in Figure 3.7, this is to illustrate that the data at multiple speeds have the same nominal radii. Using the GPS data taken during the constant radius turns it was determined that the curve had a nominal radius of 476 ft.

Steering Characteristics of the Tractor

The understeer gradient was calculated using Equation (1.2) at various speeds using the experimental data. The measurement of the road wheel was taken from the string pot data and the lateral acceleration was both calculated analytically as well as recorded via IMU measurements. The equation for the analytical calculation of the lateral acceleration is seen in Equation (3.1).
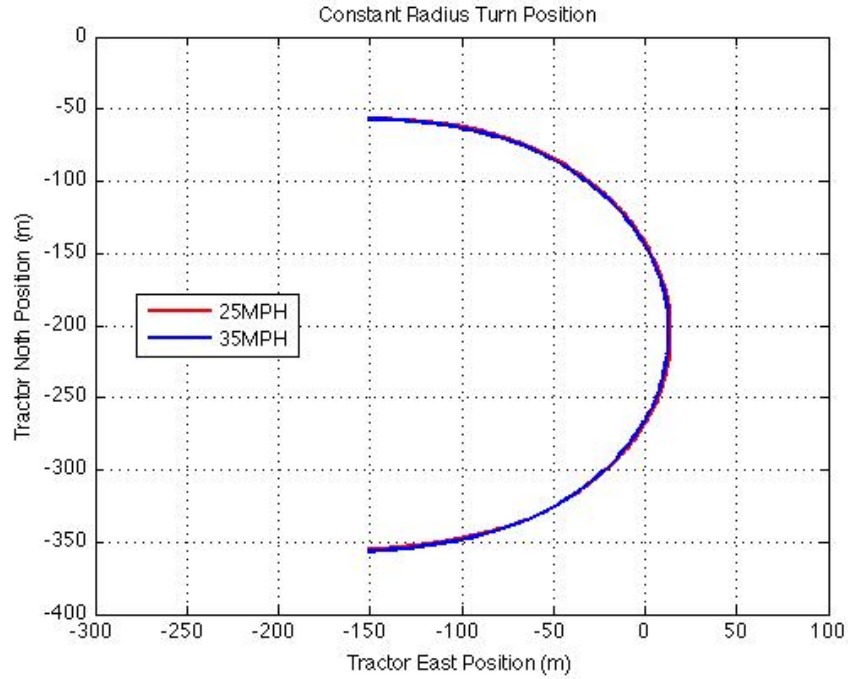
Figure 3.7: Constant Radius Maneuver Path Overlay.

$$a_y = \frac{V^2}{Rg} \tag{3.1}$$

where

a_y = Lateral Acceleration

V = Vehicle Velocity

R = Turn Radius

g = Gravitational Constant

This equation is for vehicles that undergo constant radius turns on flat surfaces which is not the case in this application. In order to correct for this, the gravitational contribution to the lateral acceleration is subtracted from the results from Equation (3.1). As described in Section 3.1, the corners in which the maneuvers took place had an 8° banking. So the resulting gravitational component of the lateral acceleration is $g * sin(8) = 4.478\frac{ft}{s^2}$. In

addition to the equation for lateral acceleration, Equation (1.2) is listed below again for reference.

$$K = \frac{\left(\delta - \left(\frac{L}{R}\right) * 57.3\right)}{a_y} \tag{1.2}$$

where

F_{zo} = Outer Vertical Tire Force

F_{zi} = Inner Vertical Tire Force

T = Track Width

M = Vehicle Mass

A_y = Lateral Acceleration

h_{cg} = Vertical Height of Center of Gravity (CG)

There other series of equations that is of use are the equations for calculating the steer angles. Equations (3.2) - (3.4) show the calculations for the steer angle of both the inner and out wheels as well as the average steer angle, which is defined as the Ackerman steer angle[16].

$$\delta_o \cong \frac{L}{(R + t/2)} \tag{3.2}$$

$$\delta_i \cong \frac{L}{(R - t/2)} \tag{3.3}$$

$$\delta = \frac{L}{R} \tag{3.4}$$

where

δ = Road Wheel Angle (deg)

L = Tractor Wheel Base Length (steer axle to drive axle center-line)

R = Turn Radius

These equations are set for low speed cornering where the lateral acceleration is negligible. In order to proceed with the calculations a value for both the road wheel steer angles and the hand wheel angle needed to be calculated from the measured data. In order to do this the data was broken down into two separate sections, the first being the period the vehicle was transitioning from the straight-a-ways into the constant radius. This portion of the data is represented at the beginning and end of the data set. An example of the two separate sections from data taken at 35 mph can be seen in Figure 3.8. The second portion is the portion of the turn data that was analyzed as the constant radius section. It was this data that was fitted with a linear regression to get best fit linear curve, the resulting equation for the line is shown in Equation (3.5), and as can be seen by the low slope value of the section of the data is representative of a constant steering angle during the constant radius maneuver.

$$y = 0.005x - 3.2160 \tag{3.5a}$$

$$R^2 = 0.00248 \tag{3.5b}$$

The same plot was generated, shown in Figure 3.9, at lower speeds to illustrate that the road wheel angle is indeed comparable. The differences between the two can be attributed to high speed corrections made by the driver in an attempt to maintain the constant radius.

The results of the calculations can be found in Table 3.1. Of note is that the understeer gradient was calculated using only six discrete data sets at the various speeds of the maneuvers.
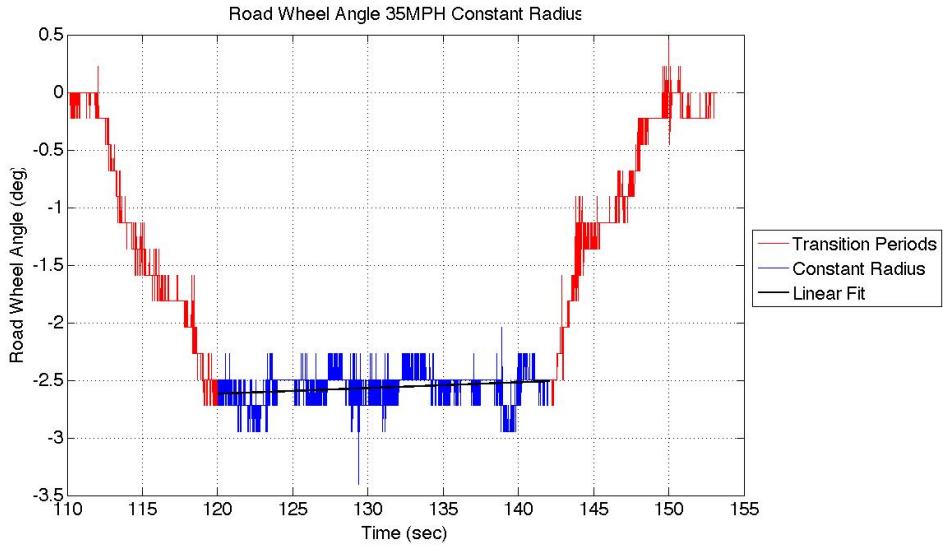
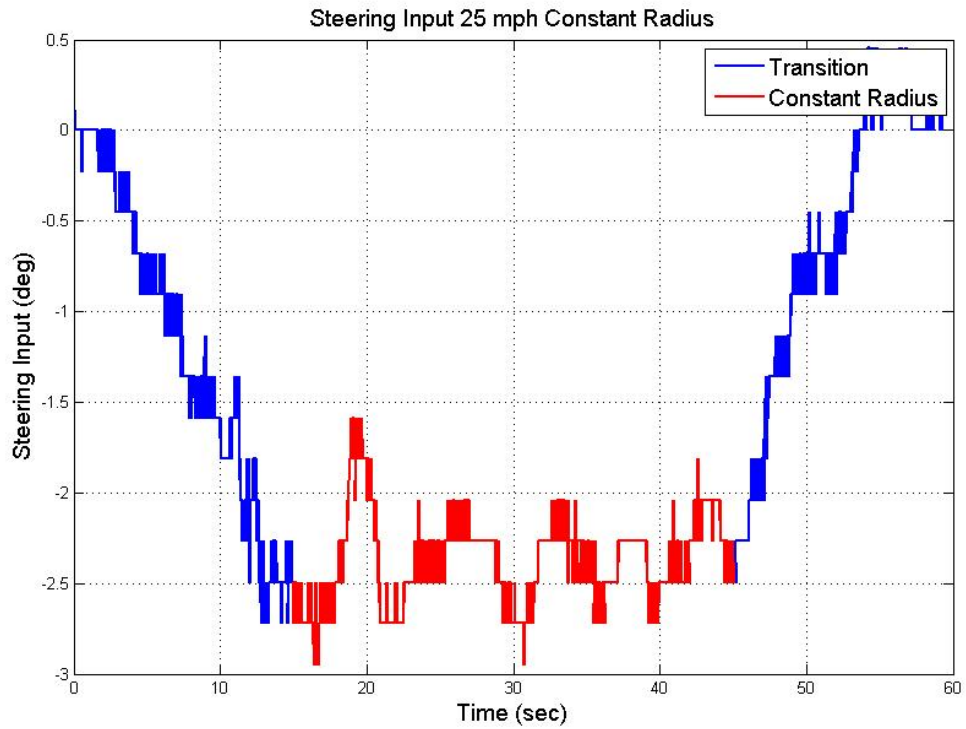Figure 3.8: Sections of Constant Radius Maneuver.

Figure 3.9: Sections of Constant Radius Maneuver.

Table 3.1: Understeer Gradient Calculations for LCV Tractor

Target Vehicle Speed (mph)	20.0	25.0	30.0	35.0	40.0	45.0
Target Vehicle Speed (m/s)	8.94	11.17	13.41	15.65	17.88	20.12
Calculated Avg. Speed (m/s)	9.1558	11.0530	13.3027	15.1395	17.2976	19.2648
Measured Road Wheel Angle (deg)	2.3960	2.5726	2.6767	2.5444	2.2074	2.1626
Ackerman Angle (deg)	1.9799	1.9799	1.9799	1.9799	1.9799	1.9799
Under/Over Steer (deg)	0.4161	0.5927	0.6968	0.5654	0.2275	0.1827
Calculated a_y (g)	0.0589	0.0859	0.1244	0.1611	0.2103	0.2609
a_y Corrected for Banking (g)	-0.0802	-0.0533	-0.0148	0.0220	0.0712	0.1217
Measured a_y (g)	-0.0130	0.0024	0.0372	0.0734	0.1289	0.1951
Understeer Gradient (deg/g)	7.0605	6.9006	5.6010	3.5035	1.0815	0.7003

Steering Characteristics of Trailer 1

The same calculations were performed on the data for the first trailer in the combination. Those results are shown in Table 3.2. In the case of the first trailer, the steer angle was measured by subtracting the measured heading of the 1st Trailer from that of the Tractor. In doing the above subtraction of heading angles the assumption was made that during the maneuver there was no slip for either of the two units. In other words the assumption is that the tires are pointed in their direction of travel [16]. This assumption can be made do to the low road wheel steer angle, should the steer angle increase above say 5 degrees then the assumption would lead to greater error then acceptable. An example of the output is shown in Figure 3.10. As illustrated the resulting steering input looks very similar to that of the Tractor.

Steering Characteristics of Trailer 2

As described in Section 3.6, there were several issues with some of the data for the second and third trailer. As a result the recorded lateral accelerations were not reliable. For those purposes there is no value recorded for the measured lateral acceleration for neither the 2nd nor 3rd trailer. The results from the second trailer can be found in Table 3.3.
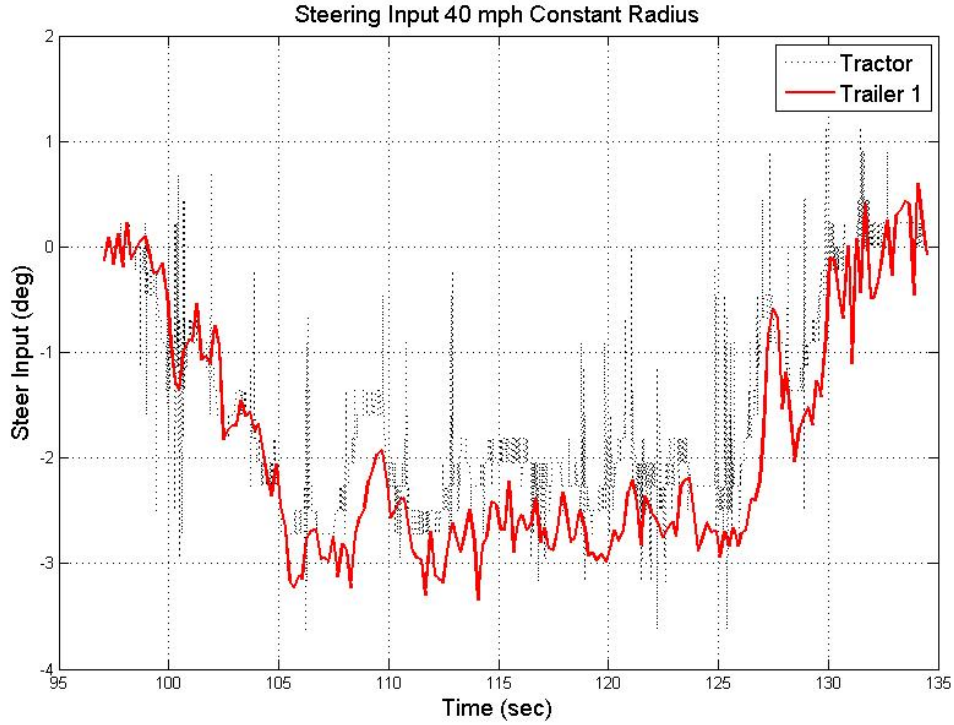
Figure 3.10: Tractor 1 Steering Input

Table 3.2: Understeer Gradient Calculations for LCV Trailer 1

Target Vehicle Speed (mph)	20.0	25.0	30.0	35.0	40.0	45.0
Target Vehicle Speed (m/s)	8.94	11.17	13.41	15.65	17.88	20.12
Calculated Avg. Speed (m/s)	9.1372	11.0246	13.3071	14.9739	17.0491	18.7962
Measured Road Wheel Angle (deg)	2.4080	2.5350	1.5999	2.8151	2.6588	2.4725
Ackerman Angle (deg)	1.8513	1.8513	1.8513	1.8513	1.8513	1.8513
Under/Over Steer (deg)	0.5566	0.6837	-0.2514	0.9638	0.8075	0.6212
Calculated a_y (g)	0.0587	0.0854	0.1245	0.1576	0.2043	0.2484
a_y Corrected for Banking (g)	-0.0805	-0.0537	-0.0147	0.0185	0.0652	0.1092
Measured a_y (g)	-0.0885	-0.0883	-0.0347	0.0119	0.0799	0.1367
Understeer Gradient (deg/g)	9.4858	8.0015	6.9825	6.1144	3.9518	2.5013

Steering Characteristics of Trailer 3

Similarly to the 2nd trailer the 3rd trailer also experienced data issues, because of this the data from the 3rd trailer was processed in the same manner that the 2nd trailer was and the outcome of the calculations is detailed in Table 3.4.

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Table 3.3: Understeer Gradient Calculations for LCV Trailer 2

Target Vehicle Speed (mph)	20.0	25.0	30.0	35.0	40.0	45.0
Target Vehicle Speed (m/s)	8.94	11.17	13.41	15.65	17.88	20.12
Calculated Avg. Speed (m/s)	9.1307	11.0151	13.3039	15.1185	17.3635	19.3044
Measured Road Wheel Angle (deg)	1.6651	1.6311	1.5666	1.8866	1.9075	2.5102
Ackerman Angle (deg)	2.0897	2.0897	2.0897	2.0897	2.0897	2.0897
Under/Over Steer (deg)	-0.4246	-0.4586	-0.5230	-0.2031	-0.1822	0.4206
Calculated a_y (g)	0.0586	0.0853	0.1244	0.1607	0.2120	0.2620
a_y Corrected for Banking (g)	-0.0806	-0.0539	-0.0147	0.0215	0.0728	0.1228
Measured a_y (g)	n/a	n/a	n/a	n/a	n/a	n/a
Understeer Gradient (deg/g)	-7.2440	-5.3767	-4.2034	-1.2639	-0.8595	1.6053

Table 3.4: Understeer Gradient Calculations for LCV Trailer 3

Target Vehicle Speed (mph)	20.0	25.0	30.0	35.0	40.0	45.0
Target Vehicle Speed (m/s)	8.94	11.17	13.41	15.65	17.88	20.12
Calculated Avg. Speed (m/s)	9.1372	11.0246	13.3071	14.9739	17.0491	18.7962
Measured Road Wheel Angle (deg)	2.4080	2.5350	1.5999	2.8151	2.6588	2.4725
Ackerman Angle (deg)	1.8513	1.8513	1.8513	1.8513	1.8513	1.8513
Under/Over Steer (deg)	0.5566	0.6837	-0.2514	0.9638	0.8075	0.6212
Calculated a_y (g)	0.0587	0.0854	0.1245	0.1576	0.2043	0.2484
a_y Corrected for Banking (g)	-0.0805	-0.0537	-0.0147	0.0185	0.0652	0.1092
Measured a_y (g)	n/a	n/a	n/a	n/a	n/a	n/a
Understeer Gradient (deg/g)	9.4858	8.0015	6.9825	6.1144	3.9518	2.5013

3.5.2   Rearward Amplification

As detailed in Section 1.2.2, rearward amplification at it's simplest form it the tendency of a unit to exaggerate the inputs. In the case of LCV dynamics, this is most clearly illustrated in path deviation, lateral acceleration, and body roll of the vehicle. The lead unit for the LCV is the tractor and the inputs came from the driver and as those inputs are passed through the 'Train' they can grow in amplitude. The magnitude of amplification can be influenced by several different factors. The most prominent ones are trailer length, dolly configuration, speed, and period of the maneuver [21]. The formal calculation of rearward amplification is defined in Equation (3.6).

$$\text{Rearward Amplification} = \frac{\text{Amplitude of Measured Unit}}{\text{Amplitude of Lead Unit}} \qquad (3.6)$$

Should this value be greater than one, then the unit under measurement experiences a greater response to the inputs of the lead vehicle.There is no set characteristic that must be used to calculate the rearward amplification. Typically the value of lateral acceleration or yaw rate is used to determine the magnitude of the amplification. However, as described in Section 3.6, there were some complications with obtaining both of those measurements accurately for the latter half of the LCV. Due to that, the measurement of body roll was used in it's place. Body roll was accurately captured for each vehicle with the use of string potentiometers attached to each unit's ride axle. In the case of the tractor the potentiometers were installed both on the steer axle and on the second drive axle. The roll of the first drive axle was assumed to be the same as the second. The input to the system is the hand wheel input by the driver. It was determined that the steering linkage had a 1/20 steering ratio, a plot of the input for a double lane change at 20 mph is illustrated in Figure 3.11. In each plot of the steering input there are eight different points of interest during the maneuver; those points are detailed below.

POI 1 Start of the left turn to enter left lane.

POI 2 Maximum left steer angle for initial lane change into left lane.

POI 3 Point where hand wheel crosses from positive to negative after initial lane change.

POI 4 Maximum right steer input for first lane change. This is the corrective steer input to maintain the vehicle in the right lane after the first lane change.

POI 5 Maximum right steer input to return the vehicle to the original (right lane) lane of travel.

POI 6 Point where the hand wheel crosses from negative to positive during final lane change.
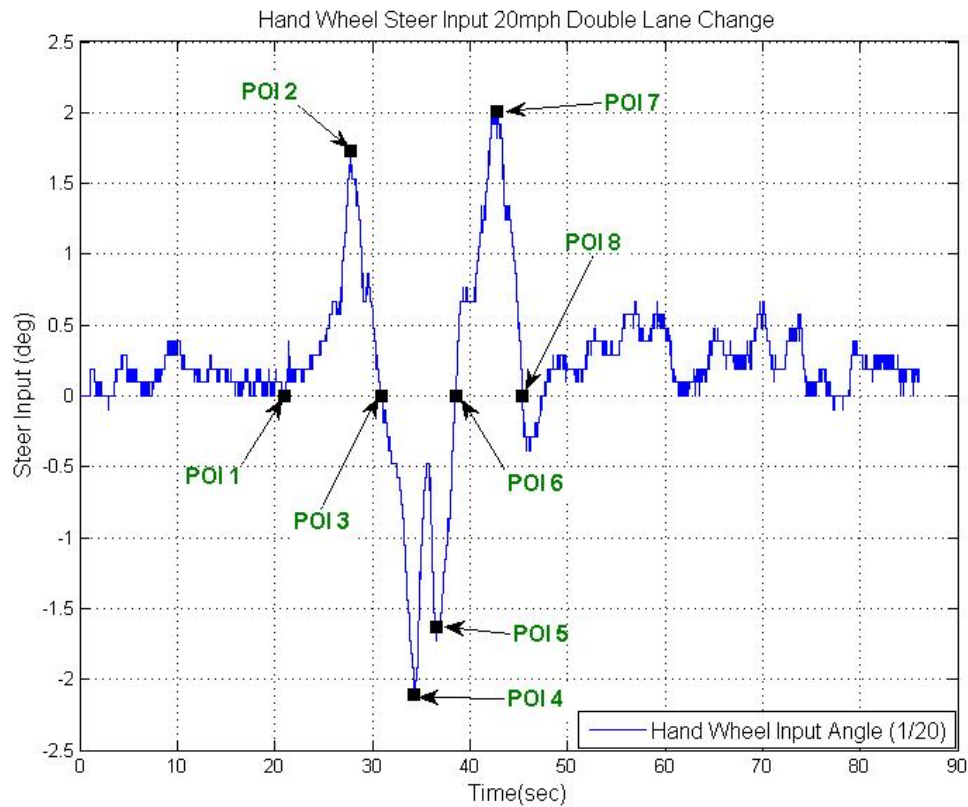
Figure 3.11: Double Lane Change Steering Input (20 mph)

POI 7 Maximum left steer input for the final lane change. This is the same corrective input that is seen at POI 4 but this is to return the right lane as opposed to enter the left lane.

POI 8 Steering input returns to zero and maneuver is ended.

Of note is that at higher speeds or shorter gate spacings POIs 4&5 are the same point on the input curve. At lower speeds or longer gate spacing there is a period of time where the driver is attempting to straighten out and steady the vehicle in the left lane. This results in two distinct peaks negative in magnitude which correlate to a right steer input. When the speeds are higher or spacing shorter there is no time for this correction and the end of the initial lane change coincides with the start of the second lane change. A plot of such input

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is shown in Figure 3.12, notice the difference between Figures 3.11 & 3.12 where there are two distinct negative peaks versus one.
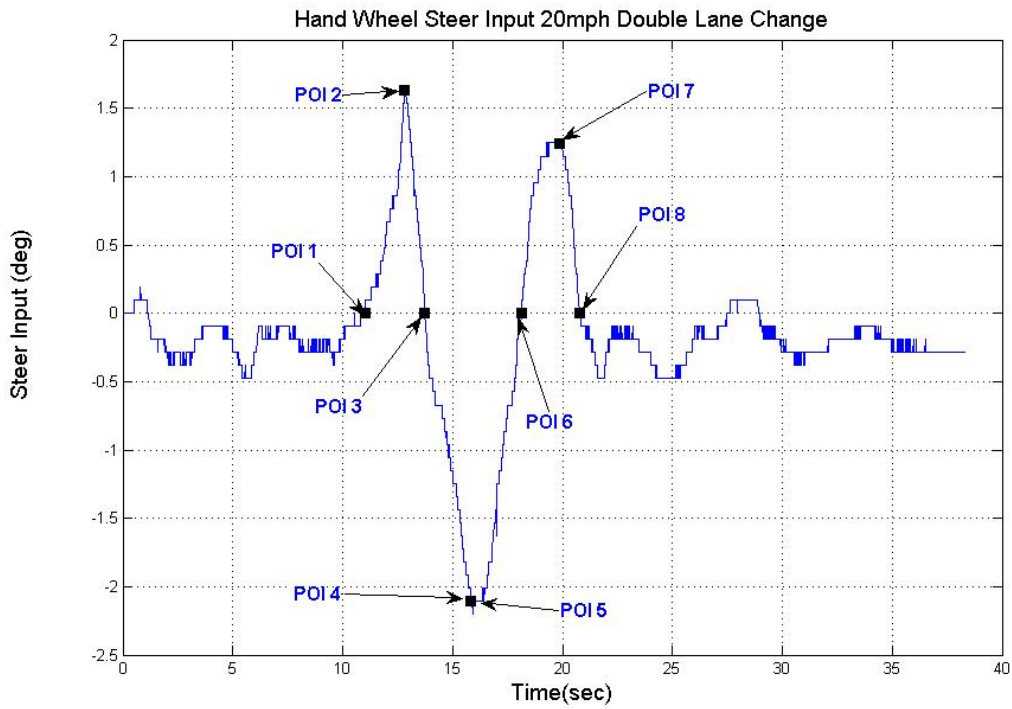

Figure 3.12: Double Lane Change Steering Input (40 mph)

3.5.3 Roll Behavior of LCV Units During 40 mph Double Lane Change

With the knowledge that the steering input given by the driver is the overall input to the system the first step is to analyze how the closest link responds to the driver's input. The first axle that responds to the input is the steer axle on the tractor. As it was one of the axles outfitted with string potentiometers the body roll angle relative to the axle was captured during testing. A plot of the resulting roll for a double lance change at 40 mph can be seen in Figure 3.13.

As illustrated, the body roll at the steer axle responds almost instantaneously to the input from the driver. This response of body roll is now the measurement that will be used to calculate the rearward amplification of all the subsequent LCV units. Keeping the analysis
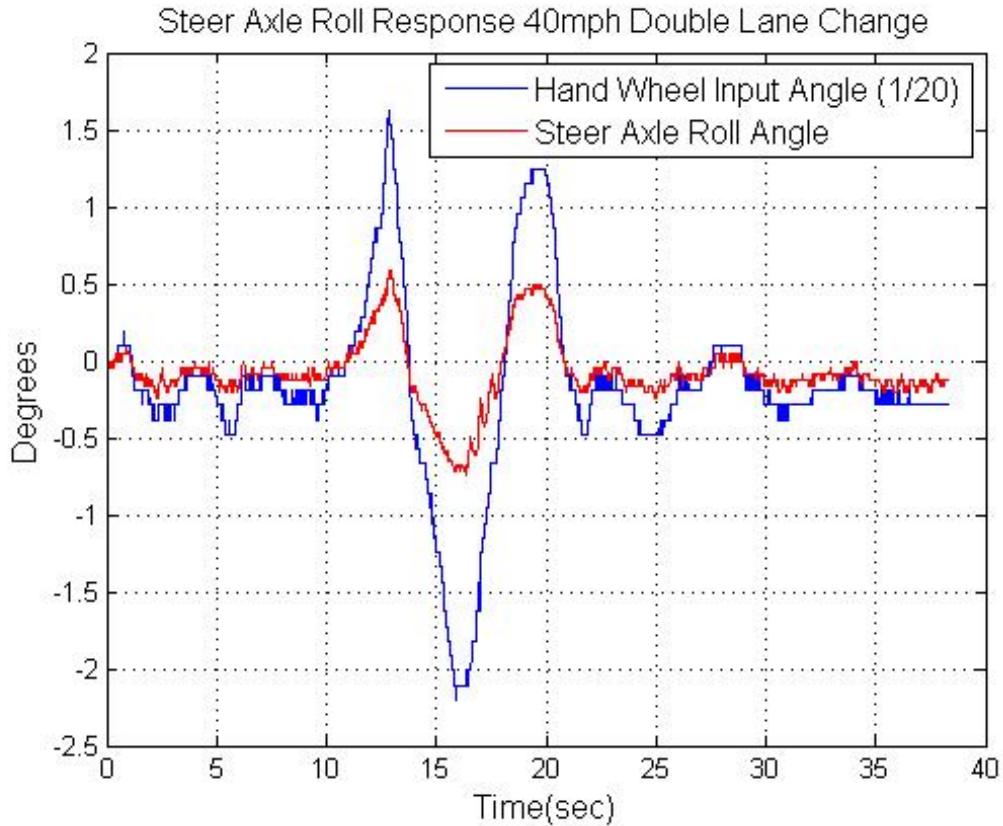
64

Figure 3.13: Steering Axle Body Roll

in the same order as the axles, the first axle to investigate is the drive axle of the tractor. Any delays here would constitute the frame of the tractor was twisting during testing and causing a delay and /or amplification. A plot of the Steer axle roll compared to the drive axle roll can be seen in Figure 3.14. The same plot was generated for each of the towed trailers. That plot can be seen in Figure 3.15.

As somewhat evident in the collection on plots in Figure 3.15, a slight delay and amplification can be seen in the responses of the subsequent trailers. All of the signals were combined on the same plot and the outcome of that effort is illustrated in Figure 3.16.

As with some of the previous data sets it was necessary to filter the data in order to better analyze it as well as visualize it in plots. The signal for the body roll of all the axes except the steer axis were subjected to a low pass 10th order Butterworth filter with a cut-off
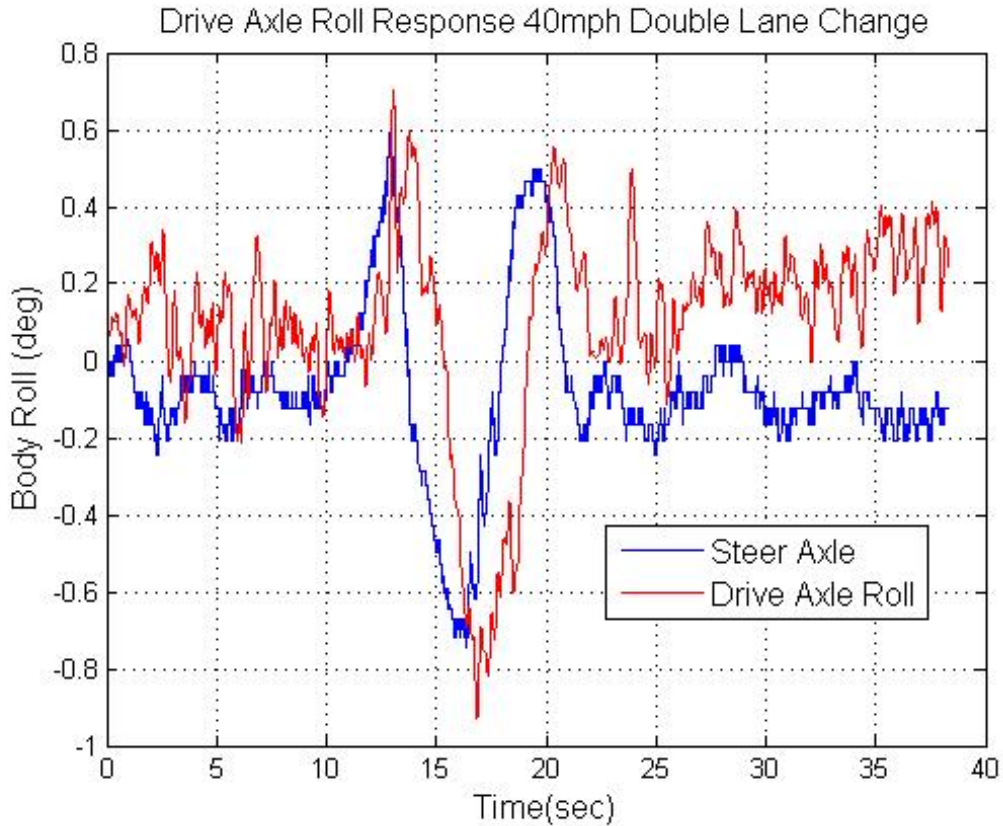
Figure 3.14: Drive Axle Body Roll

frequency of 5 Hz. The new filtered responses were plotted again and produced Figure 3.17. As clearly shown in Figure 3.17 there is a definite delay as well as a definite increase in magnitude as the input is propagated down the LCV.

In order to calculate an instantaneous value for the rearward amplification one point on the curve during the dynamics had to be chosen. For the following discussions and table the point that was chosen was the roll response to the highest input steer that was in right direction, POI 4& 5 in Figure 3.12. Using that point and the definition of Rearward Amplification Equation (3.6), Table 3.5 was populated with the results from the calculations as well as the values used to plug into the equation.
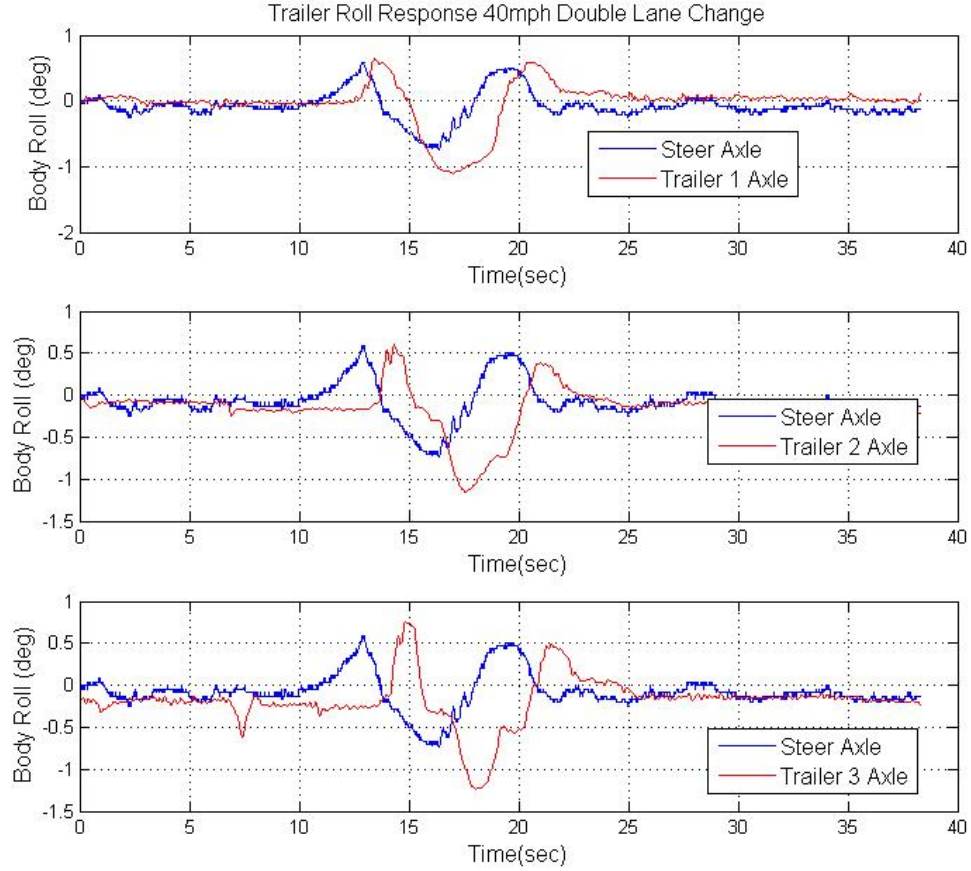
Figure 3.15: Trailer Body Roll

Table 3.5: Rearward Amplification for LCV during 40 mph Double Lane Change

	POI 4		Delta		Rearward
	t	ϕ	∇t	$\nabla \phi$	Amplification
HandWheel	16.12	-2.1080	n/a	n/a	n/a
Steer Axle	16.35	-0.7204	0.00	0.00	1.00
Drive Axle	16.84	-0.9271	0.49	-0.21	1.29
Trailer 1	17.08	-1.0980	0.73	-0.38	1.52
Trailer 2	17.60	-1.1510	1.25	-0.43	1.60
Trailer 3	18.05	-1.2310	1.70	-0.51	1.71

3.6   Data Quality Issues

The first specific issue to arise was the attachment point for the string pot used to measure the horizontal displacement of the steer axle on the right side of the tractor had broken, so the string pot measured zero for the majority of the test week. Additionally it
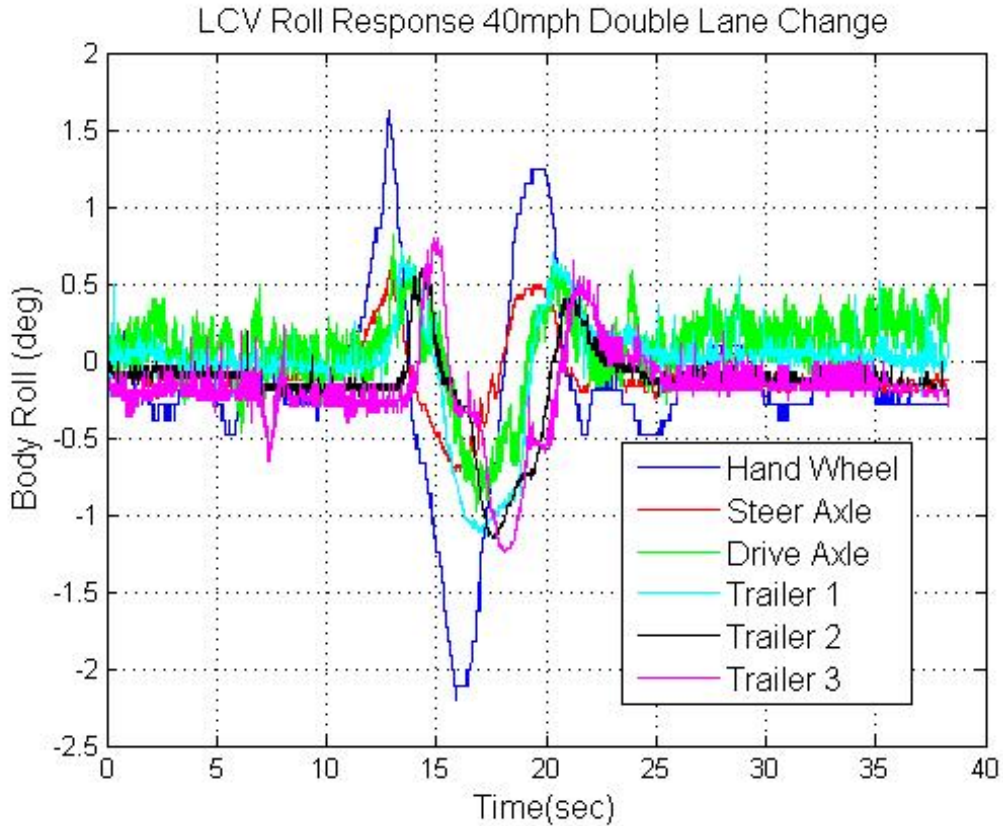
Figure 3.16: LCV Body Roll (Un-Filtered)

was discovered was that the messages from the engine CAN-bus were not logged. This was a result of code changing during the first few days of the test week and the log statements that tell the computer which messages to be logged where not in the correct place in the configuration files for the DAQ.

Noise was an issue raised for the string pots but this was not a result of anything other than process noise. Since the string pots were used to measure linear displacement they were put in a position as to track as much linear movement as possible for the axles; this meant a string pot was placed directly above and directly horizontal to the axle in its static position, shown in Figure 3.18.

Due to the nature of the testing, recording noise-free data is not practically feasible. The string pot data reflects this with all the noise induced by the environment embedded
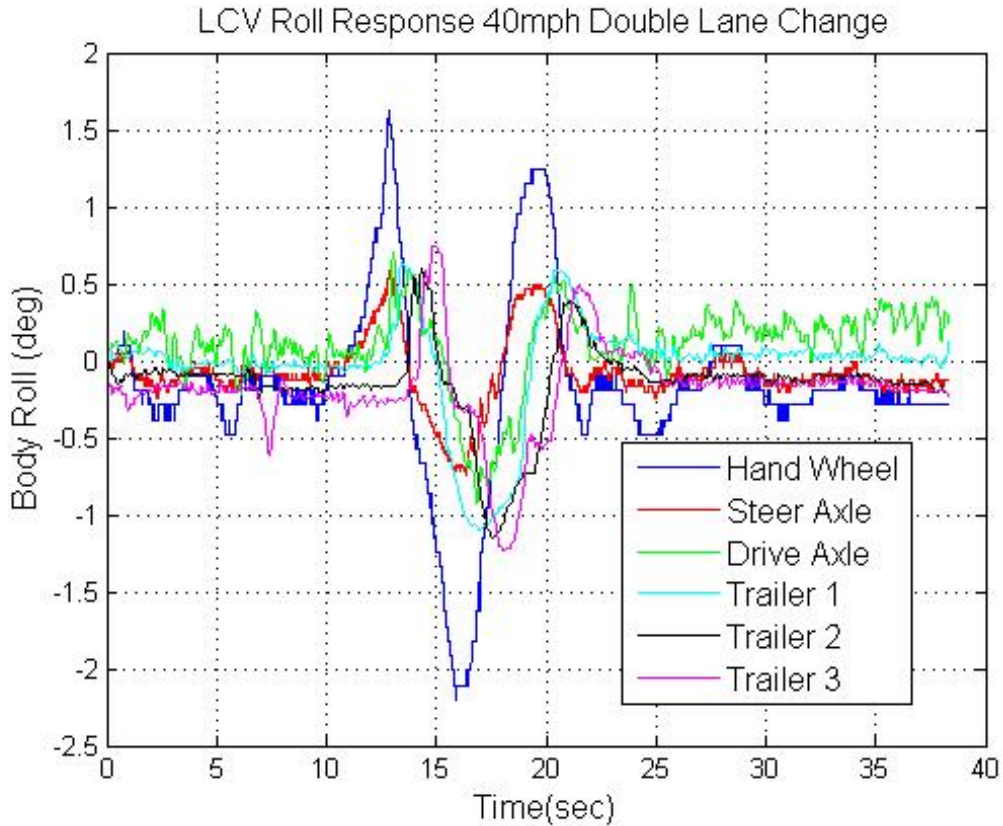
Figure 3.17: LCV Body Roll (Filtered)

Figure 3.18: Lever arm mounting for string pots

in each measurement. The string pots were mounted on 80/20 frames to the undercarriage of the vehicle in various positions. These axles are the rotation axis for the tires, which themselves experience a great deal of noise from the surface of the road. Not only does the

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uneven pavement introduce noise to the measurements, but also the vibration of the test vehicle as it is driven down the road can be enough to affect the data.

In addition to the string pot issues, the two Oxford measurement units were used to record the positional and orientation data needed to fully characterize the motion of the two rear trailers of the test vehicle. An Oxford RT2500 was positioned on Trailer 2 and a RT3100 unit was located on Trailer 3 of the LCV. The RT units use both GPS and an inertial measurement unit (IMU) to measure the motion of the vehicle, and Kalman filtering is automatically applied by the RT system to fuse the data from these two types of sensor for optimal accuracy. Unfortunately, the devices were not configured/initialized properly for the measurements and the RT data recorded were discovered to be erroneous. This was not uncovered until the data was thoroughly analyzed, as described below the initial data looked to be noisy but correct.

Initially, it was observed that more noise was present in the signals than what had been expected or previously experienced. Filtering of some of the signals while the testing was being conducted showed results that were consistent with the expected motions of the vehicle for the maneuvers performed. As a result of various delays prior to testing and the resulting pressure to complete all testing within the planned time-frame, the testing had to be continued without a complete review and validation of the data integrity.

Chapter 4

Vehicle Simulation Results

TruckSim® is a simulation software that is developed by Mechanical Simulation Inc. The software is highly configurable to allow for customization of the simulation to best match that of the desired vehicle. TruckSim® is geared towards the heavy truck industry. This includes but is not limited to commercial vehicles, military vehicles, and large buses. TruckSim® allows the user to input mass properties as well dynamic characteristics of the vehicle under test. These characteristics are normally entered as linear coefficients or tables of data. Once the vehicle has been configured the user can then run the vehicle through a infinite number of sceneries. The user can either choose from pre-defined maneuvers or can create their own. For this research the maneuvers that were undertaken during the experimental phase were mirrored in the simulation as closely as possible. Of note is that as packaged TruckSim® cannot simulate the NCAT LCV as it can only simulate up to a double trailer configuration out of the box. In order to resolve this issue, a custom math package was purchased from Mechanical Simulation Inc. to allow for the simulation of the NCAT LCV.

Out of the box with the custom solvers installed, TruckSim® contains generic models of several different types of trailers to be implemented on the LCV. The default model was used as the starting point for the simulations. The data that was taken during the LCV characterization phase in conjunction with Western Michigan University was used to configure the simulation model in order to more accurately represent that of the test vehicle. A screen shot of the TruckSim® environment with the representative model can be seen in Figure 4.1. The LCV characterization report that was used to set up the model can be found in the appendices of [6].

Figure 4.1: Screen Shot of TruckSim® Environment

4.1 Vehicle Configuration

As mentioned, the vehicle was configured using the parameters that were determined during the characterization effort, when measurements were not available the standard TruckSim® parameters were left alone. The paths for each of the maneuvers described in Section 3.3 were entered in as closed-loop driver input paths. An example of this for the maneuver of a Double Lane Change is shown in Figure 4.2. The goal of this is to match the results of the simulation to that of the experimental in order to confirm that that simulation data is accurate and can therefore be used to simulate the vehicle in conditions that were not able to be run experimentally due to safety concerns. Complete details of the set-up of TruckSim® can be found in Appendix A.

Since the vehicle is a combination of six independent components it is unreasonable to expect the LCV to behave as a single vehicle. This means that when traveling in a straight line one should not expect all of the subsequent components to have zero for steer angles even if the lead unit does. What this means is that the driver must compensate for the different
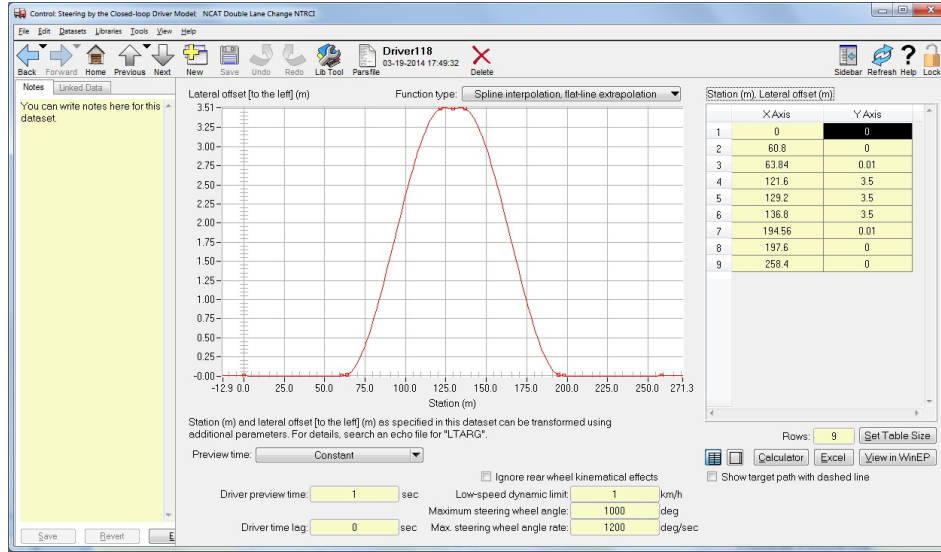
Figure 4.2: Screen Shot of TruckSim® Steering Path Input for Double Lane Change

steer angles when attempting to drive in a straight line or along a specified path. The driver must constantly correct with slight turns of the steering wheel in order to maintain a straight path. This is a result of many minor contributions of the LCV components such as steering misalignment, suspension wear & misalignment, tire variations, and many other effects. In an attempt to illustrate this, a simulation was run with the NCAT vehicle with no steering input at all. What this is indicative of is the driver removing their hands from the steering wheel and letting the vehicle settle at some steady state. The steering input from the hand wheel is shown in Figure 4.3.

As shown, the steering input does not stay at zero as the vehicle settles to steady state. Additionally this is illustrated in the yaw of each of the units, shown in Figure 4.4. While the magnitude of the difference is small it still stands to illustrate that the vehicle does not track perfectly straight. In all of the subsequent plots regarding the TruckSim® data the nomenclature for the plots are detailed in Table 4.1.

The response to the zero steering input serves another purpose other than illustrating the steady state characteristics of the LCV. It also serves to prove that the model is indeed stable and suitable for continuing the simulations. One crucial result of the simulation is

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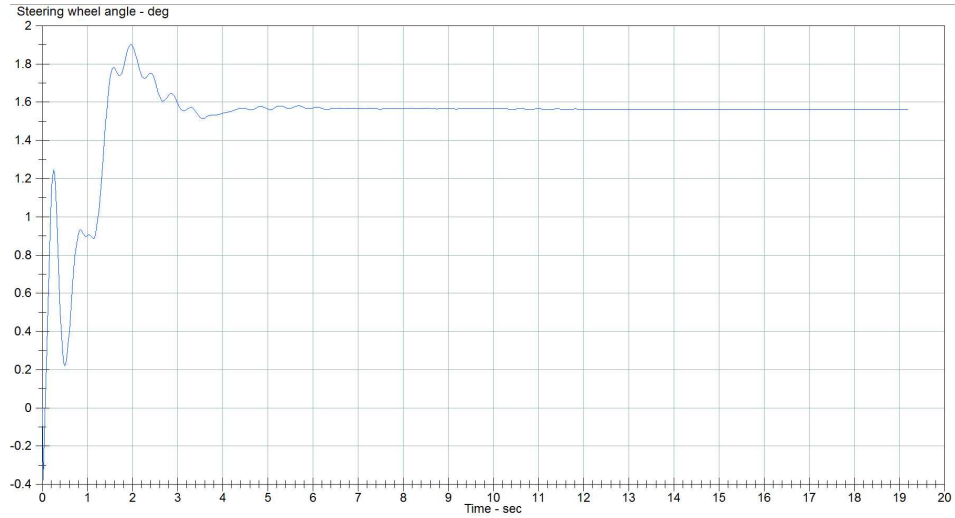
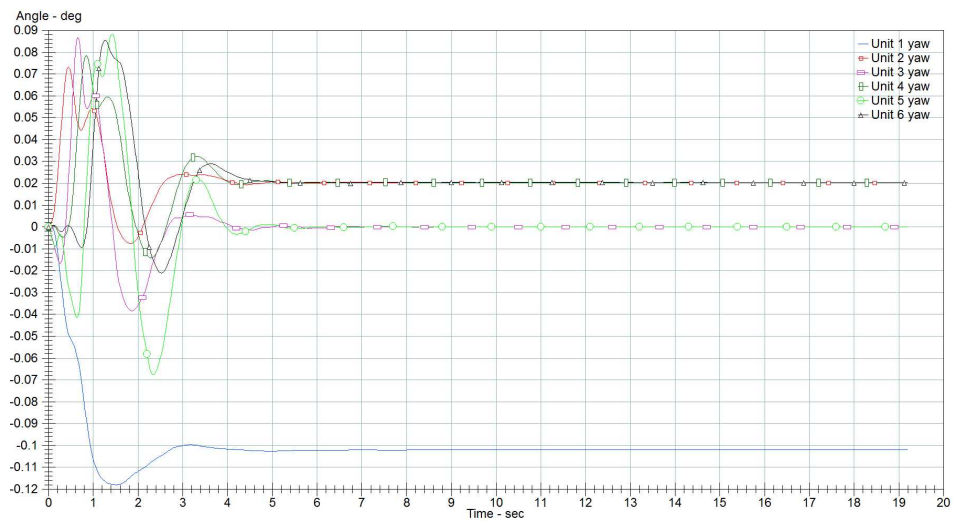Figure 4.3: Steering Wheel Response to No Steering Input

Figure 4.4: Yaw Response to No Steering Input

the observation that it takes several seconds for each unit to settle after the start of the maneuver. For that reason extra time was added to the beginning of all the simulations to ensure that the vehicle was in steady-state prior to performing the maneuver.

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Axle 1	Tractor Steer Axle
Unit 1	Freightliner Tractor
Axle 3	Rear Drive Axle of Tractor
Unit 2	Trailer 1
Axle 4	Trailer 1 Rear Axle
Unit 3	Converter Dolly Connecting Trailers 1 & 2
Unit 4	Trailer 2
Axle 6	Trailer 2 Rear Axle
Unit 5	Converter Dolly Connecting Trailers 2 & 3
Unit 6	Trailer 3
Axle 8	Trailer 3 Rear Axle

Table 4.1: Simulation Plot Key

4.2 Experimental Maneuver Simulation

In order to simulate the maneuvers that were undertaken on the test track the steering inputs had to be placed into TruckSim. This was done by filling in tables of data with desired positions of the LCV and TruckSim would then steer the vehicle so that it would follow that path as best as it could. An example of such input is shown above in Figure 4.2. Each of the maneuvers and subsequent speeds that were undertaken on the test track were duplicated in the TruckSim environment. However, for the sake of space only the results from two of the speeds will be presented for each maneuver in this thesis.

4.2.1 Constant Radius Turn

The constant radius maneuver is exactly what it sounds like, the vehicle travels through a constant radius curve at a constant speed. A screen shot of the animation of the LCV traveling trough the curve is shown in Figure 4.5. The path the vehicle traveled is shown in Figure 4.6. This path is the same for all speeds. Figures 4.7 & 4.8 show the roll of the vehicle at 25 & 40 mph respectively. Of note for the roll figures is that the roll is less for the 40 mph than the 20, this is due to the vehicle traveling at higher speeds and therefor having a greater lateral acceleration that counteracts the gravitational forces that are leading the vehicle to roll in the negative direction. Figure 4.9 illustrates the off-tracking of the LCV

during the constant radius turn. You can easily see that none of the units are actually able to follow the designed path and that each unit tracks to the inside of the previous unit in the combination.

Figure 4.5: Screen Shot of Animation for Constant Radius Turn
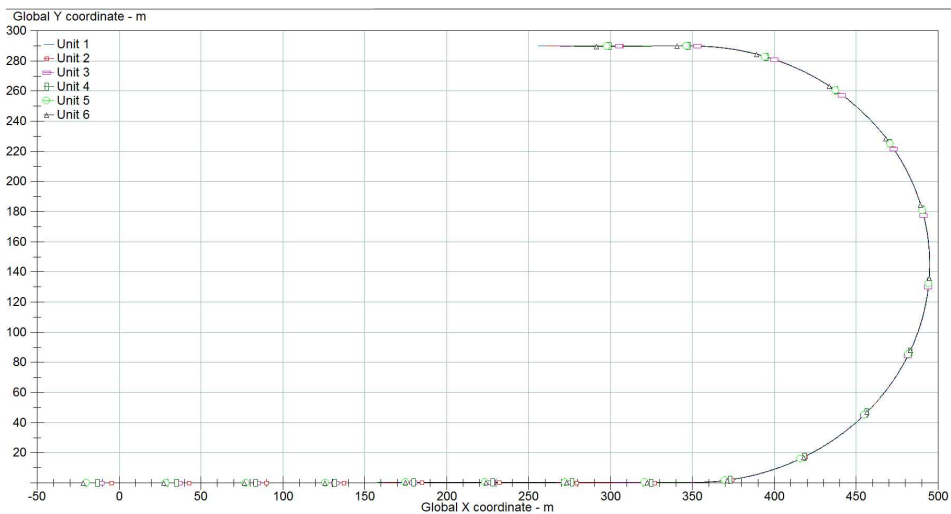
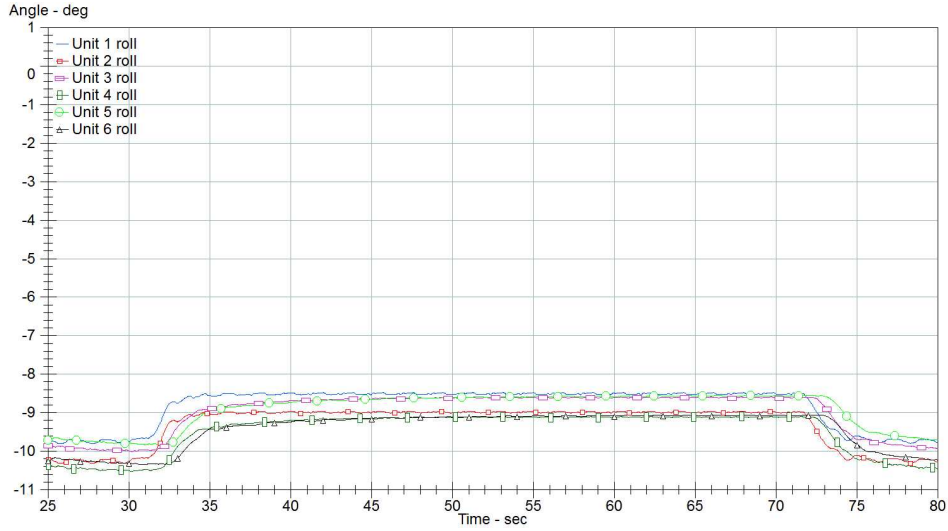

Figure 4.6: Path of LCV During Constant Radius Turn

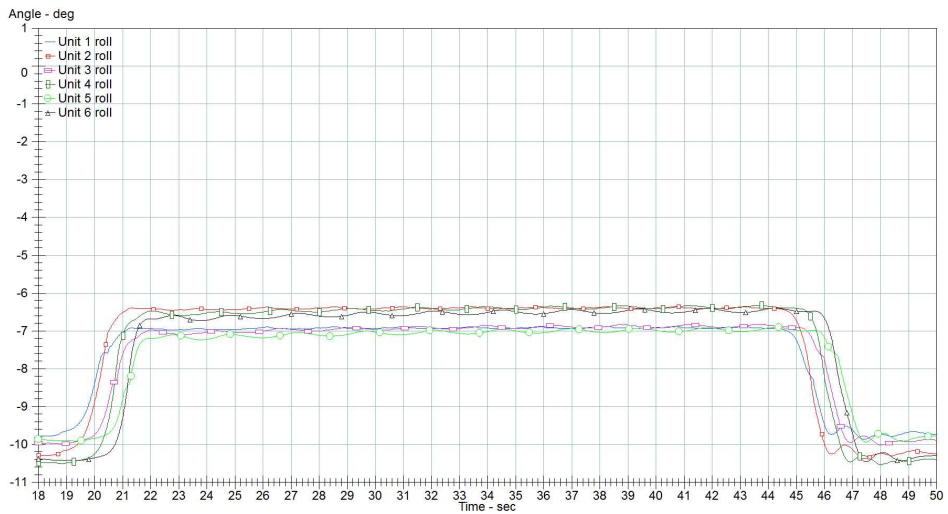Figure 4.7: Roll of Each Unit for 25 mph Constant Radius Turn

Figure 4.8: Roll of Each Unit for 40 mph Constant Radius Turn

4.2.2 Single Lane Change

The single lane change is simply maneuvering the vehicle from one lane to the other within the specified gate spacing. For this testing the gate spacing was set at 200 ft. The maneuver isn't initiated until the vehicle is in a steady-state. The path is illustrated in Figure 4.10. In the constant radius turn the off-tracking that was evident was each unit traveling to the inside of the path set by the preceding vehicle. In the case of lane change

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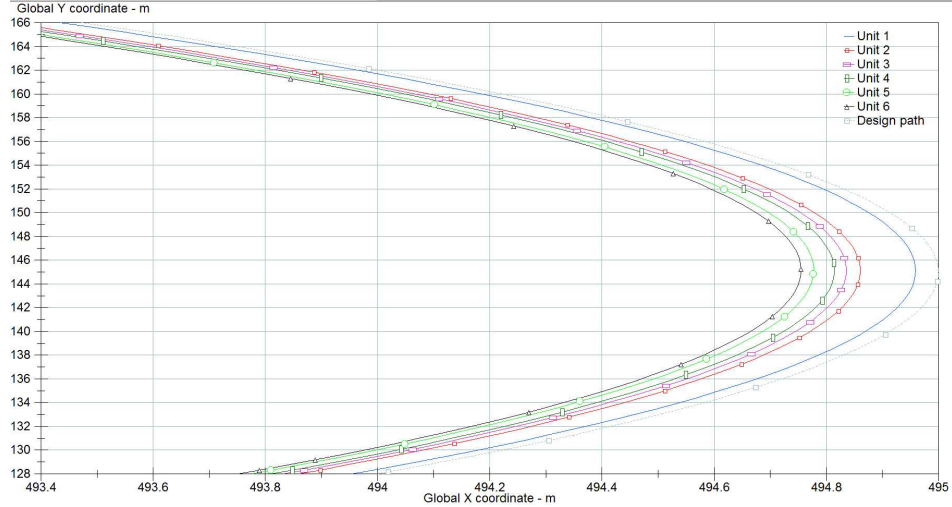
Figure 4.9: Unit Off-Tracking During 40 mph Constant Radius Turn

maneuvers, the same offset direction is seen at lower speeds. Yet as the speed increases the offset decreases, eventually becoming such that the trailing vehicle tracks outside of the leading vehicle. This is illustrated in Figures 4.11 & 4.13 where the first is a zoomed section of of the single lane change at 25 mph and the second is a zoomed section of the single lane change at 45 mph. To illustrate the off-tracking focus should be paid to the rear axles of each unit, those being axle three and greater. The full version of the 45 mph single lane change is shown in Figure 4.12.

The fact that the off-tracking switched from inside to out is due to the speed increase between maneuvers. The speed at which the off-tracking transitions is at 40 mph; below that the trailing axles track fully inside the lead axle whereas above that speed the axles begin to track outside the path of the lead axle. The same response can be seen in the plots of lateral acceleration as well as yaw. In both cases the highest values are that of the tractor and then decreasing down the LCV. Whereas at high speeds that behavior is reversed and the further back in the LCV the point of interest is the greater the response. This is the notion of rearward amplification. At lower speeds the rearward amplification is less than one, but after the vehicle crosses the critical speed limit the magnitude of the amplification becomes greater than one. That is to simply say the trailing vehicle exhibits
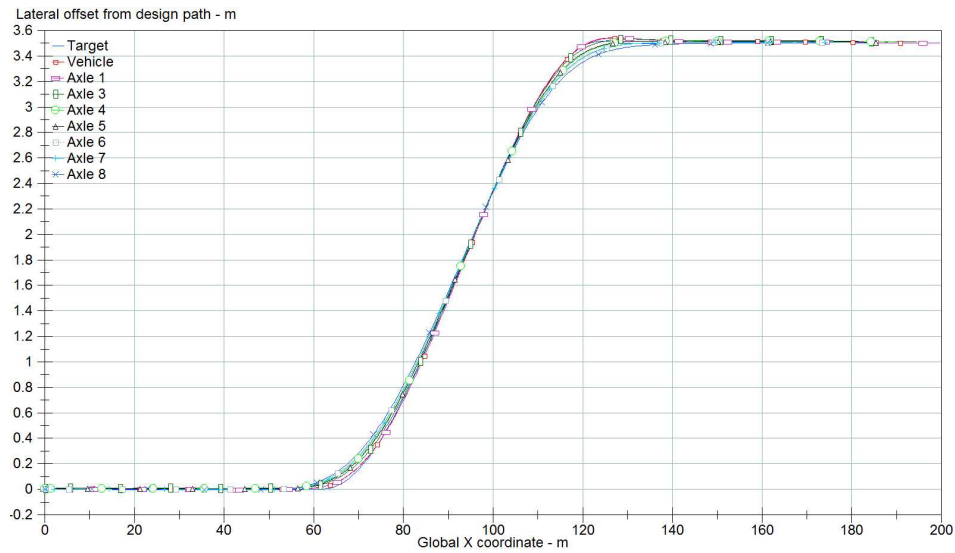
78

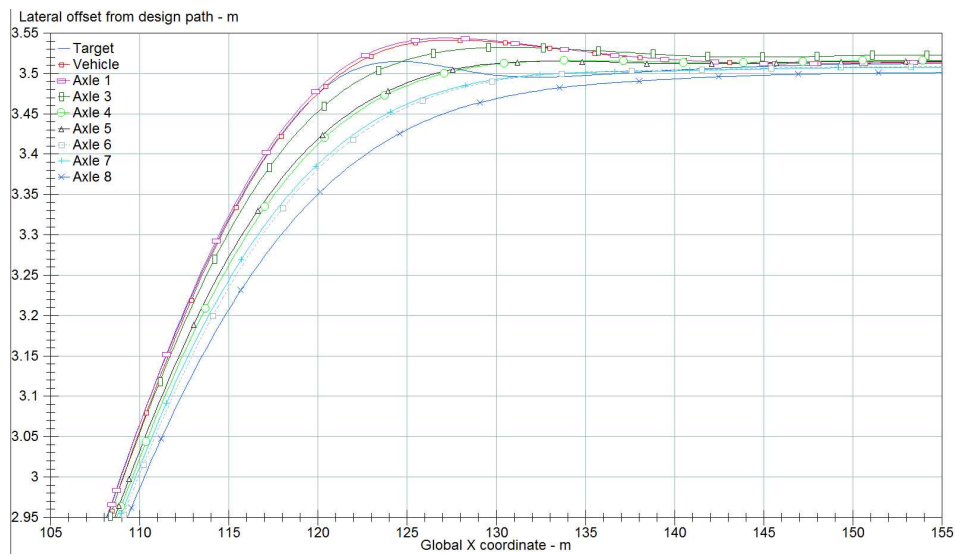Figure 4.10: Path of LCV During 25 mph Single Lane Change

Figure 4.11: Low Speed Off-Tracking During 25 mph Single Lane Change

a greater response than that of the leading vehicle. This is shown in the following figures; Figure 4.14 (Lateral Acceleration 25 mph) & Figure 4.15 (Lateral Acceleration 45 mph) & Figure 4.17 (Unit Yaw 25 mph) & lastly Figure 4.17 (Unit Yaw 45 mph).
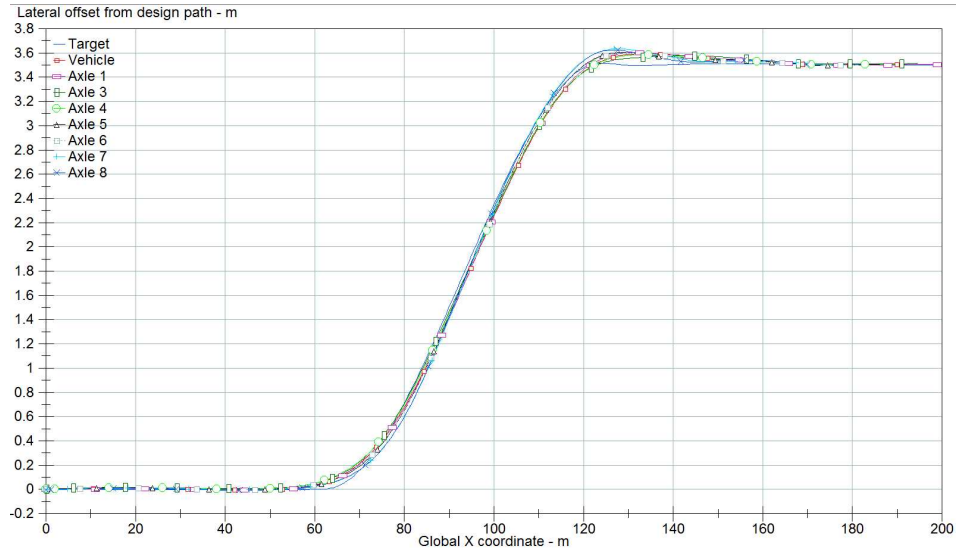
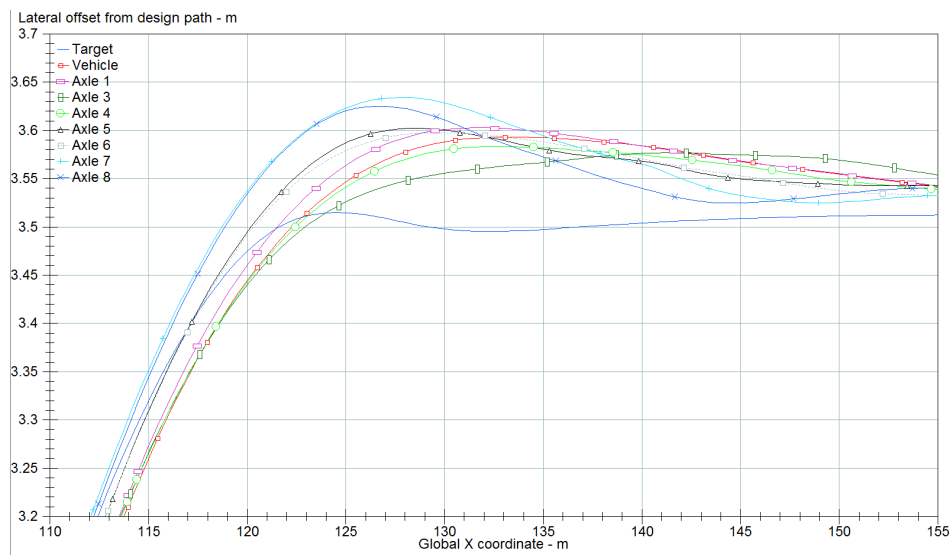Figure 4.12: Path of LCV During 45 mph Single Lane Change

Figure 4.13: High Speed Off-Tracking During 45 mph Single Lane Change

4.2.3 Double Lane Change

The double lane change (DLC) is an obstacle avoidance simulation maneuver. The aim is to view the response of the vehicle to two quick subsequent lane changes that would occur in the case of the lane being suddenly obstructed and the driver having to rapidly adjust. The maneuver begins in the right lane and once the vehicle is at steady state the
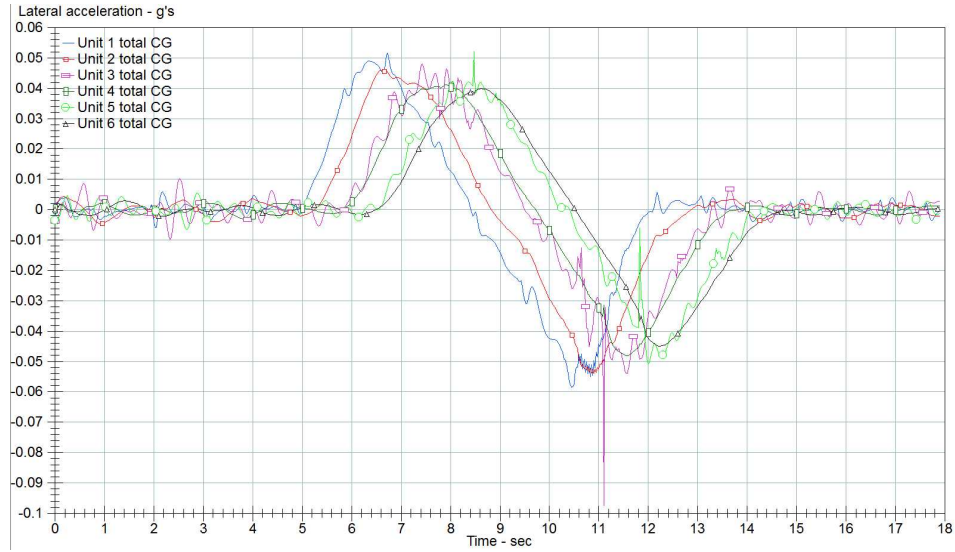
Figure 4.14: Lateral Acceleration During 25 mph Single Lane Change
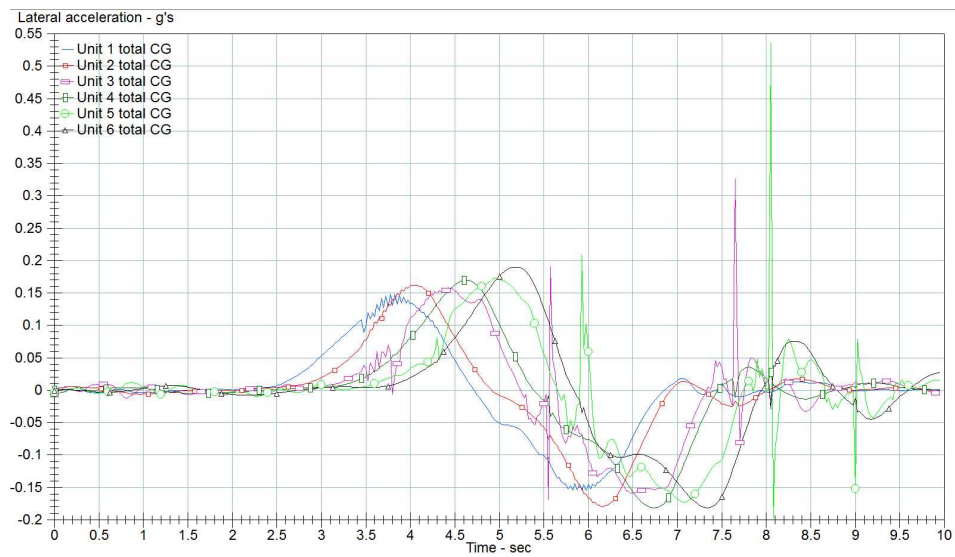
Figure 4.15: Lateral Acceleration During 45 mph Single Lane Change

driver steers the vehicle over to the left lane within a pre-defined gate spacing. Once in the

left lane the driver then returns to the right lane within the same gate spacing. A more

detailed description of the maneuver was provided previously in Section 3.3. Most of the

same characteristics are looked at for the double lane change that were examined for the

single lane change. The differences is that the double tends to excite larger amplifications as
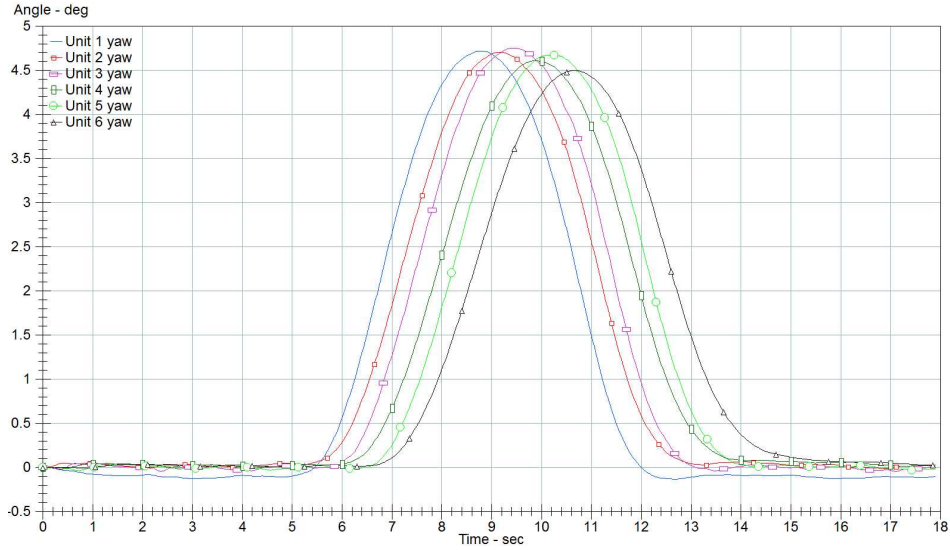
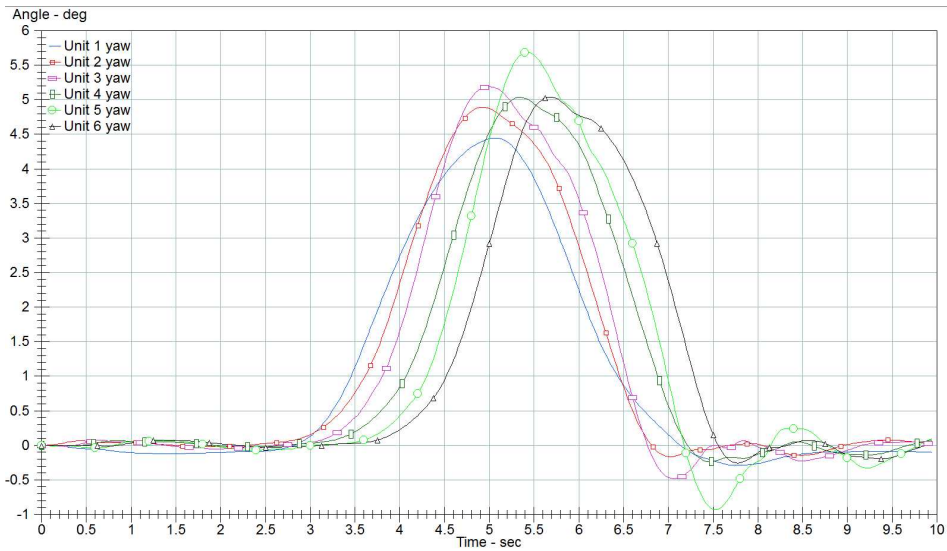Figure 4.16: Unit Yaw During 25 mph Single Lane Change

Figure 4.17: Unit Yaw During 45 mph Single Lane Change

it is the culmination of two rapid lane changes instead of only one. The same gate spacing of 200 ft was used for the double that was utilized in the single lane change. The path of the double lane change is shown in Figure 4.18 (25 mph), the plot for 45 mph DLC is shown in Figure 4.19.
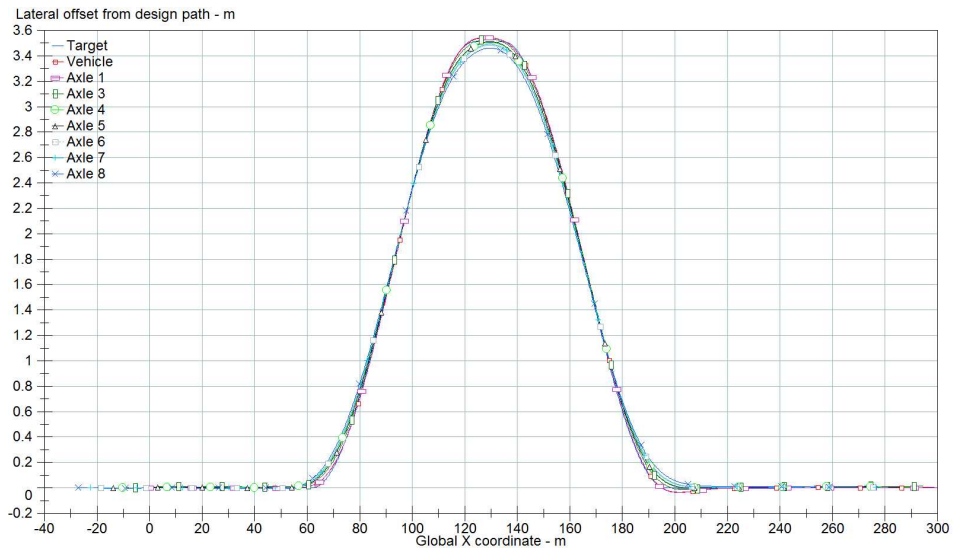
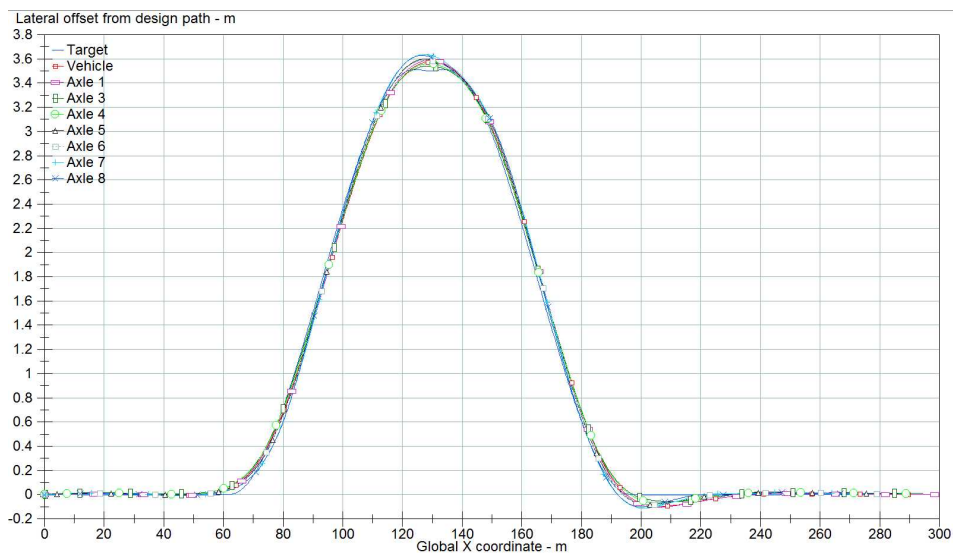Figure 4.18: Path of LCV During 25 mph Double Lane Change

Figure 4.19: Path of LCV During 45 mph Double Lane Change

One of the differences between the single and double lane changes is that due to the short distance that is traveled in the left lane prior to performing the 2nd lane change there is little to no off-tracking shown in the first lane change regardless of speed. This is illustrated in Figures 4.20 & 4.21 which are for 25 and 45 mph respectively.
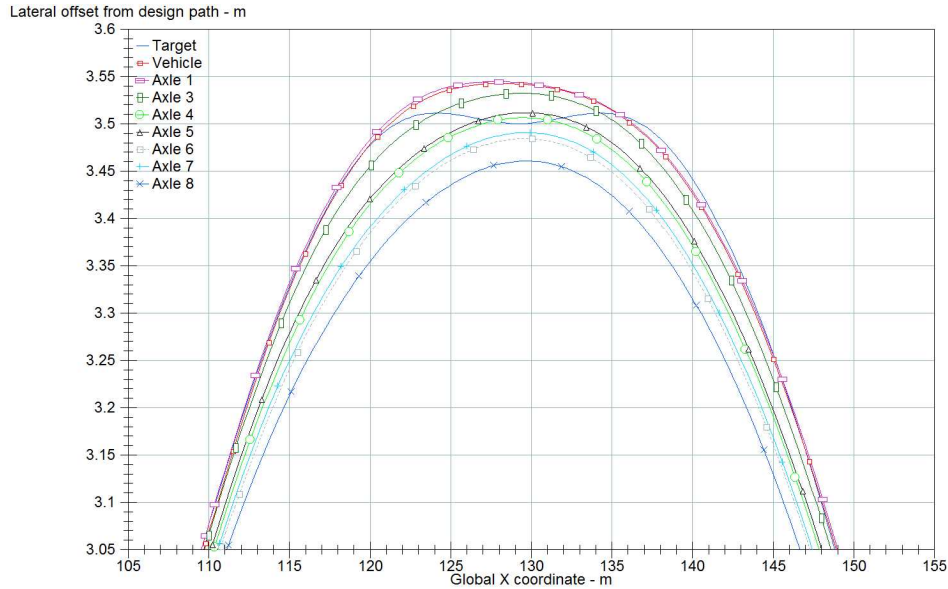
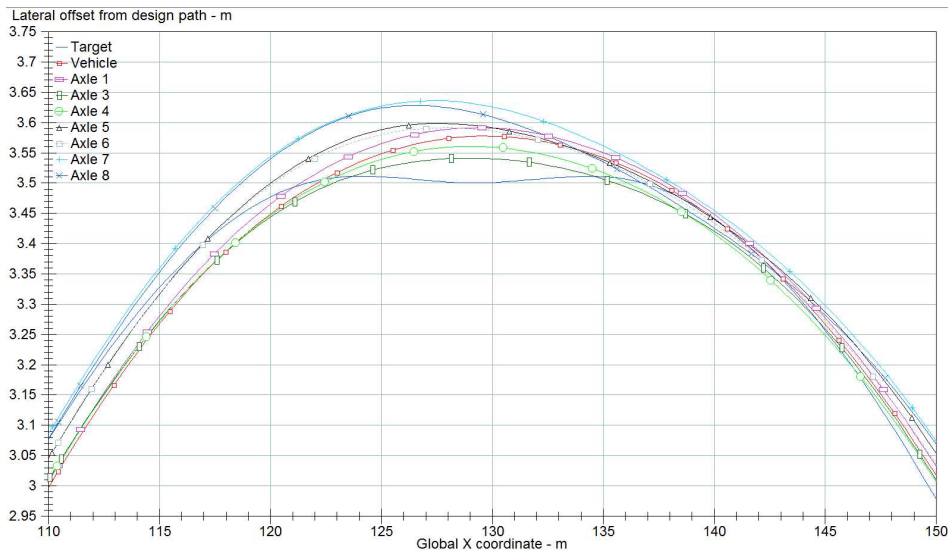Figure 4.20: Low Speed Off-Tracking During 25 mph Double Lane Change (1st Lane Change)

Figure 4.21: High Speed Off-Tracking During 45 mph Double Lane Change (1st Lane Change)

However when examining the 2nd lane change you can discern the same experience with the off-tacking as illustrated in the single lane change. This is explained by understanding that the initial lane change is never fully completed as the vehicle is not allowed to settle prior to commencing the return lane change. To examine the off-tracking for the return lane change see Figures 4.22 & 4.23 again for 25 and 45 mph respectively.
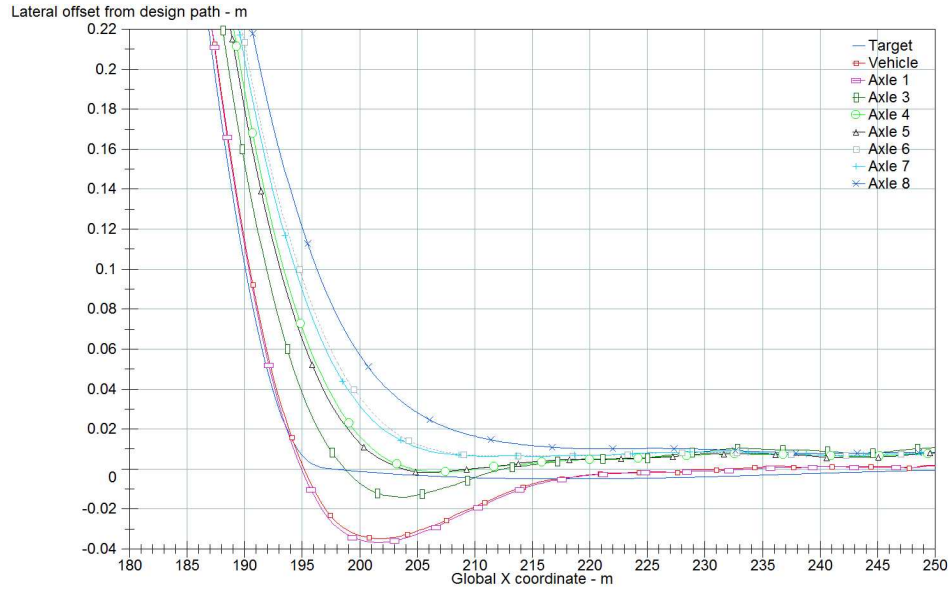
Figure 4.22: Low Speed Off-Tracking During 25 mph Double Lane Change (2nd Lane Change)
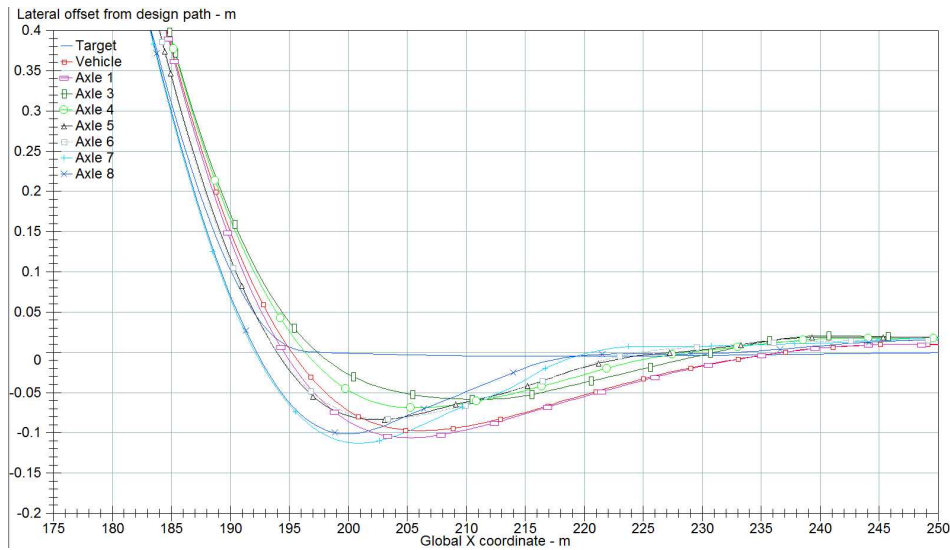

Figure 4.23: High Speed Off-Tracking During 45 mph Double Lane Change (2nd Lane Change)

One of the most informative plots to look at for the double lane change is the lateral acceleration of each unit in the LCV. From this plot, not only can rearward amplification be examined but also settling time and stability of the units can be assessed. Figures 4.24 &

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4.25 show the lateral acceleration according to TruckSim for the 25 and 45 mph double lane changes.
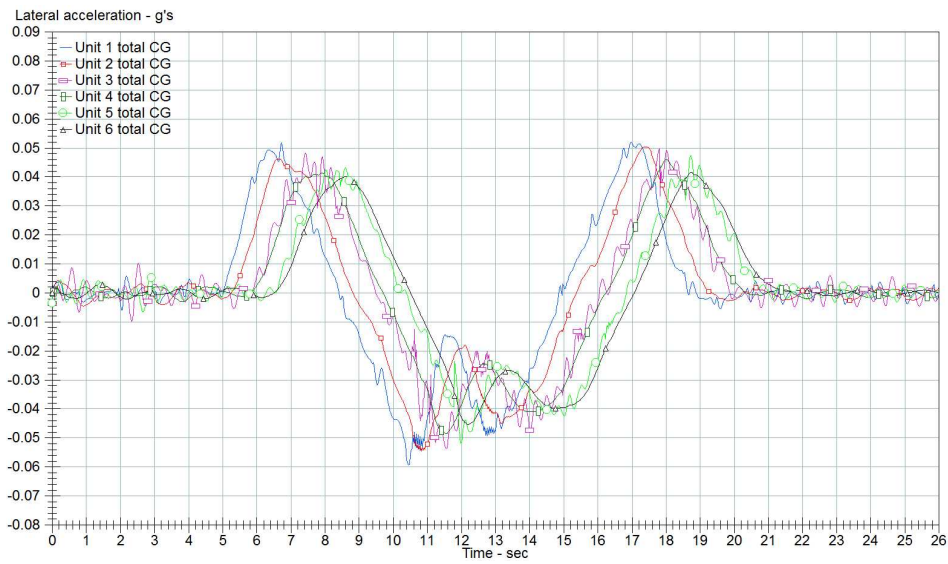

Figure 4.24: Lateral Acceleration During 25 mph Double Lane Change
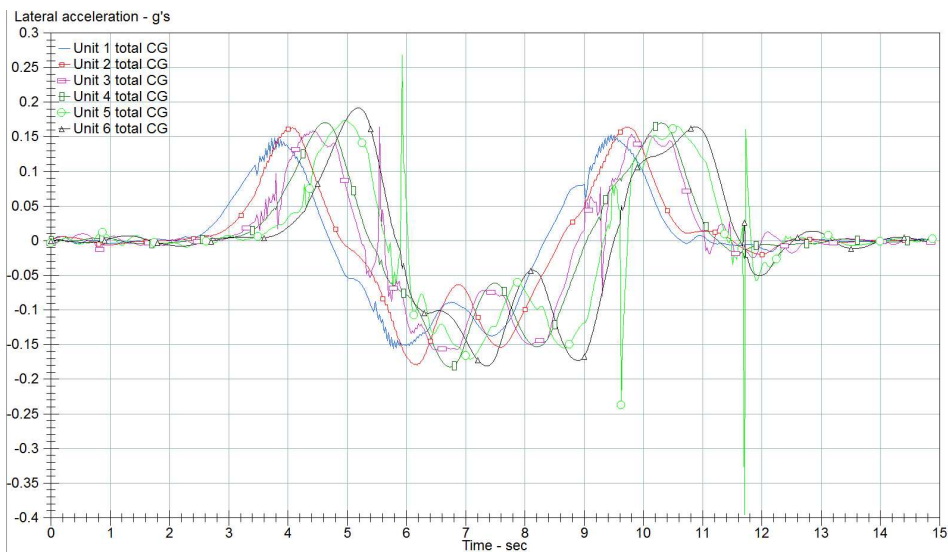

Figure 4.25: Lateral Acceleration During 45 mph Double Lane Change

As shown in the single lane change, the rearward amplification is less than one at the lower speed of 25 mph and greater than one at the higher speed of 45 mph. The more interesting element is the settling time of the third trailer as well as the amplitude of the

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oscillation in the acceleration. At the lower speed of 25 mph the third trailer follows the acceleration patterns of the rest of the LCV fairly indistinguishably. Yet with an increase of only 15 mph, the third trailer becomes rather unstable and very oscillatory in it's response. This is specifically evident in the return lane change. This gross increase in lateral acceleration led to the simulation at highway speeds of 60 mph for exploratory purposes. That plot is shown in Figure 4.26.
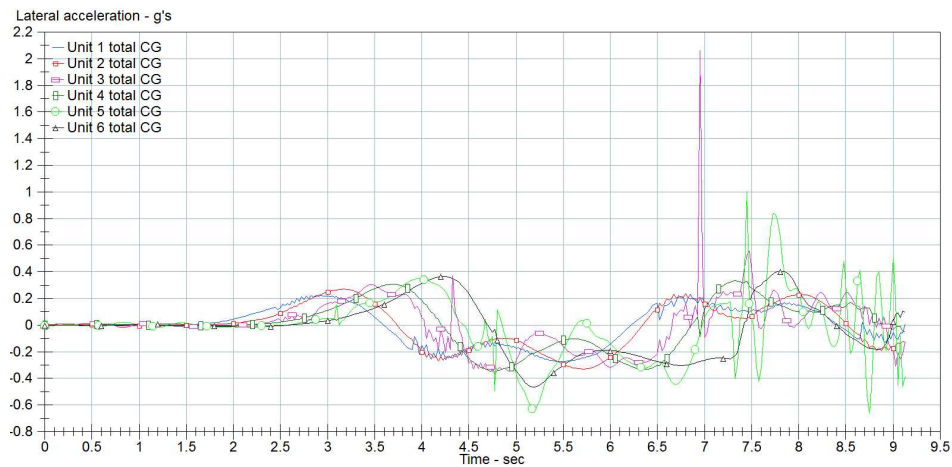

Figure 4.26: Lateral Acceleration During 60 mph Double Lane Change

While it may be hard to discern what occurred during the maneuver, it is easily noted that the behavior of the third trailer is nothing like that of any other unit. The reason for this is that at the speed of 60 mph the simulation of the double lane change resulted in the third trailer rolling over in the middle of the return lane change, which is easily illustrated in the plot of unit roll for the maneuver which is shown in Figure 4.27. The third trailer of the LCV actually experiences wheel lift-off in the middle of the initial lane change and then when the tractor tries to navigate back into the original lane the third trailer rolls over and takes the second converter dolly with it. Another property of the 60 mph double lane change is how the tractor seems to be uninterrupted by the instability and subsequent crashing of the third trailer during the maneuver.
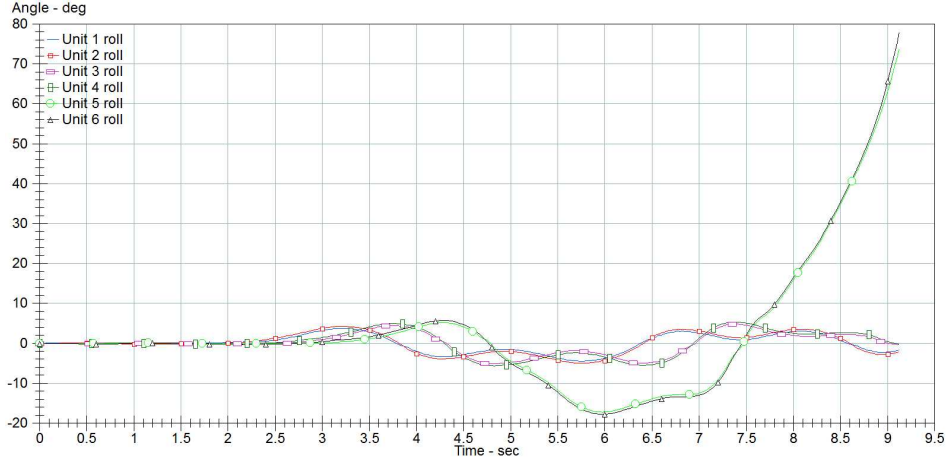
Figure 4.27: Unit Roll During 60 mph Double Lane Change

4.3 Experimental vs. Simulation

In an attempt to compare the results from the TruckSim simulations and that of the data taken experimentally, several overlay plots were generated. The following plots represent the data collected and simulated for a 30 mph double lane change. The first plot to examine is the driver input which is the hand wheel angle. That comparison is illustrated in Figure 4.28.

There are several key differences between the two data sets. The most noticeable is the early steer into the left lane in the experimental data. This can be explained by understanding that the driver in the experimental phase had a much longer preview time than the simulation did. That is to say that the driver knew what was coming and started to turn to the left sooner than he should have. Whereas in the simulation, the computer does exactly what is laid out in the simulation and does not begin to make the turn until the exact moment the LCV passes through gate 1. This results in a lower steer input for both the initial departure from the original lane as well as the return into the original lane. Additional effects of this discrepancy will be described shortly.

Another key point of interest is the articulation angle of the two converter dollies. The experimental data was passed through a low pass filter to remove some of the noise so that
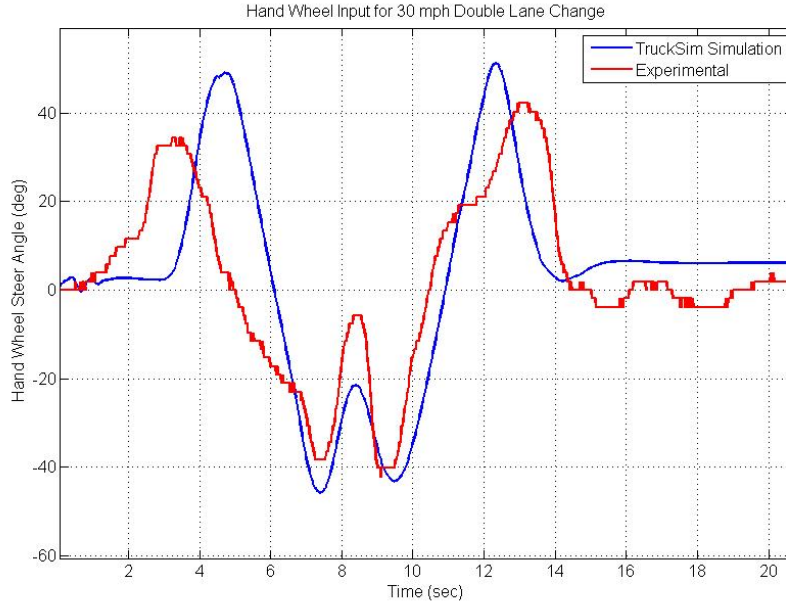
88

Figure 4.28: Steering Input Comparison for Simulation & Experimental Data

the two data sets could be plotted together. The calculated and measured articulation angles are presented in Figure 4.29 & 4.30 for the first and second dolly respectively for the 30 mph double lane change.

As shown, the two data sets match up rather well with minimal disagreements. The early steer input can be seen in both plots as well. This measurement was of some concern as it was the combination of two different string potentiometers placed adjacent to one another and measuring the linear displacement of the proceeding trailer. That measurement was then converted to an angle based on the radius of the trailer tongue. This shows that the methodology and implementation of the articulation measurement was sufficient in capturing the angle. This articulation angle serves as the steer input into the proceeding trailer, hence why from a dynamic analysis standpoint it is a crucial measurement to get right.

The last set of comparison plots to present are that of unit roll. The roll for the first and last trailers is presented below in Figure 4.31 & 4.32 respectively. While the two do not agree as much as would be desired the differences are believed to be because of the longer
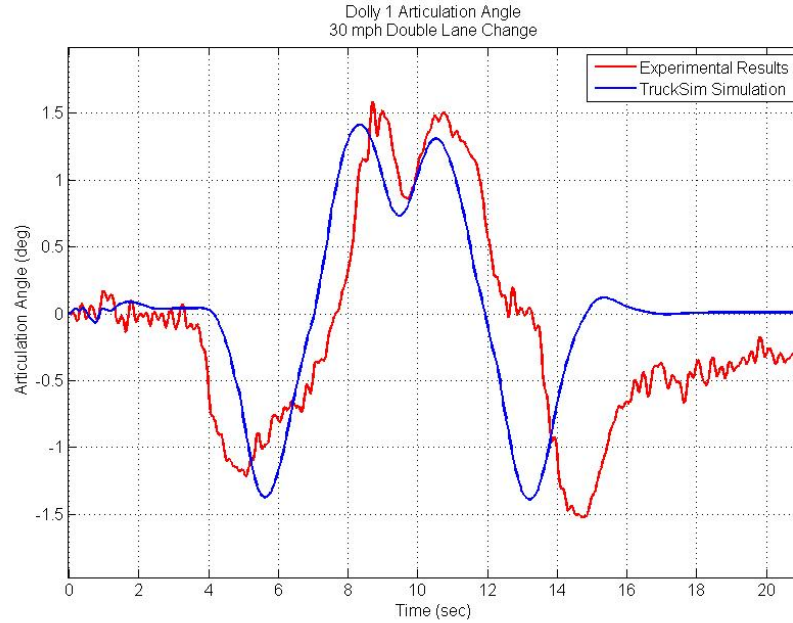
89

Figure 4.29: Dolly 1 Articulation Angle Comparison for Simulation & Experimental Data
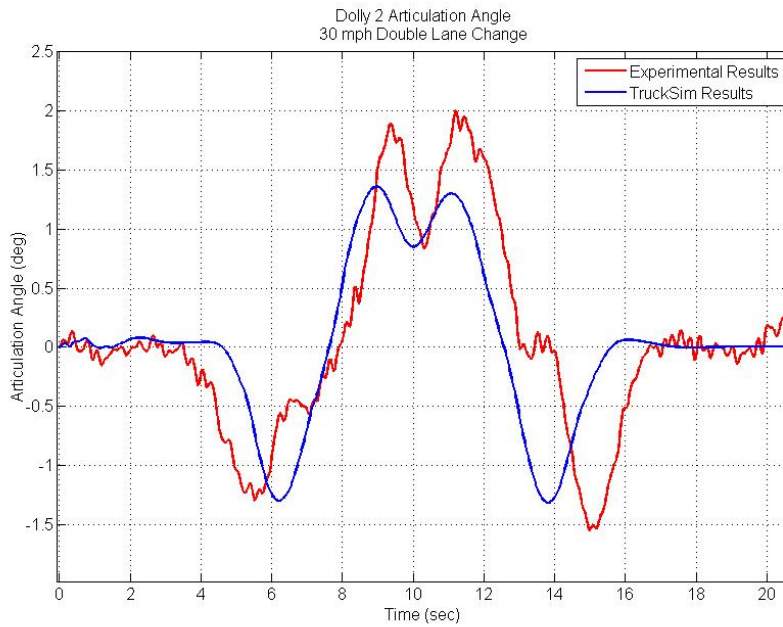

Figure 4.30: Dolly 2 Articulation Angle Comparison for Simulation & Experimental Data

preview time described above. Since there was a lower steer rate input for the experimental data than that of the simulation data set it would be expected that the input would not

incite as much roll. Of interest is that for the steer input back into the original lane of travel the first trailer comparison appears to match rather well. This is due to the preview time of the drive being shortened during the middle of the maneuver. In essence by the time the driver has successfully navigated the vehicle into the left lane, he has to begin his transition back into the original lane of travel. this causes an increased steer rate than that of the original lane change and therefore incites a greater roll response from the subsequent units.
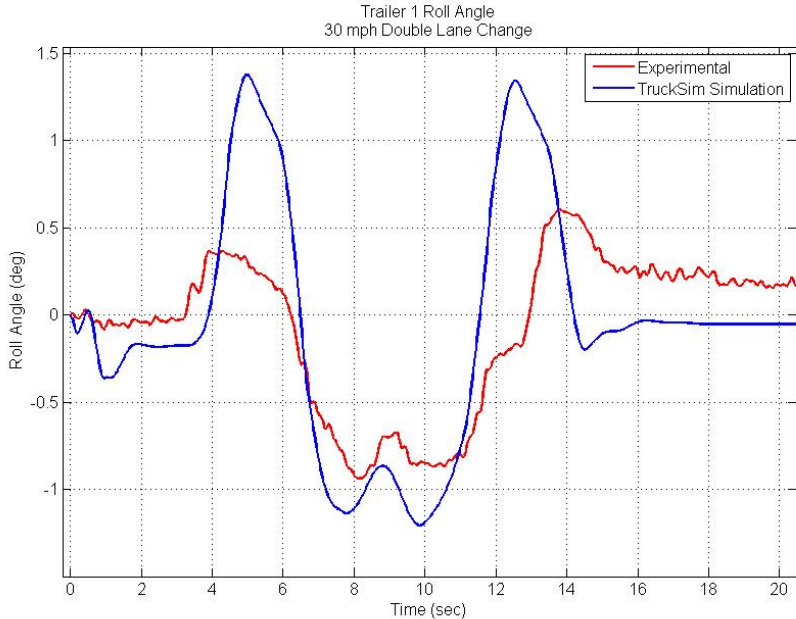

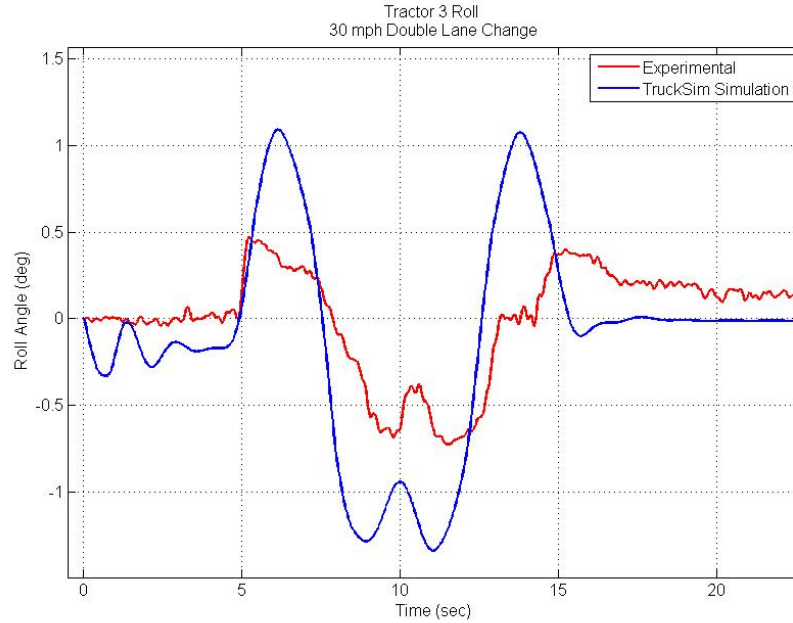Figure 4.31: Trailer 1 Roll Comparison for Simulation & Experimental Data

Figure 4.32: Trailer 3 Roll Comparison for Simulation & Experimental Data

4.4 Double vs. Triple LCV

One of the best ways to assess the safety of a triple is to compare it to a standard that is prominent currently. To that end, several simulations were run using a standard double semi-trailer configuration. The settings for the vehicle were all left as packaged from TruckSim with the assumption that they were representative of the average parameters for the vehicle. Three separate simulations were chosen for comparison, two of which were double lane change maneuvers and the third a single lane change. The double lane changes were run at 45, 55, and 60 mph. The single lane changes were compared at 45, 55, and 65 mph. For all of the maneuvers the characteristics of interest where roll, yaw, and lateral acceleration; each of those values will be plotted for comparison.

4.4.1 Single Lane Change Comparison

The single lane change is a good starting point for assessing the stability of any vehicle. It is a low risk maneuver as it is not intended to excite large dynamic responses, especially in the case of the SLC set up for this research with a gate spacing of 200 ft. Figures 4.33 - 4.35 show the varying yaw responses for 45, 55, and 65 mph respectively.
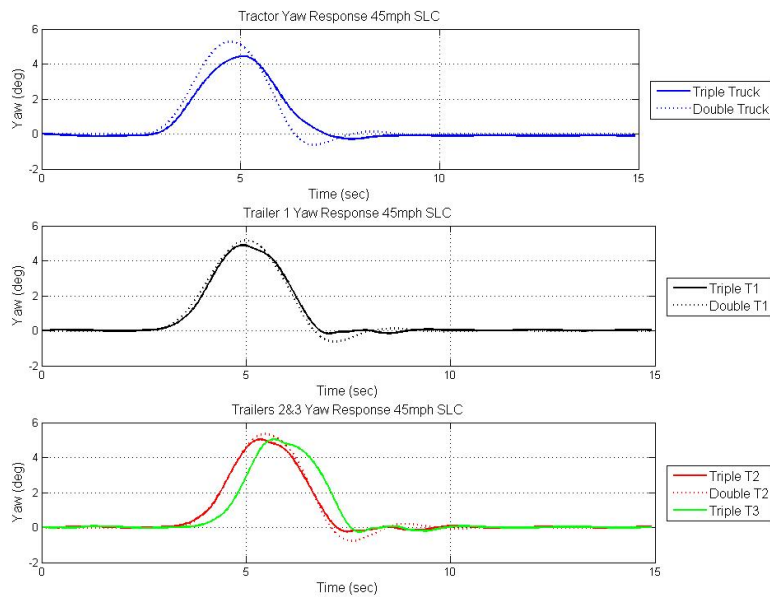

Figure 4.33: 45 mph Single Lane Change Double vs. Triple Yaw Comparison

As illustrated in the figures, at lower speeds the units tend to behave identical. This is especially the case with the trailers. As the speeds increase though the responses begin to vary, most notably with respect to the tractor. Of note is that at the 65 mph speed the triple LCV experienced rollover of the third trailer, that is why the triple data plots end abruptly. One interesting characteristic that is illustrated is the lower oscillation of the tractor, this is a result of the heavier load in the triple. At the lower speeds the heavier load does not require as much correctional steering as the double. That correctional steering to keep the vehicle in the lane is the cause of the oscillation in the yaw of the double combination. The next characteristic to observe is the roll behavior of each vehicle during the same double
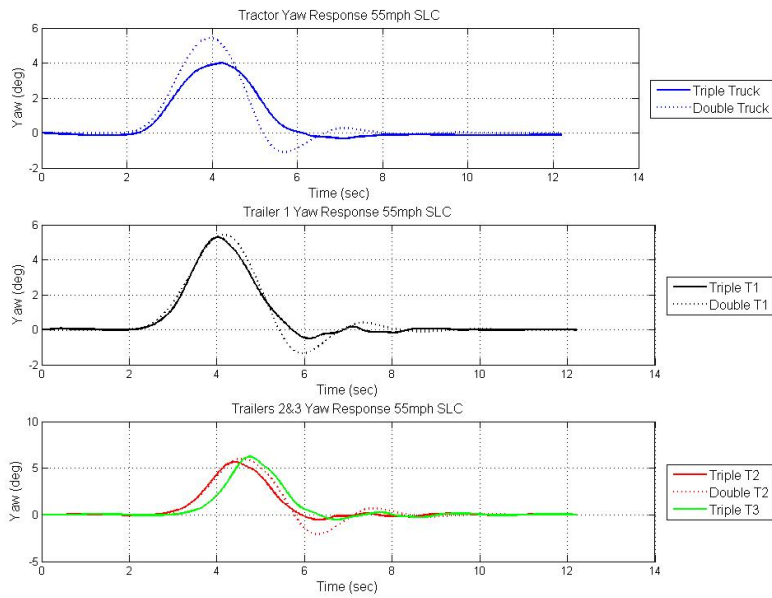
Figure 4.34: 55 mph Single Lane Change Double vs. Triple Yaw Comparison
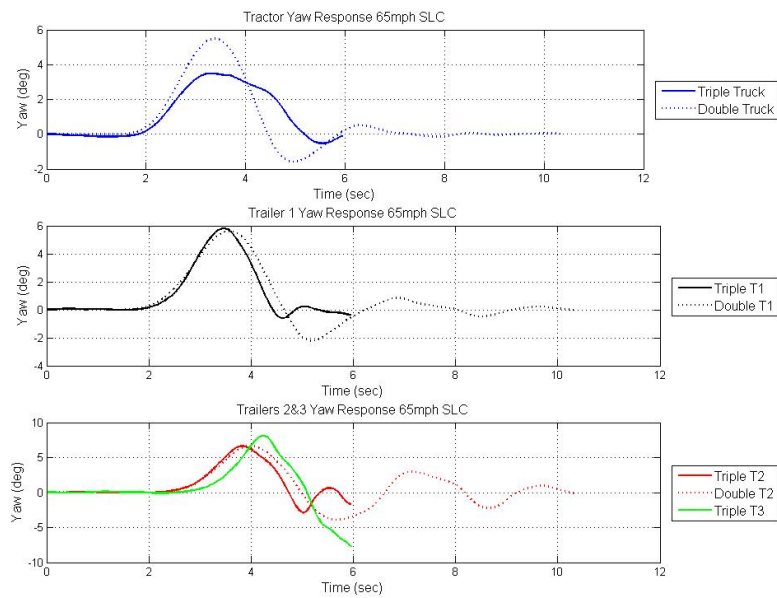
Figure 4.35: 65 mph Single Lane Change Double vs. Triple Yaw Comparison

lane change maneuvers. Figures 4.36 - 4.38 show the varying roll responses for 45, 55, and 65 mph respectively.

Figure 4.36: 45 mph Single Lane Change Double vs. Triple Roll Comparison

Figure 4.37: 55 mph Single Lane Change Double vs. Triple Roll Comparison

The same heavier load that helped the triple in the yaw comparison hurts it in the roll comparison. Because of the heavier load, the vehicle experiences much larger roll than that

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Figure 4.38: 65 mph Single Lane Change Double vs. Triple Roll Comparison
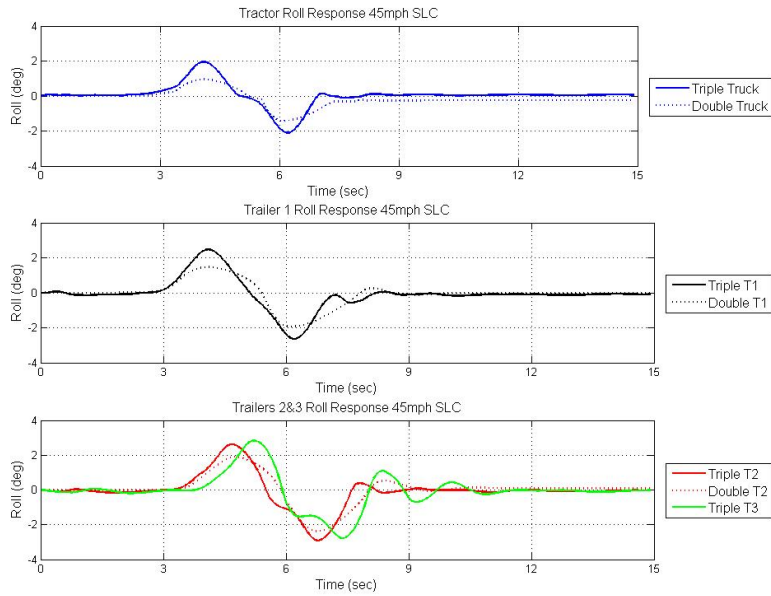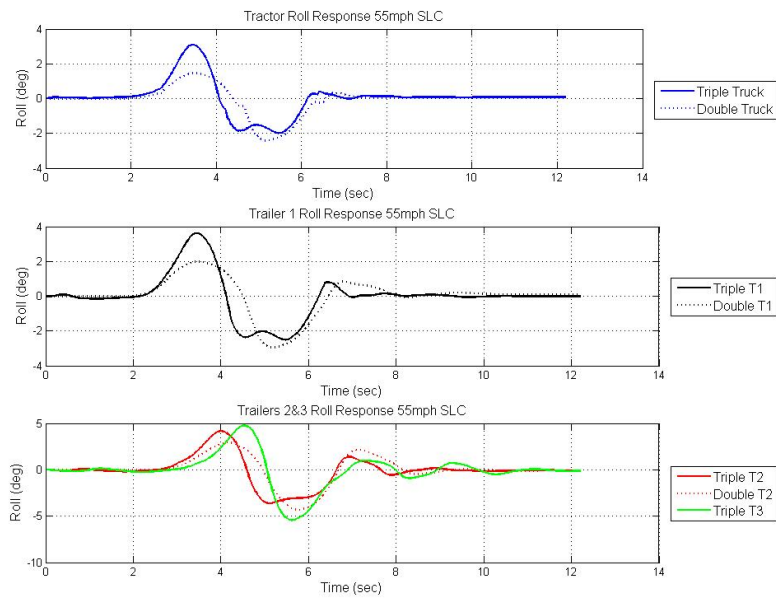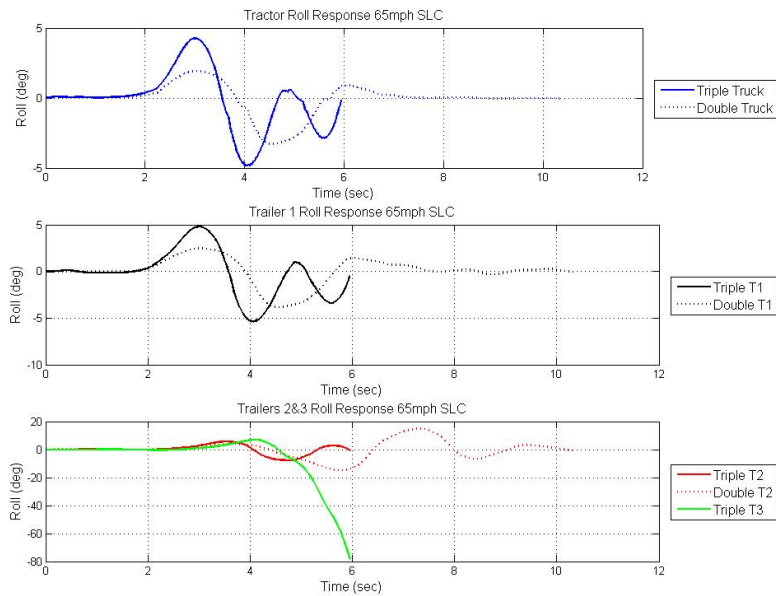
of the double. This also causes the triple to 'rock' after each maneuver and takes some time to settle out. The roll of the vehicle is the most visual evident characteristic for large trucks with their innate high center of gravity. Of note is that none of these speeds were even attempted during the experimental phase as they were all beyond the driver's comfort level. The visual of the triple settling out after the lane change is not one that would be comforting to any motorist. The final characteristic that will be explored is the lateral acceleration of the units in the combinations. Those responses for 45, 55, & 65 mph are plotted below in Figures 4.39 - 4.41 respectively.

The lateral acceleration response is somewhat a combination of both the Yaw response and the Roll response. The trailers appear to response identically at the lower speeds, as the speeds increase the triple begins to experience higher amplitude along with a shorter period of oscillation for the response. It can be seen in Figure 4.40 that the third trailer on the triple takes a considerable amount of time to settle after the maneuver. This is an indication
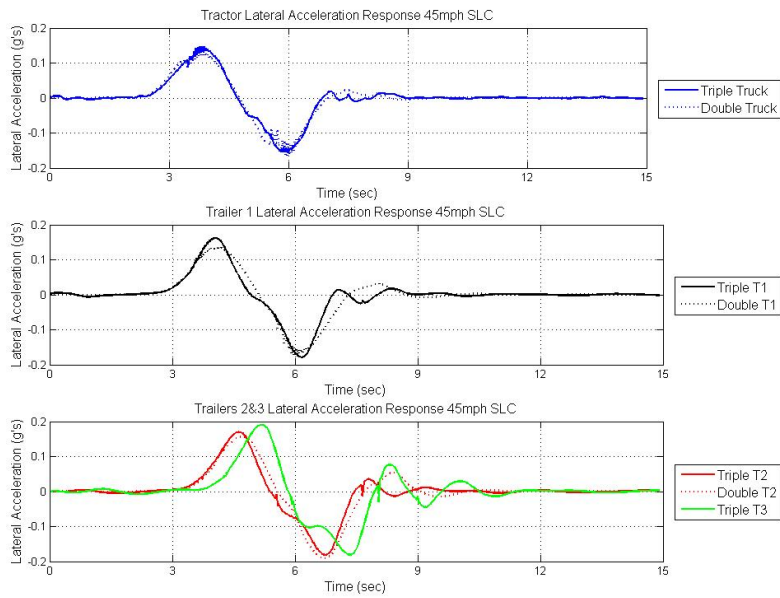
Figure 4.39: 45 mph Single Lane Change Double vs. Triple Lateral Acceleration Comparison
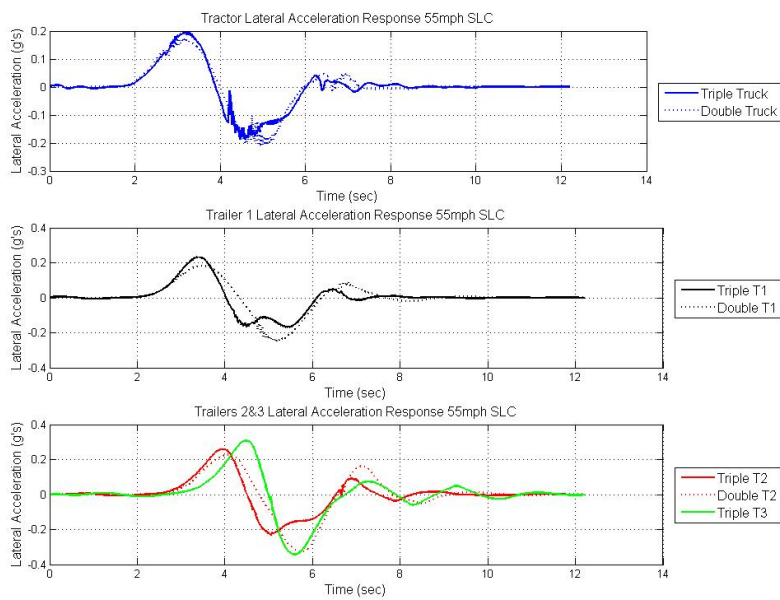

Figure 4.40: 55 mph Single Lane Change Double vs. Triple Lateral Acceleration Comparison

that the trailer is approaching it's stability moment and any increase in speed could lead to rollover, which is exactly what happens at 60 mph.
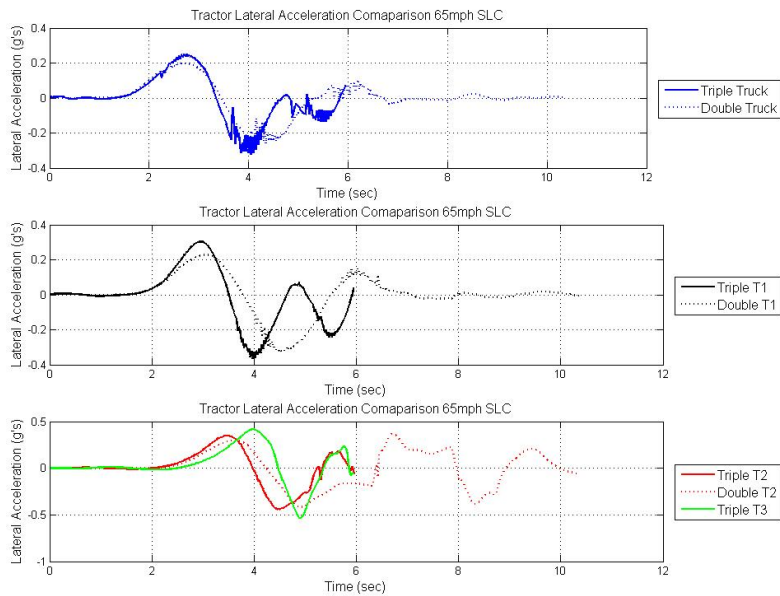
Figure 4.41: 65 mph Single Lane Change Double vs. Triple Lateral Acceleration Comparison

4.4.2 Double Lane Change Comparison

The next maneuver that was simulated for comparison was the Double Lane Change (DLC). This maneuver is meant to excite large dynamic responses and that is very evident at the higher speeds. Figures 4.42 - 4.44 show the varying yaw responses for 45, 55, and 60 mph respectively.

The yaw responses of the vehicles behaves similar to that of the single lane change. At lower speeds the units, especially the tractors appear almost identical. Then as the speeds increase the tractor experiences a decrease in amplitude while the trailers appear to be unaffected. That is, until you reach 60 mph at which the third trailer in the triple combination experiences rollover. The next characteristic to observe is the roll behavior of each vehicle during the same double lane change maneuvers. Figures 4.45 - 4.47 show the varying roll responses for 45, 55, and 60 mph respectively.

The roll response of the triple especially does not look ideal at any speed. The third trailer fails to settle fully in any of the simulations. The responses of the triple truck and

Figure 4.42: 45 mph Double Lane Change Double vs. Triple Yaw Comparison
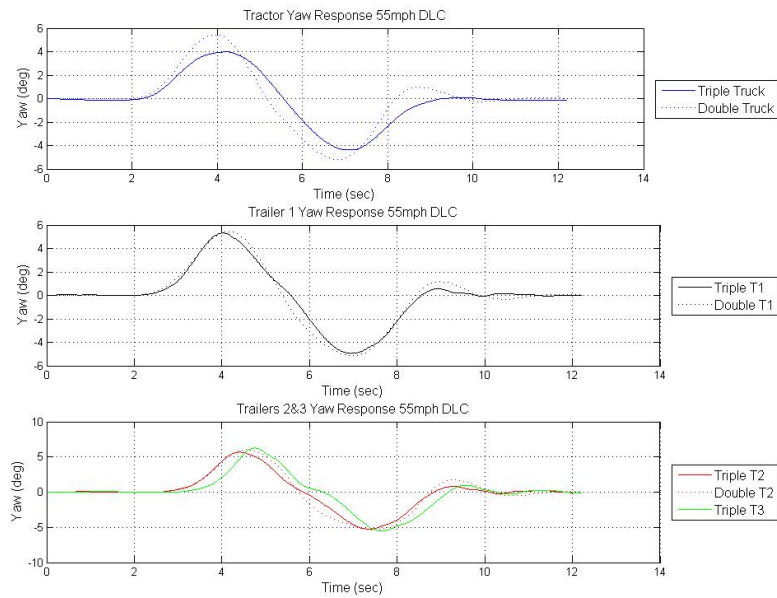
Figure 4.43: 55 mph Double Lane Change Double vs. Triple Yaw Comparison

first trailer appear to match that of the double truck and first trailer more closely during the double lane change than the single lane change. This is believed to be because once in the

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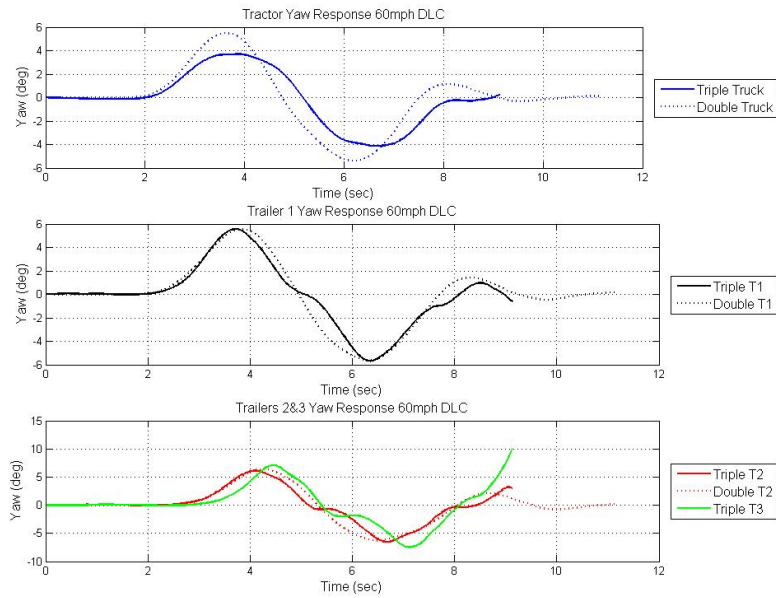
Figure 4.44: 60 mph Double Lane Change Double vs. Triple Yaw Comparison
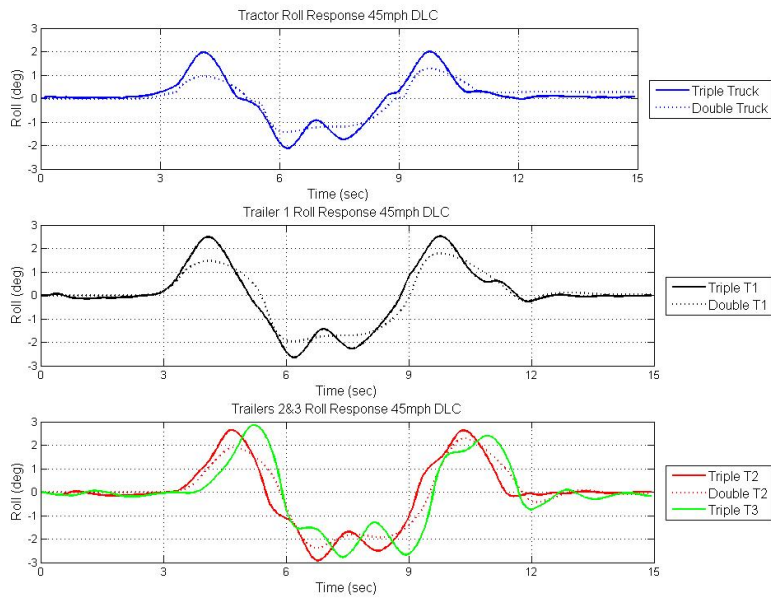
Figure 4.45: 45 mph Double Lane Change Double vs. Triple Roll Comparison

left lane the driver must already begin the maneuver to go back to the right lane, therefor not allowing any of the units to begin to settle in the left lane. The final characteristic that
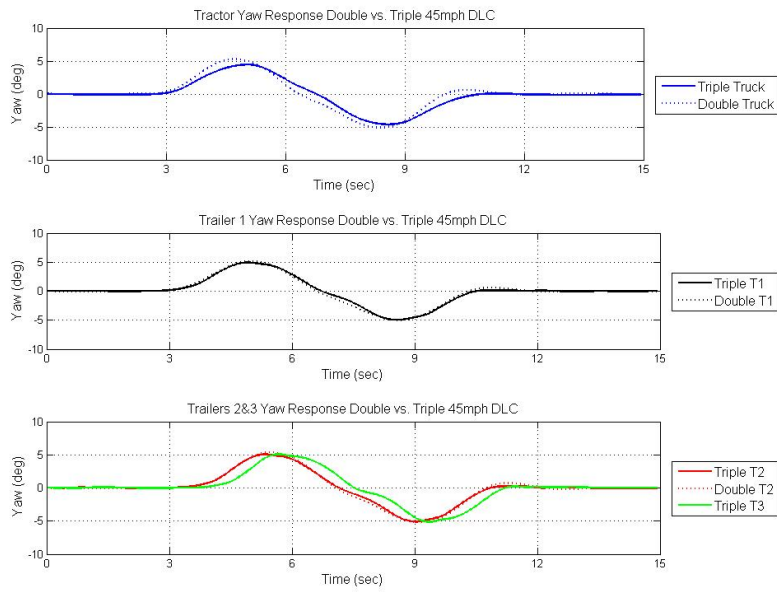
100
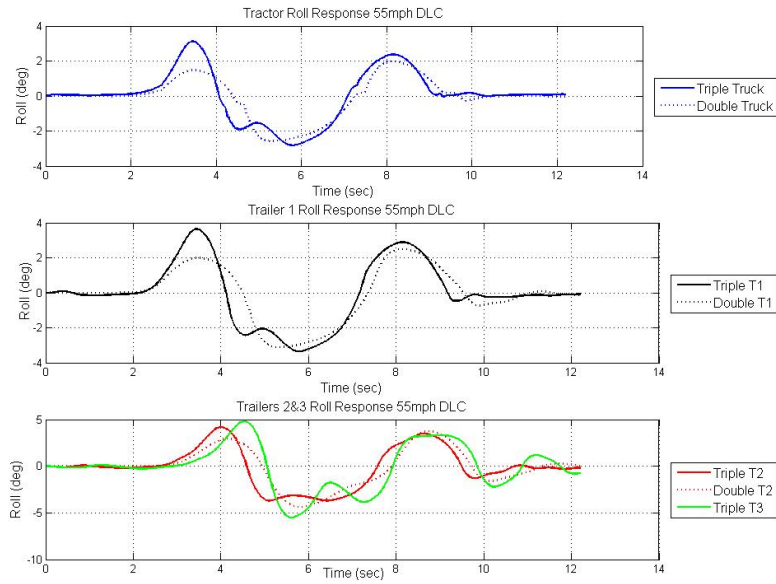
Figure 4.46: 55 mph Double Lane Change Double vs. Triple Roll Comparison
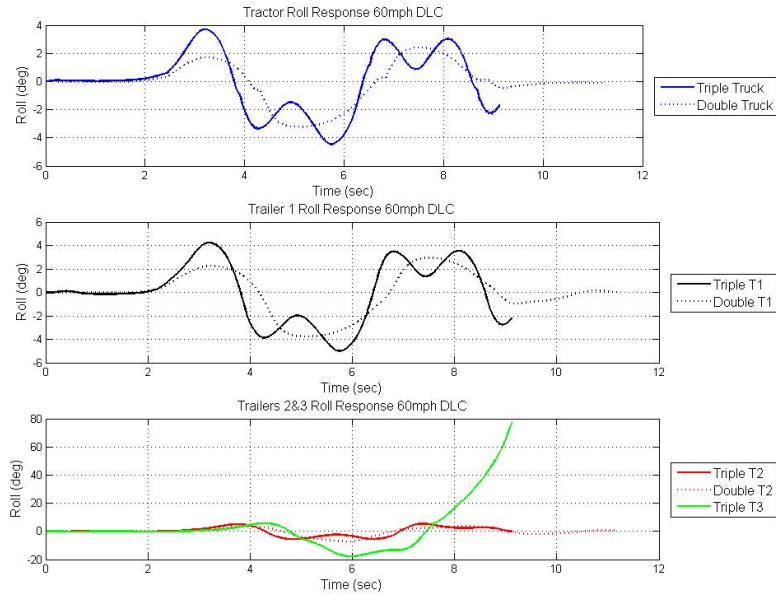
Figure 4.47: 60 mph Double Lane Change Double vs. Triple Roll Comparison

will be explored is the lateral acceleration of the units in the combinations. Those responses for 45, 55, & 60 mph are plotted below in Figures 4.48 - 4.50 respectively.

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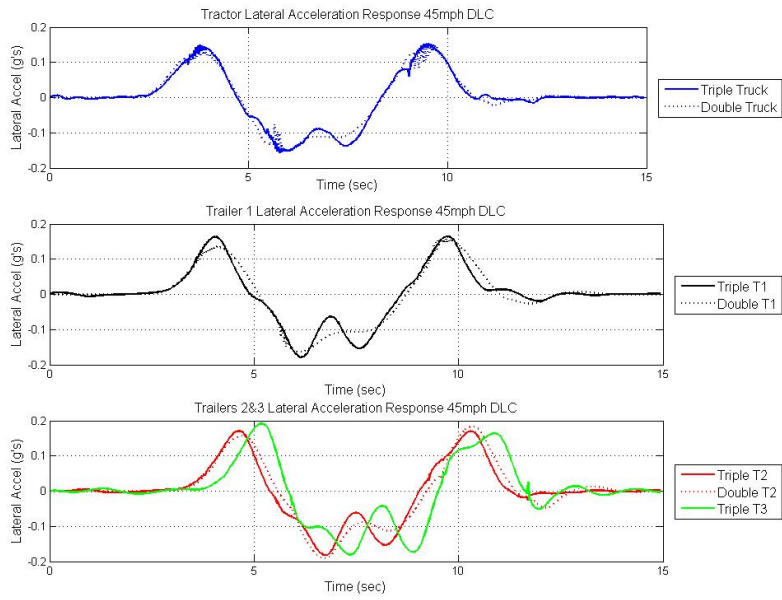
Figure 4.48: 45 mph Double Lane Change Double vs. Triple Lateral Acceleration Comparison
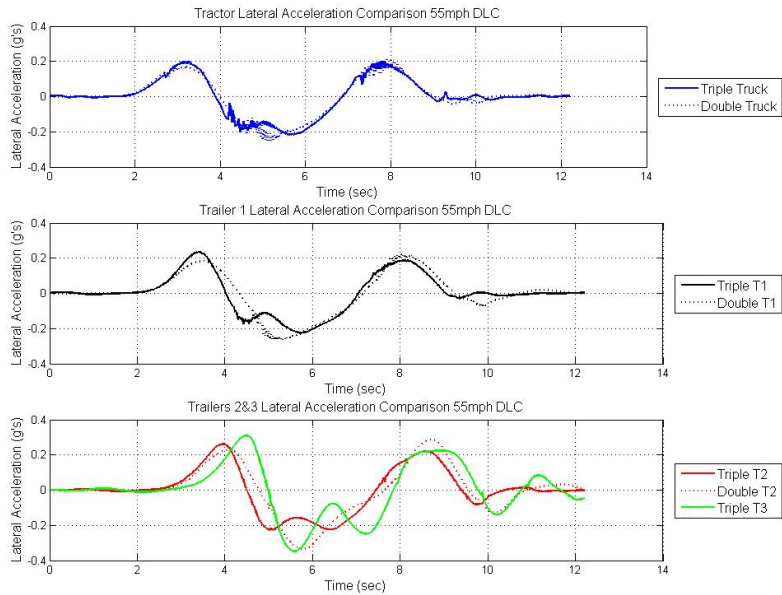
Figure 4.49: 55 mph Double Lane Change Double vs. Triple Lateral Acceleration Comparison
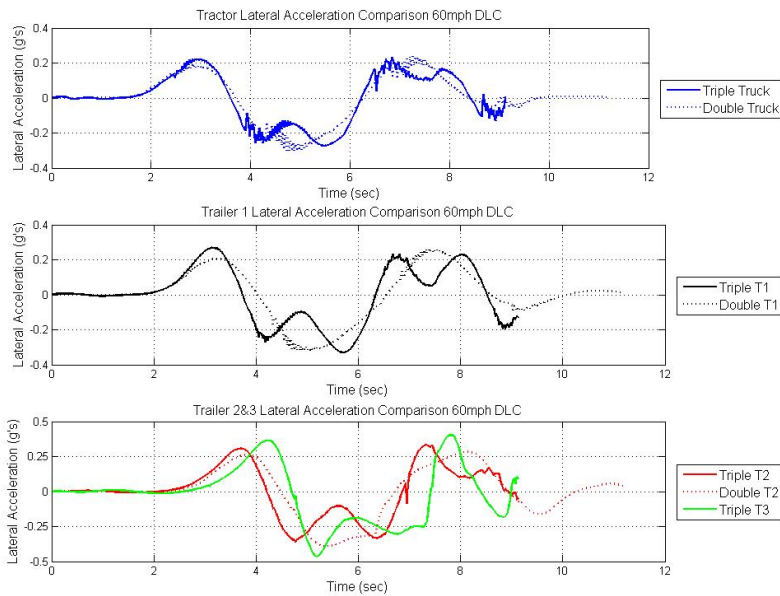
Figure 4.50: 60 mph Double Lane Change Double vs. Triple Lateral Acceleration Comparison

The lateral acceleration of the units for the double lane change is not a good vote for the legalization of triple trailers on highways across the nation. The lateral acceleration the triple undergoes in the 45 mph maneuver alone is enough cause for concern. The double lane change is a maneuver that happens often and any vehicle that is going to be traveling at highway speeds needs to have the ability to perform such a maneuver in the event of an emergency. The triple LCV does not show any indication that it would be able to perform the double lane change at any speed greater than that of residential with any form of safety. This was also experienced in the experimental phase when it was attempted to perform the double lane change at 40 mph. After performing the maneuver the driver decided that it was too fast and only one attempt was made at that speed.

4.4.3 Double vs. Triple Conclusions

After running the simulations and comparing the outputs it was interesting to see that for the most part the vehicle performed identical at lower speeds. This shows that the trailing

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vehicles have little effect on the leading vehicles from a dynamics standpoint at the lower speeds. However, as the speeds increased it was easy to see that the triple is much less stable and has a higher propensity for rollover making it unsafe. The triple experiences rollover in the double lane change maneuver at approximately 58 mph and at approximately 62 mph in the single lane change, both speeds that are well within the expected operating speed of any highway vehicle. It would appear that the triple needs much more safety integration before being suitable for the highway.

4.5 Sources of Error

There were several large sources of error that were encountered in this project. the mitigation of such sources is key to improving the research and increasing the fidelity of the simulation. The main source of error for this phase of the research was human error in calculation the LCV characteristics. All of the distance measurements were ascertained by hand which innately leads to some margin of error. Additionally, material property assumptions had to be made in order to estimate both mass as well as compliance for the suspension system. Another source of error is the lack of complete characteristic data for the LCV as found at NCAT. As described in detail in Appendix A, there were a multitude of instances that characteristics were left as packaged from TruckSim. These characteristics might be a representative value of the average tractor and/or trailer they were not specific to the NCAT LCV. It is unknown if there were any assumptions made in the creation of the simulation package for TruckSim that may be violated by the NCAT vehicle, which could serve as another source of error.

4.6 Improvements for Future Simulations

As with any simulation, there is always room to improve upon it. This simulation is no different as there were several different areas in which the model was lacking to some extent. The most critical area in which the fidelity can be improved upon is the tire data. The tires

for the simulation were left as packaged from TruckSim. If the model is to be improved, the first step suggested would be to obtain more accurate tire data and insert that data into the simulation. In addition to the tire data, more knowledge about the suspension kinematics would help serve the simulation. The data was also limited to what could be obtained by hand without the use large test equipment specifically engineered to characterize heavy trucks. Some examples of such equipment would be a tilt table to better locate the CG of the units and a Kinematics and Compliance (K&C) measurement machine to better characterize the suspension.

Chapter 5

Conclusions

This project was but a step in the direction of the research that needs to be completed to fully understand and characterize the dynamics of Longer Combination Vehicles. In conjuncture with experimental testing, an analytical model was developed and simulated through the use of a computer simulation package. The models created in the simulation phase are available for improvement and future use in parallel research. The known characteristics of LCV dynamics were shown to be present in both the experimental and simulation results. A method for capturing dynamic data on a LCV was both designed as well as tested. If the efforts were to be summed into one transfer function that would be Equation (5.1). The characteristic of most concern is that of the roll behavior of the third trailer as it reacts to the driver input of steer angle. This relationship is the basis for stability and subsequent safety assessments talked about in this chapter.

$$TF = \frac{ThirdTrailerRollResponse}{DriverSteerInput} \tag{5.1}$$

5.1 Experimental Conclusions

The experimental data concluded that the measurement of roll angle of the separate trailers was a reasonable predictor of rearward amplification of roll angle between the tractor and subsequent trailers. Additionally, the tractor and trailers showed understeer gradients that were expected given the mechanical linkage between the units. The custom designed DAQ worked adequately for the project, yet had it's shortcomings. As described lateral acceleration data was not obtained for half of the LCV and as a result the traditional method for determining rearward amplification wasn't possible. In future efforts, closer

considerations and precautions should be taken to ensure the correct data is being recorded and that the data recorded is reasonable in magnitude and shape.

5.2 Simulation Conclusions

The simulation environment enabled multiple different scenarios being explored and allowed for the exploration of the behavior at higher speed unattainable during the experimental phase. Many different maneuvers were simulated at many different speeds, for example through the iterative process it was determined that the critical speed for stability of the LCV during the double lane change was 58 mph. At speeds less than that the LCV would recover from the extensive dynamic response that was incited via the double lane change. Whereas at speeds above that, the vehicle would not recover and the third trailer would roll over during the returning lane change. This threshold is illustrated in Figures 5.1 & 5.2 where the roll of each unit is plotted versus time for 55 mph and 60 mph respectively.
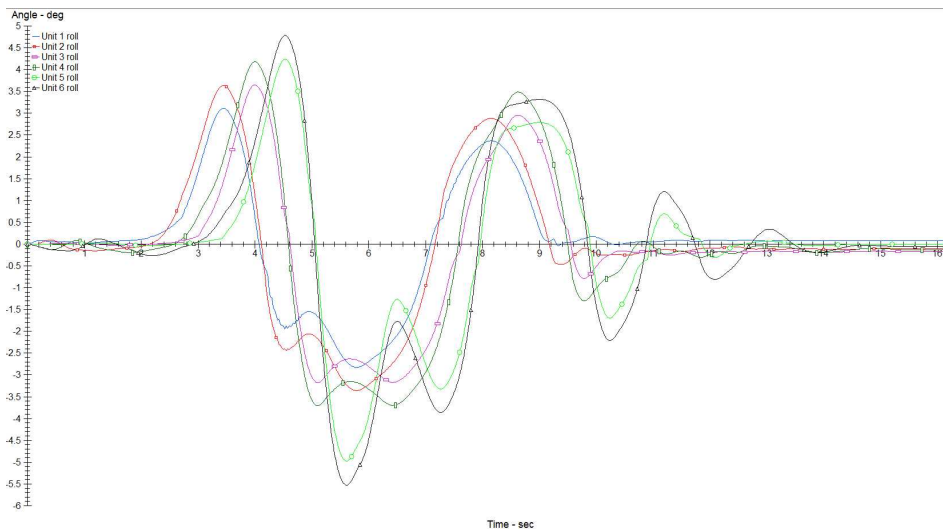

Figure 5.1: Unit Roll During 55 mph Double Lane Change

In comparing the Triple LCV to a standard Double Trailer configuration it was shown that the triple had a lower stability limit in that it had a higher propensity for rollover at speeds that are to be expected of a highway vehicle. In addition, given the unsettling feeling
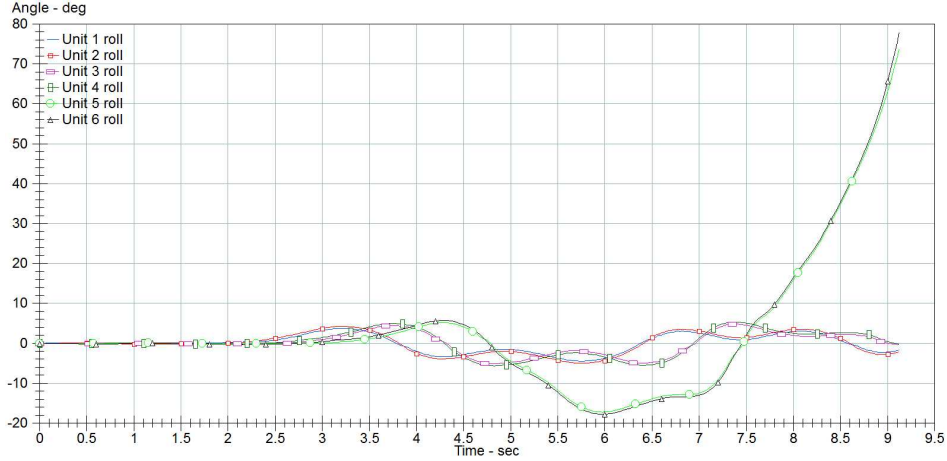
Figure 5.2: Unit Roll During 60 mph Double Lane Change

most motorists have towards the double trailers it is hard to envision a triple trailer being received well if at all.

5.3 Final Conclusions

Several of the dynamic characteristics were confirmed when comparing the experimental data to the output of the simulation. Measurements of all articulation angles along with visual observations of the LCV (specifically the third trailer) were in agreement. The rearward amplification of the unit roll and articulation were successfully measured and compared for single and double lane change maneuvers. Understeer properties were successfully measured using a constant radius turn. The combination of the above was adequate for a partial verification of the simulation.

Taking all of this into consideration, the initial conclusions at this stage in the research is that LCV triples need a large number of safety equipment that is not yet available before they should be permitted on all highways throughout the US. Some of those improvements include a robust Electronic Stability Control (ESC) that can implement differential braking on all of the units, as well the possibility of inducing torque on the fifth wheel of each trailer in order to dampen out the oscillatory response seen in the simulations at higher

speeds. In order to achieve this, the communications between the trailers will need to be greatly improved. That improvement can be accomplished via a CAN bus that is common to the entire LCV. The additions that would be required would be more complete sensor packages that include but not limited to IMU's, GPS receivers, and linear displacement measurements. The combination of the aforementioned sensors could be implemented into a control algorithm to predict and monitor the safety threshold for the unit and control the ESC accordingly to prevent any unwanted behavior.

5.4 Future Research

The simulation model can be used to predict the potential impact of any changes in the configuration of the LCV. This includes changes in payload, dimensions, mechanical properties, and many others. The vehicle used in this research was chosen because of both it's availability and the availability of the testing course. It is to some level indicative of what a commercial LCV would be but that relationship could be improved upon. Most notably by payload weight and configuration. In addition the the payloads, the suspension characteristics of the units were assumed to be the same, if this research is to become complete that assumption has to be thrown out and each individual unit needs to be accurately modeled and tested.

Perhaps the most influential modification lies underneath the LCV. The tires are how the LCV interacts with the road, all of the forces that act between the ground and the LCV go through the tires. Due to this relationship, the tire properties are a crucial improvement in order to increase the fidelity of the model. There are two ways of improving those properties, either extensive experimental efforts or some propriety agreement with a tire manufacture.

The simulations showed that the vehicle was unstable at highway speeds, a potential area of interest would be to investigate how to best increase the stable speed of the LCV through either weight distribution or some other mechanical property adjustment. This could be achieved first in simulation prior to being implemented on any vehicle fro experimental

testing. An additional area of interest would be to incorporate the ESC system described above, or some subset of it in order to asses it's performance in increasing the stability and safety of the LCV for the purpose of highway travel.

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TruckSim® Configuration

A.1   TruckSim® General Overview

TruckSim is a software package offered by Mechanical Simulation. It is specific to simulating and analyzing the dynamic behavior of medium to heavy trucks. Mechanical Simulation also produces CarSim, which is geared towards the more typical vehicle dynamics of smaller vehicles. The package provides the ability to run modeled vehicles through user-defined tests and output the results in forms varying from tabular data, synchronous log files, plots, animations, and more. Data characterizing the vehicle to be modeled is entered into TruckSim in the form of mechanical properties, linear coefficients, or tables. As packaged, TruckSim cannot simulate an LCV triple; the most trailers that can be attached on the standard version is two. For that reason, a custom solver was purchased from Mechanical Simulation to enable to simulation of the LCV triple. Since it is a custom solution the set-up differs slightly from the generic. Once the custom solvers were installed, the task of entering in the vehicle specific data that represented the NCAT LCV was undertaken. A screen shot of TruckSim animating a simulation of the NCAT Triple can be seen in Figure A.1.

A.2   Model Formulation

The vehicle was modeled according to the measurements taken in conjuncture with Western Michigan University as part of an LCV characterization effort. Where measurements were not available, the standard parameters in TruckSim were used. The following sections will describe in detail the steps taken to enter in the kinematic and dynamic properties of the NCAT LCV. Once installed and launched the first screen that the user encounters is the

Figure A.1: Screen Shot of Simulation Animation

main screen. That screen is shown in Figure A.2. In this window the user can select which vehicle configuration to use, which procedure to run, and what output if any they desire for the results. A description of all the options and why they are set that way is found in Table A.1.

A.2.1 Vehicle Configuration

Under vehicle configuration the user selects a vehicle class which in the case of the NCAT triple is S_SS + S + dS + S + dS + S, each S represents an axle and each dS represents a converter dolly. Upon entering the configuration window for the vehicle the user is presented with the vehicle selection window, which is shown in Figure A.3. It is here that the user will select which vehicle components that are to be configured to make up the vehicle under test. A description of the settings is shown in Table A.2

As seen, there are numerous different properties to be set. Of note is that for the NCAT LCV the second trailer is actually two trailers and a dolly which is why the vehicle type for
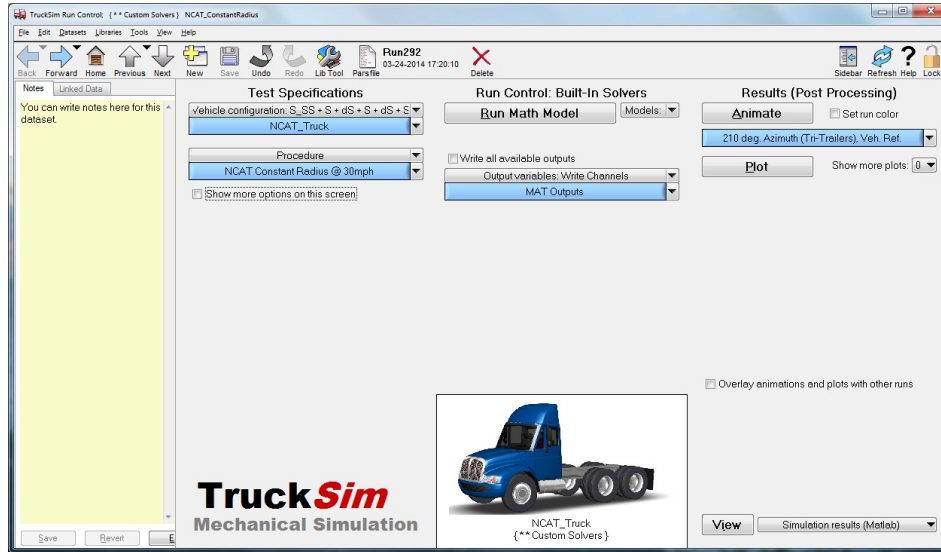
Figure A.2: TruckSim Main Window

Table A.1: TruckSim Main Set-Up Screen Options

| Test Specifications	
Vehicle Configuration	Set the the data set of S_SS + S + dS + S + dS + S to represent the custom solver for triple trailers. The vehicle selected is the custom vehicle built to match that of the test vehicle at NCAT, that process is detailed in Section A.2.
Procedure	Select which procedure is to be run. The set up for the procedures is detailed in Section A.4.
Run Control	
Run Math Model	The START button, will run simulation based on the selections made on page.
Output Variables	Can write selected variables to external files such as .csv files or MATLAB .mat files.
Results	
Animate	Will run the animation and create a video of the simulation. Will not run if output variables are written to file.
Plot	Will plot the defined plots selected in the procedure set up (Section A.4), can additionally define extra plots of interest.
More Options	
Screen Options	Can overwrite certain parameters defined in the procedure set-up.
Overlay Animations	Can plot other simulations simultaneously as well as animate multiple simulations at once.
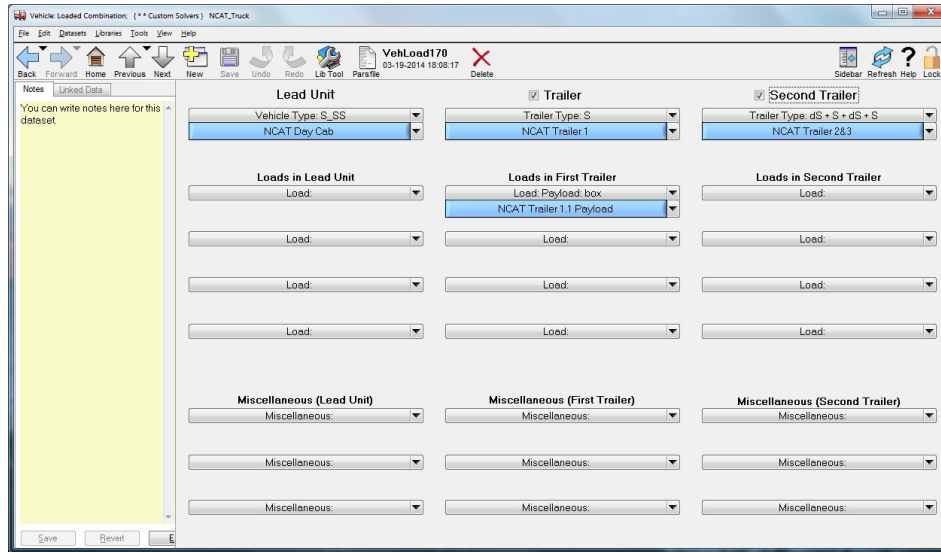
Figure A.3: TruckSim Vehicle Window

Table A.2: TruckSim Vehicle Configuration Options

| Lead Unit	
Vehicle Type	The Tractor class is S_SS as it is a single steer axle with double drive axles.
Vehicle Definition	Set to the configuration that resembles the NCAT Tractor, the detailed configuration for the Tractor is described in section A.4.
Trailer	
Trailer Type	The selection here is a single axle trailer, which is what the single S represents.
Trailer Definition	The Configuration that best represents the first trailer in the combination is selected, that configuration is detailed in Section A.2.3.
Loads in First Trailer	The payload is selected that represents the first trailer, this too is detailed in Section A.2.3.
Second Trailer	
Trailer Type	For the second trailer the type dS + S + dS + S is selected to represent the remaining two trailers and converter dollies. This is selected as such because of the custom solvers that had to be installed in order to simulate a triple trailer.
Trailer Definition	The configuration for the Second & Third Trailer is outlined in the following paragraph and accompanying pictures and tables.
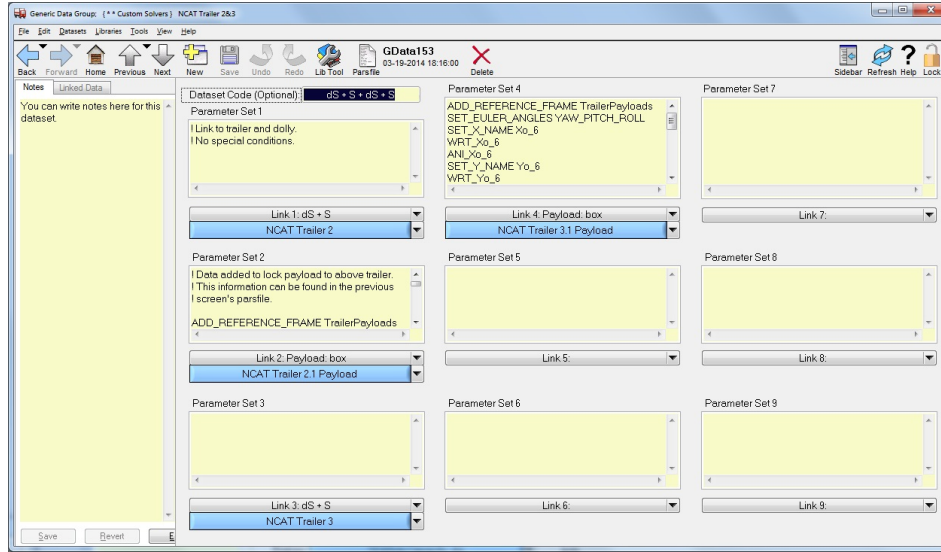
Figure A.4: TruckSim Custom Second Trailer Configuration

the second trailer is dS + S + dS + S instead of just dS + S for a typical double trailer configuration. In order to complete the configuration of the vehicle the user most configure the custom solver options that are found once entering the configuration for the custom second trailer. Upon entering said configuration the screen encountered is shown in Figure A.4 and the accompanying description of options is outlined in Table A.3.

A.2.2 Tractor Configuration

The first unit to be configured is the tractor, upon exiting the custom configuration and returning to the main vehicle configuration screen (A.3)) the user can enter the configuration for the tractor. Once in the configuration the user sees the vehicle configuration screen shown here in Figure A.5. It is here that the mechanical properties of the tractor will be assigned and other properties defined. A description of the settings is detailed in Table A.4.

Tractor Sprung Mass Characteristics

For the NCAT LCV the 2A Day Can Sprung Mass was selected as the vehicle type as that most closely reflects the actual tractor. The aerodynamics, animator shape, tires,

Table A.3: TruckSim Custom Solver Options

| Dataset Code	
This is left as packaged from TruckSim Custom Installation, additionally all of the comments in the parameter set boxes are untouched.	
Link 1	
Link Type	The selection here is a single axle trailer with a converter dolly, which is represented by dS + S.
Link Definition	The Configuration that best represents the second trailer in the combination is selected, that configuration is detailed in Section A.2.4.
Link 2	
Link Type	The second link for the custom solver is the payload options of the second trailer.
Link Definition	The payload for the Second Trailer is defined in Section A.2.4.
Link 3	
Link Type	The selection here is a single axle trailer with a converter dolly, which is represented by dS + S.
Link Definition	The Configuration that best represents the third trailer in the combination is selected, that configuration is detailed in Section A.2.4.
Link 4	
Link Type	The fourth and final link for the custom solver is the payload options of the third trailer.
Link Definition	The payload for the Third Trailer is defined in Section A.2.4.
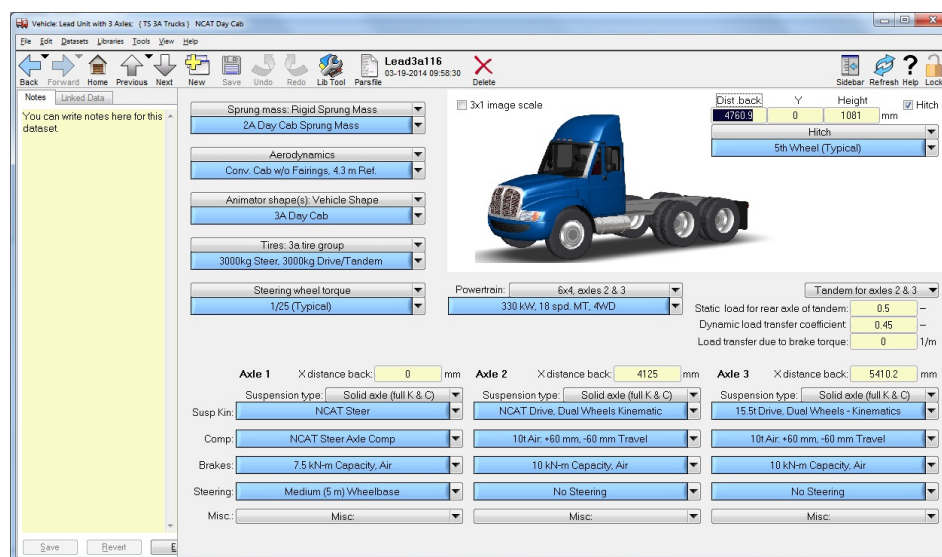
Figure A.5: Vehicle Configuration Window

Table A.4: TruckSim Tractor Set-Up Screen Options

| Sprung Mass	
Class & Definition	Rigid Spring Mass; 2A Day Cab Sprung Mass. These selections were left as packaged.
Aerodynamics	
Definition	Conv. Cab w/o Fairings 4.3 m Ref. Again selection was left as packaged as no information about the aerodynamics was obtained.
Animator Shape	
Definition	3A Day Cab, selection was made to aesthetically represent the sprung mass selection. Configuration was left as packaged.
Tires	
Definition	3000 kg Steer, 3000 kg Drive/Tandem. Selection left as packaged.
Steering Wheel	
Definition	1/25 (Typical) - Left as packaged
Powertrain	
Class	6 x 4, axles 2 & 3
Definition	330 kW, 18 spd MT, 4WD - selection was left as packaged.
Axle 1	
Class	Solid Axle (full K & C)
Susp Kin,	Configuration made to match that of the kinematics of the steer axle.
Comp	Configuration changed to mirror that of the NCAT tractor steer axle.
Brakes	Left as packaged
Steering	Selection was left as packaged
Axle 2 & 3	
Class	Solid Axle (full K & C)
Susp Kin,	Configuration made to match that of the kinematics of the drive axles.
Comp	Configuration changed to mirror that of the NCAT tractor drive axles.
Brakes	Left as packaged
Steering	No steering on the drive axles
Hitch	
Definition	5th Wheel - left as packaged.
Position	Dist Back (4760.9 mm) Y (0 mm) Height (1081 mm)
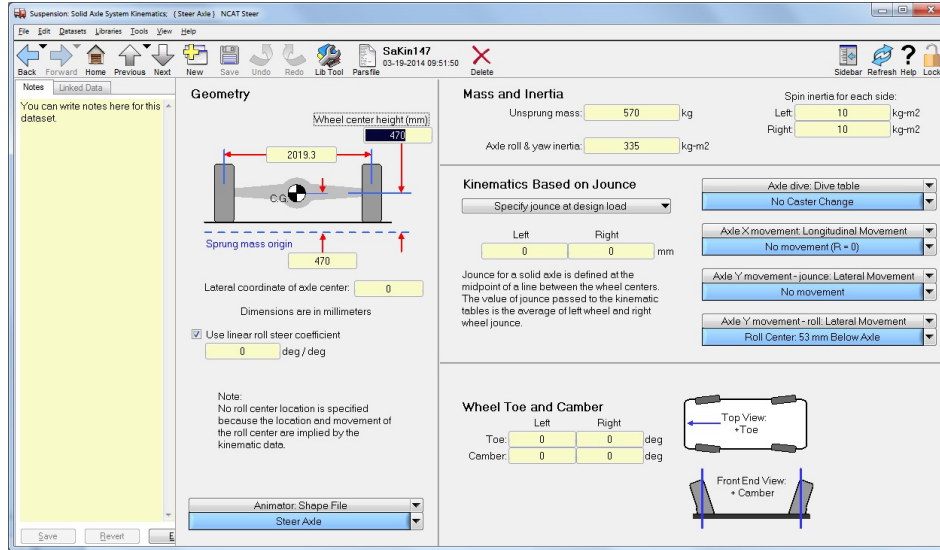
Figure A.6: Steer Axle Kinematic Configuration Window

and steering wheel torque were left as packaged. The power-train was set at 6x4, axles 2 & 3 with the 330 kW, 18 spd, MT, 4WD transmission selected. The distances placed in all of the yellow boxes came from the LCV Characterization report. In the lower half of the window, the user is to select and configure the suspension properties of the tractor the first axle being the steering axle was configured first. The first aspect to configure was the suspension kinematics, this window is shown in Figure A.6. Again, the measurements that are placed in the yellow boxes are either reflective of the LCV Characterization Report or left as packaged in TruckSim.

Tractor Steer Axle Suspension Characteristics

Once back to the Vehicle Configuration Window, Figure A.5 the next set of properties to configure are the suspension characteristics for the steer axle. That window is illustrated in Figure A.7.

The first property to set is the spring characteristics, based off the LCV Characterization Report the leaf springs where given a stiffness of 263N/mm at 2000N. The only other characteristic that wasn't left as packages is the roll moment for the steer axle. That was
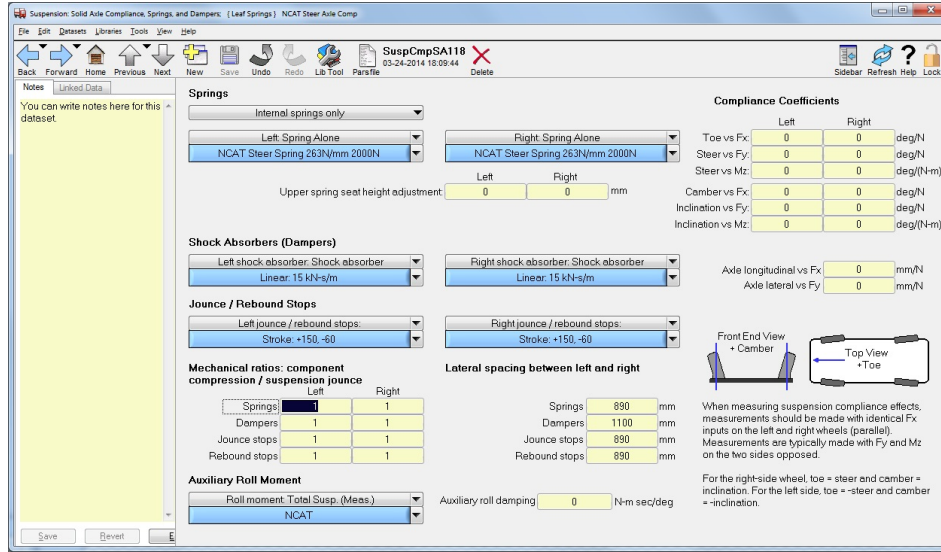
Figure A.7: Steer Axle Suspension Configuration Window

configured using data collected during the LCV characterization effort. That screen is shown in Figure A.8.

Tractor Drive Axle Suspension Characteristics

The last component of the tractor to be configured is the drive axles kinematics and suspension properties. The first is the kinematic data, that screen is shown in Figure A.9.

For the drive axles, the data from the characterization report was entered where applicable. In addition to the static data, the roll steer for the drive axle was not a simple linear coefficient as it was for the steer axle. Upon entering the configuration for the roll steer the user should see Figure A.10. The data for the roll steer was taken from the characterization report. This is the completion of the tractor configuration.

A.2.3 Trailer 1 Configuration

Once the configuration of the tractor is complete the next unit to configure is the first trailer. That screen is represented in Figure A.11, with the description of the fields in Table A.5.
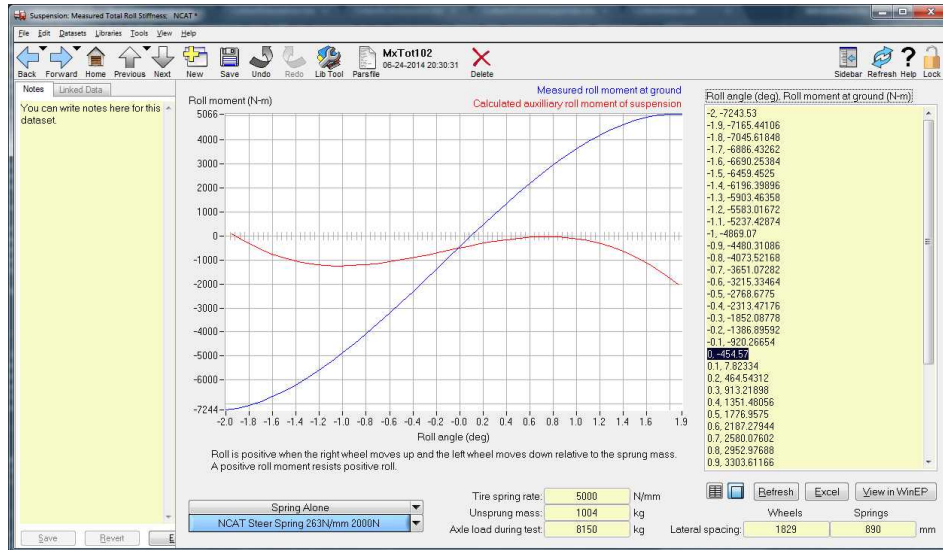
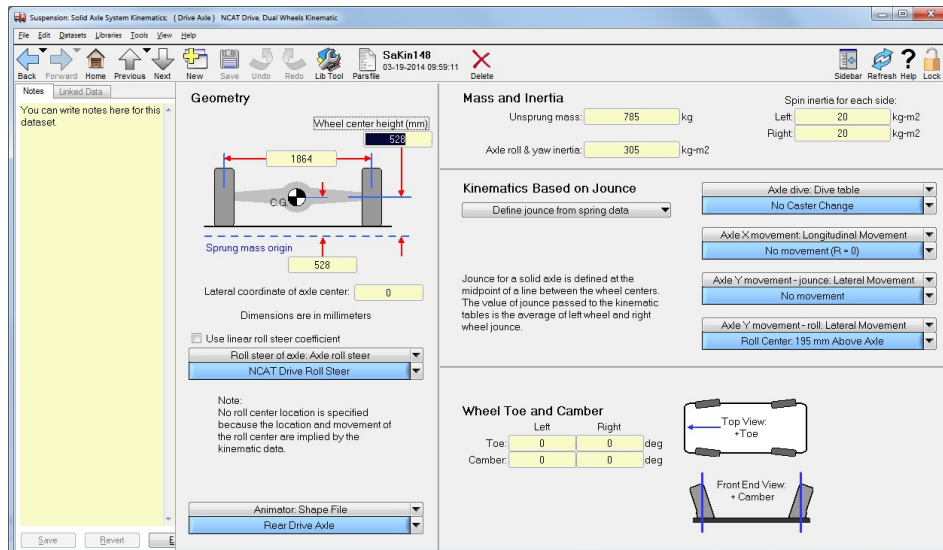Figure A.8: Steer Axle Roll Stiffness Configuration Window

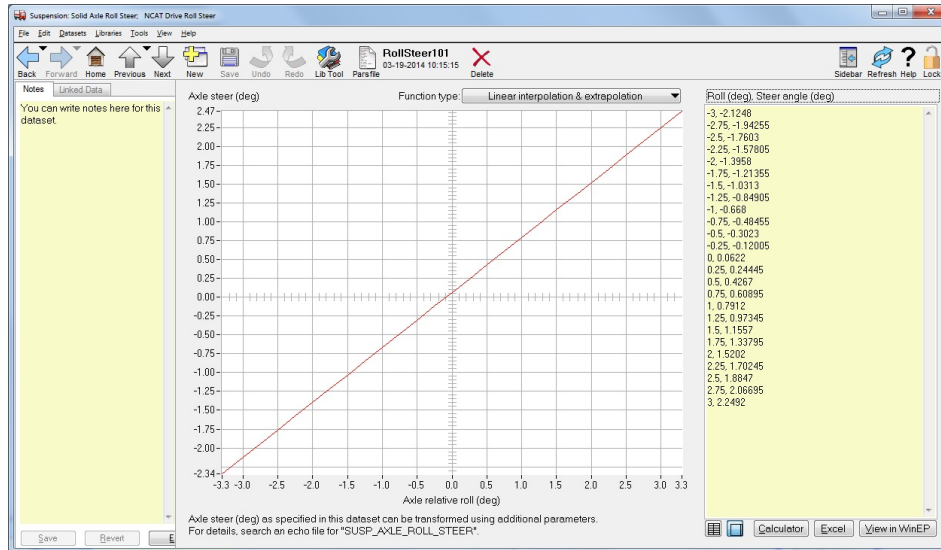Figure A.9: Drive Axle Kinematic Configuration Window
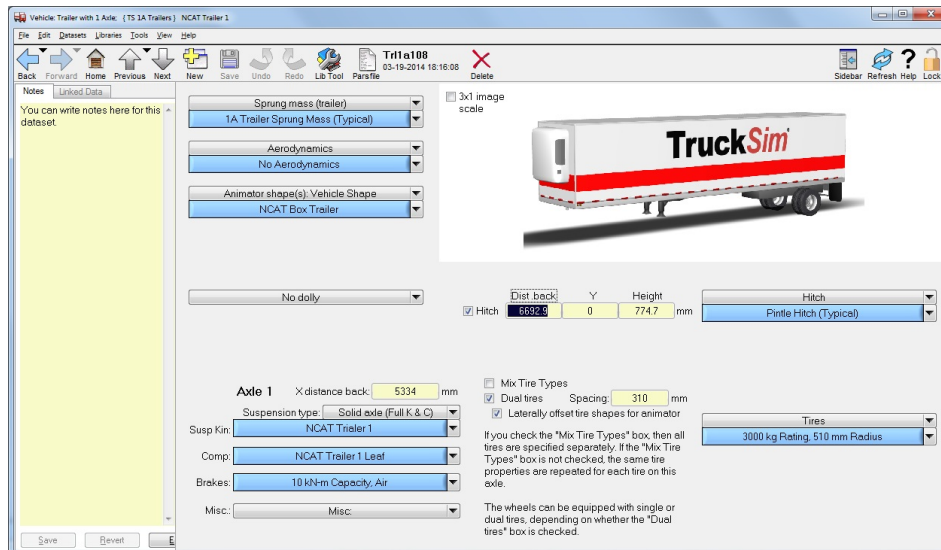
Figure A.10: Drive Axle Roll Steer Window

Figure A.11: Trailer Main Configuration Window

Table A.5: Trailer Configuration Options

Sprung Mass	1A Trailer - Since the trailers were permanently loaded, measuring the sprung mass was not possible. Therefor the mass properties were adjusted using payload modifications.
Aerodynamics	No Aerodynamics
Animator Shape	NCAT Box - Some minor adjustments were made to the default settings for cosmetic reasons, they bared no effect on the simulation
Dolly	There is no dolly on the first trailer as it attached to the fifth wheel on the tractor.
Tires	Left as packaged as tire data was unavailable.
Axle 1	
Kinematics	Configured to match NCAT Trailer.
Compliance	Entered characterization report values.
Brakes	Left as Packaged
Hitch	
Position	
Definition	

Trailer Kinematic Characteristics

The first configuration to complete for the trailer suspension is the kinematic data for the trailer axle, that configuration can be seen in Figure A.12. As with the other configurations, the data was either left as packaged or taken from the LCV characterization report.

Trailer Compliance Characteristics

Next, the leaf springs needed characterization, that screen is shown in Figure A.13. The additional configuration of the roll moment is illustrated in Figure A.14.

Trailer Payload Configuration

The last step in configuring the first trailer is to adjust the payload to match that of the loaded NCAT Trailer. The screen in which this is done is accessed through the main vehicle configuration window, Figure A.2, and is captured in Figure A.15. The numbers that were entered for the payload were taken from the vehicle characterization report and
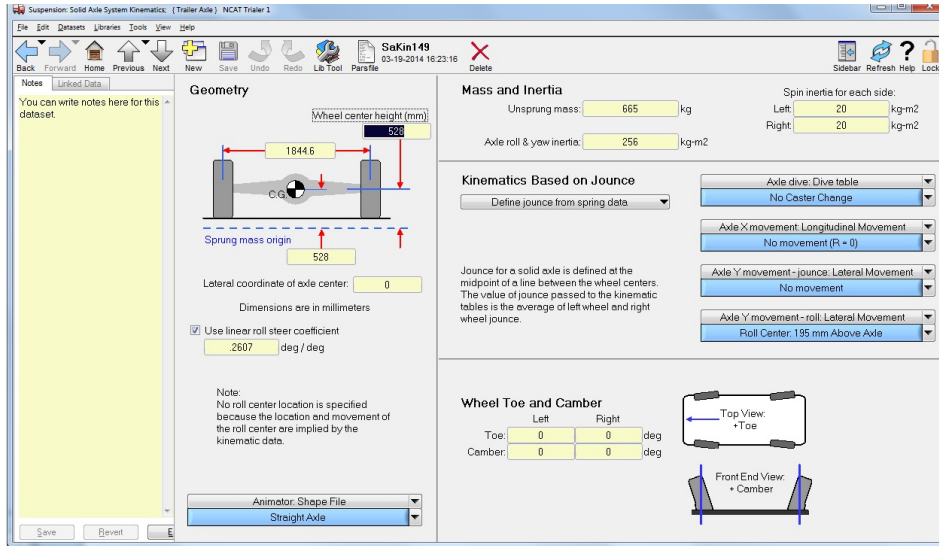
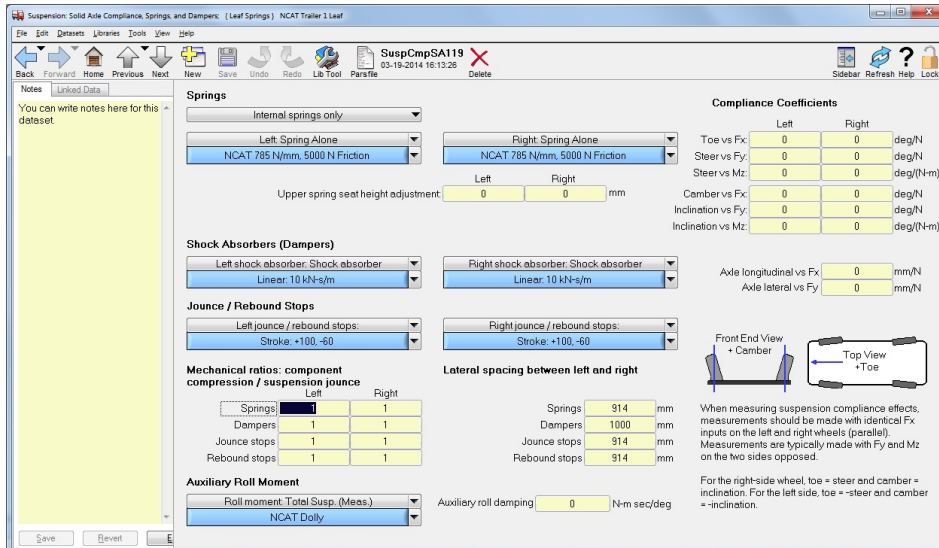Figure A.12: Trailer 1 Axle Kinematics Window

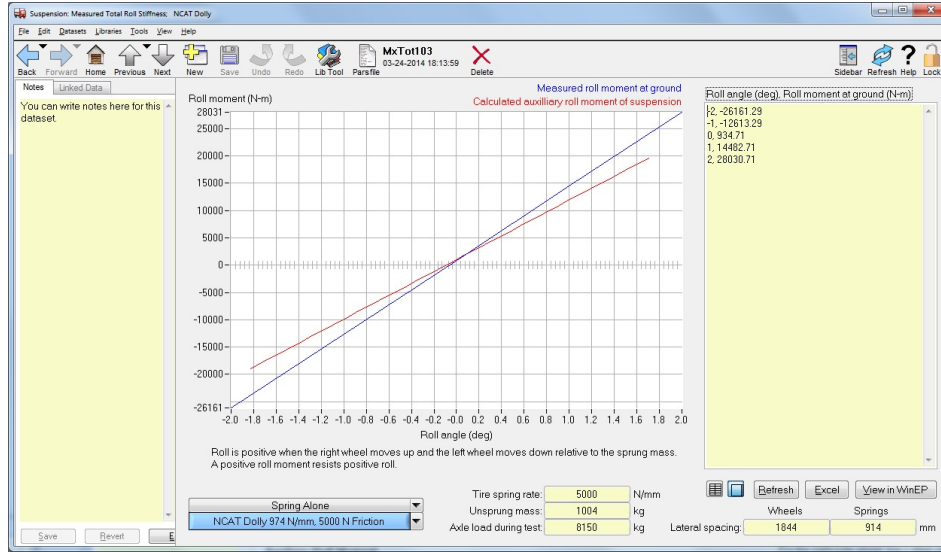Figure A.13: Trailer 1 Axle Leaf Suspension Configuration Window

Figure A.14: Trailer 1 Roll Stiffness Configuration Window

were generated during the weighing of the loaded LCV axle by axle. This completes the configuration of the first trailer.

A.2.4 Trailers 2 & 3 Configuration

The suspension of each trailer was configured the same as that of the first trailer since all of the trailers had identical suspensions and axles. The main difference in the configuration of the second and third trailer versus the first is the additional step(s) in configuring the dolly that accompanies the trailer. That process is detailed below in Section A.2.5. Seeing that the second and third trailers were identical from a kinematics and compliance standpoint, they were configured exactly the same minus the variations in payload weight. That variation, along with the first trailer is detailed in Table A.6.

A.2.5 Configuring the Converter Dollies

In order to configure the converter dollies the user first needs to ensure that all of the trailers are configured correctly with respect to dollies and pintle hitches. In order for a trailer to ride on a converter dolly it must be specified in the trailer configuration that is
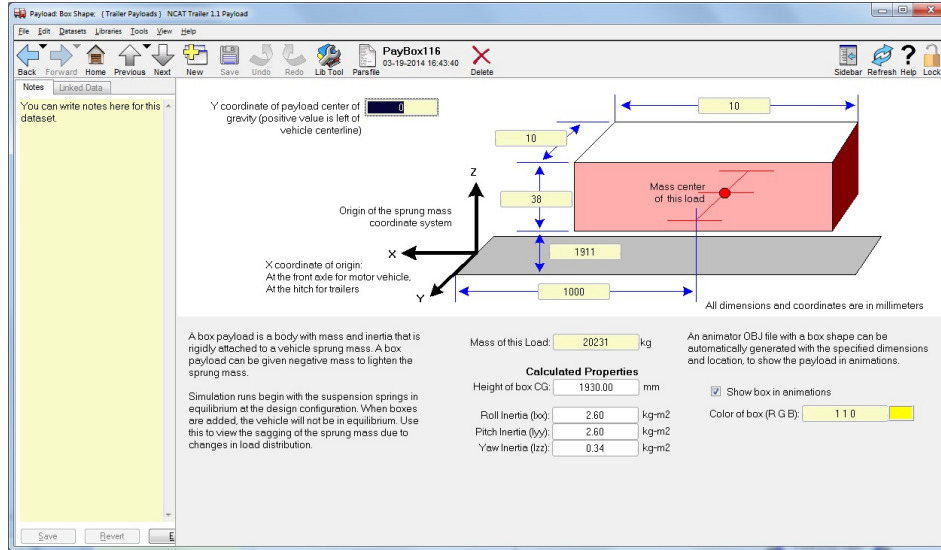
Figure A.15: Trailer 1 Payload Configuration Window

Table A.6: NCAT Vehicle Gross Weight

	Measured	TruckSim	Measured	TruckSim
Unit	kg	kg	lb	lb
Tractor & Trailer 1	32,986	33,029	72,900	72,994
Trailer 2	19,186	13,013	42,400	42,019
Trailer 3	18,552	18,588	41,000	41,080
Whole Vehicle	70,724	70,630	156,300	156,093

Table A.7: Trailer Linkage Configuration

Unit	Dolly Y/N	Pintle Hitch				Fifth Wheel			
		Y/N	Dist. Back (mm)	Y (mm)	Height (mm)	Y/N	Dist. Back (mm)	Y (mm)	Height (mm)
Tractor	N/A					Yes	4760.9	0	1081
Trailer 1	No	Yes	6692.9	0	774.70	No	N/A		
Dolly 1	N/A					Yes	1829	0	1100
Trailer 2	No	Yes	6692.9	0	774.70	No	N/A		
Dolly 2	N/A					Yes	1829	0	1100
Trailer 3	Yes	No	N/A			No	N/A		

to use that dolly. That is to say for the second trailer that rides on the converter dolly between the first and second trailer the dolly must be configured within the second trailer configuration. The first trailer is different because the fifth wheel joint it rides on is part of the tractor and is included in the tractor configuration. Similarly, for the trailers that are to attach to a converter dolly (1st & 2nd) the pintle hitch must be defined for the converter dolly to attach to. Table A.7 details which settings need to be configured on each trailer such that the linkage is correct. All of the distances and heights came from the LCV characterization report.

Once all of the linkages has been correctly configured the last step in the model formulation is the configuration of the converter dolly compliance and kinematic data. Upon entering the dolly configuration screen the user should see Figure A.16. The settings of the converter dolly are detailed in Table A.8.

Dolly Sprung Mass Characteristics

The sprung mass configuration screen is shown in Figure A.17, the information was taken from the characterization report.
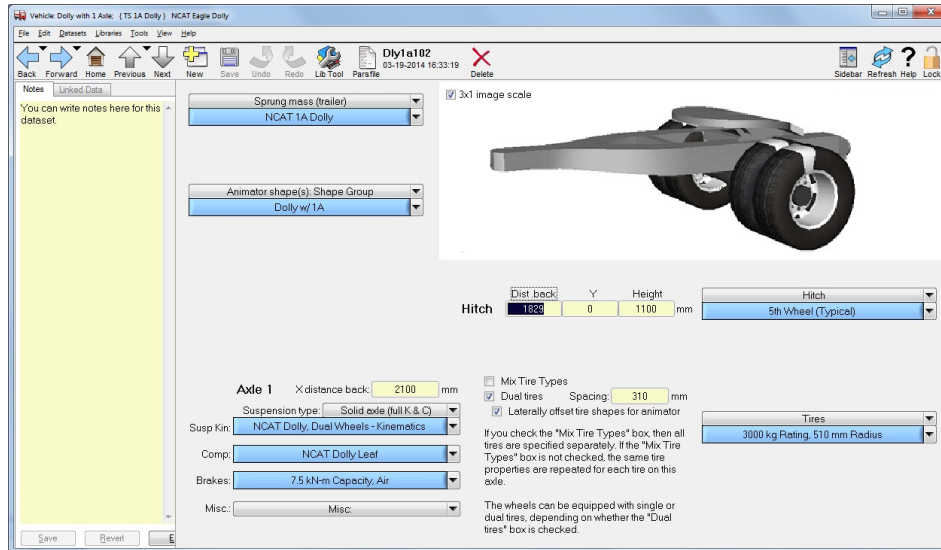
Dolly Kinematics Characteristics

Figure A.16: Converter Dolly Configuration Window

Table A.8: Converter Dolly Configuration Options

General Options	
Sprung Mass	NCAT 1A Dolly
Animator Shape	Dolly w/1A
Tires	Left as packaged as tire data was unavailable.
Axle 1	
X Dist. Back	2100 mm
Kinematics	Configured to match NCAT Dolly.
Compliance	Entered characterization report values.
Brakes	Left as Packaged
Hitch	
Position	Dist. (1829 mm) Y (0 mm) H (1100 mm)
Definition	5th Wheel Typical - As Packaged
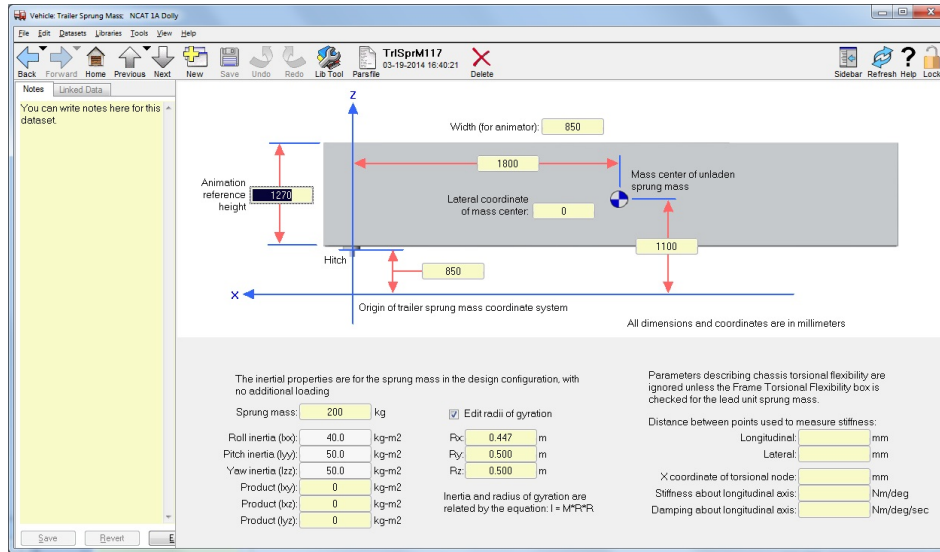
Figure A.17: Converter Dolly Sprung Mass Configuration Window

The kinematics configuration screen is shown in Figure A.18, the information was taken from the characterization report.

Dolly Compliance Characteristics

The suspension compliance configuration screen is shown in Figure A.19. The configuration screen for the roll stiffness of the converter dollies is shown in Figure A.20. In both cases the information was taken from the characterization report.

A.3 Model Stability

An LCV should not be expected to move as a single unit in a straight line with zero steer angles in any of the constituent units. The driver must guide the vehicle straight with alternating right and left motions of the hand wheel to compensate for disturbance from wind and road. Tolerances and wear of the vehicle can cause misalignment to occur, requiring units of the vehicle to maintain a steer angle to keep an apparently steady state straight motion. This can be due to any minor differences between the units such as steering misalignment, steering gear wear, suspension angle misalignment, frame damage, suspension
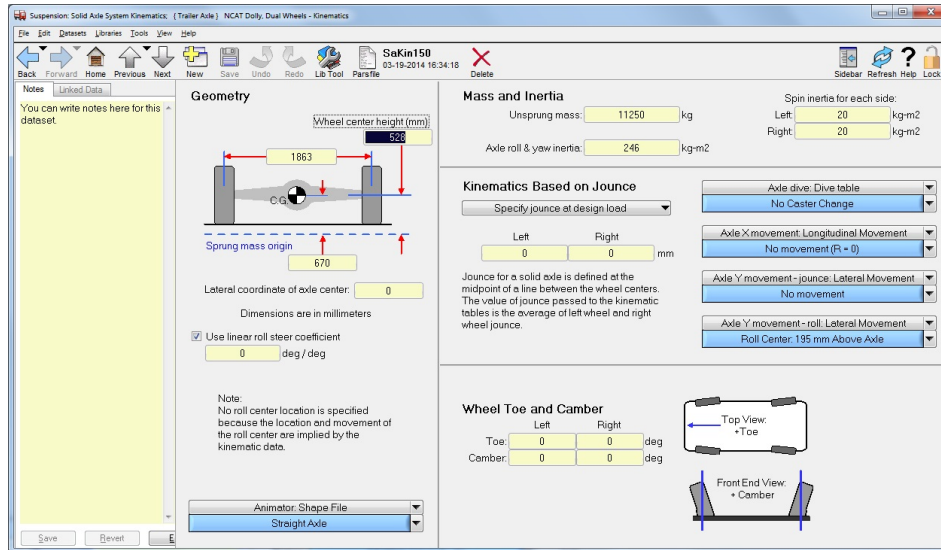
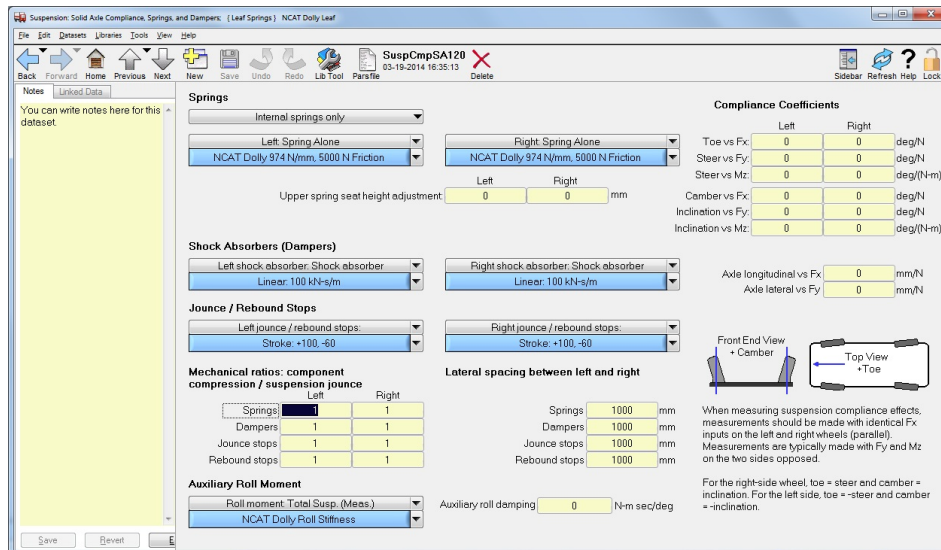Figure A.18: Converter Dolly Kinematics Configuration Window

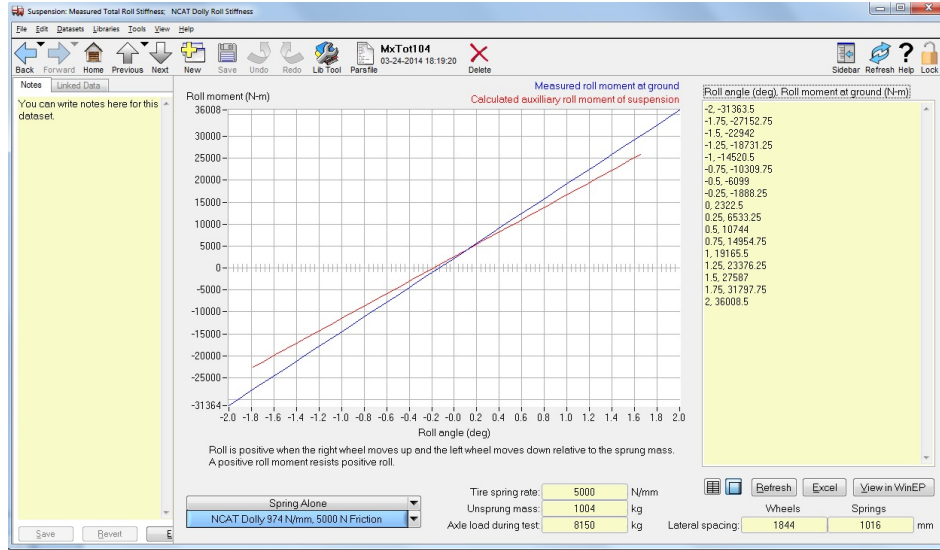Figure A.19: Converter Dolly Kinematics Configuration Window

Figure A.20: Converter Dolly Roll Stiffness Configuration Window

wear, tire inflation variation, road crown, or even bearing drag. Measurement offsets can also be present in the test data as a result of imprecise alignment of sensors, imprecise calibration, or other systematic errors associated with the instrumentation setup. While it is impossible to pinpoint a cause for this behavior in the NCAT test vehicle, it was apparent in the test data. Of concern during analysis, TruckSim demonstrates a starting transient behavior that can be mitigated but not completely eliminated. This starting instability causes the simulation to start in a dynamic out-of-line orientation, which settles into a constant angle of articulation between the units of the LCV. This attitude continues for the duration of the simulation.FigureA.21 shows the yaw angles of each unit in the LCV during an un-steered simulation at 72 km/h (45 mph).

This was simulated by setting the model in motion at a constant 72 km/h (45 mph) with an open loop steer controller having no steer angle defined, which is as if the driver takes his hands off the steering wheel while maintaining the constant speed. This simulation was performed in order to demonstrate the stability of the model, but the results also show some interesting characteristics that are relevant to the transient maneuvers.. The results show transient dynamics during the first few seconds. Afterwards, the vehicle stabilizes until a
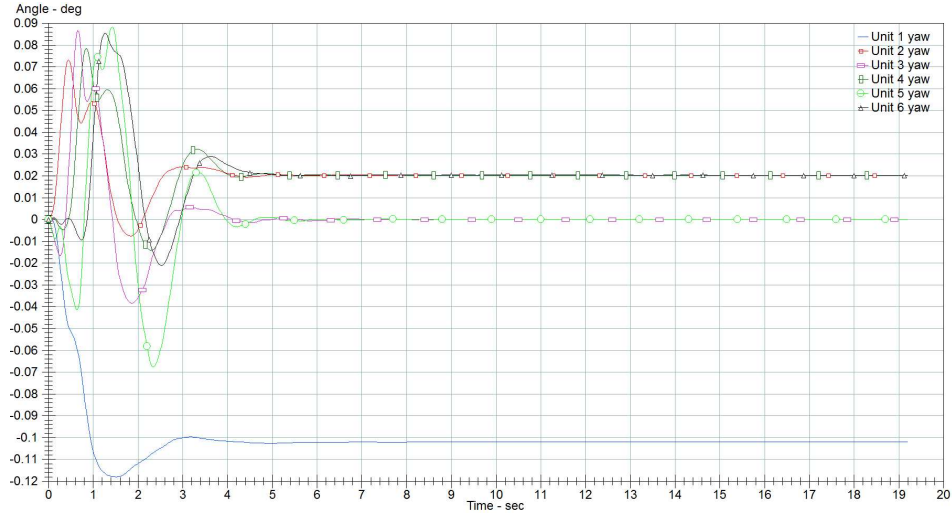
Figure A.21: Unit Yaw During Open-Loop Maneuver

dynamically neutral attitude is achieved, where the yaw angles of each unit maintain a near straight trajectory. This initial oscillation is typical of simulations as the masses "settle" from their initial conditions into equilibrium. Each maneuver begins with a short straight section during which the vehicle simulation is allowed to stabilize before the primary steering inputs begin. The steering wheel angle during this open-loop maneuver is plotted below in Figure A.22.

A.4 Maneuver Paths & Configuration

TruckSim came packaged with a multitude of default maneuvers as well as other inputs such as speed control profiles. For the sake of this research the speed controller was always set to constant as that was the goal of the maneuvers during the experimental phase. Each maneuver was set up as described below, when the user enters into the maneuver profile screen they are presented with the screen shot shown in Figure A.23.

The description of each setting and the subsequent selection is described in Table
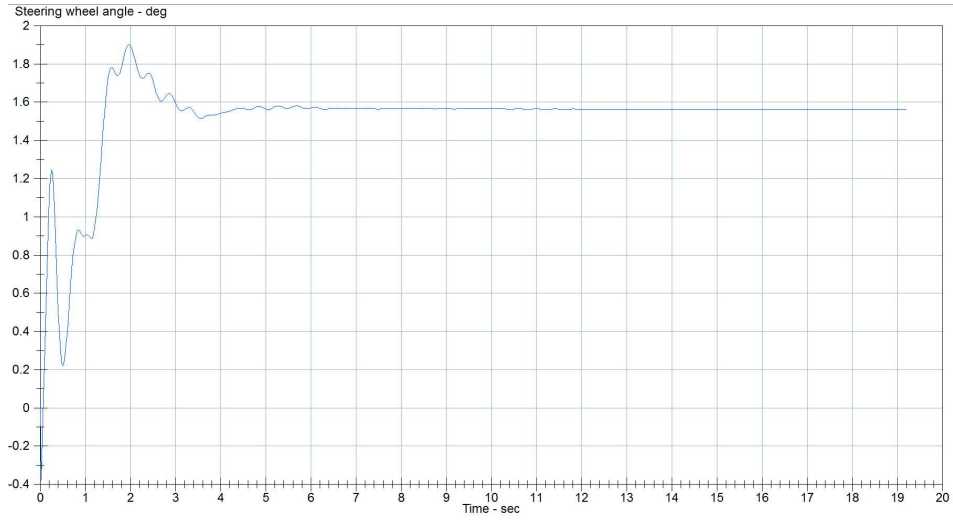
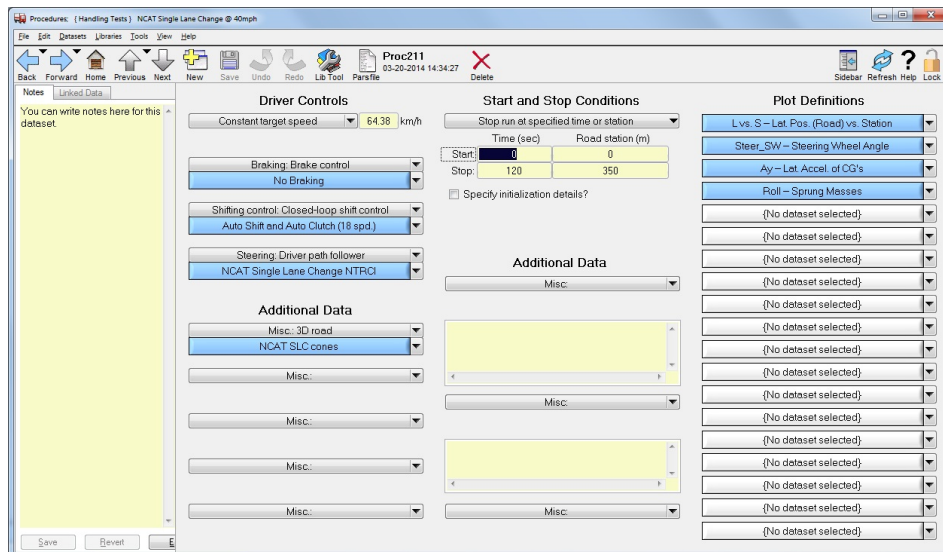Figure A.22: Steering Wheel Angle During Open-Loop Maneuver

Figure A.23: Screen Shot of Maneuver Setup Screen

Table A.9: TruckSim Maneuver Set-Up Screen Options

Driver Controls	
Target Speed	Set to constant speed based on which maneuver it was to represent
Braking	No braking needs as speed was to be constant
Shifting	Set to allow TruckSim to determine shift points using an 18 speed transmission
Steering	Selected the driver input path needed for the desired maneuver
Additional Data	
3D Road	Selected the 3D road configuration that was detailed for desired maneuver
Start and Stop Conditions	
Start	Start at 0,0 for time and position on path
Stop	Stop at either 120 seconds or 350 m, whichever comes first
Plot Definitions	
Define which plots that are desired when the data is plotted inside of TruckSim	

A.4.1   The Constant Radius Maneuver

The constant radius maneuver was simulated by creating a circular path with two tangent roads that would slowly twist until the correct banking was achieved. The curve of the constant radius was created using the equation for a circle with a radius of 479 ft. The X-Y coordinates were calculated for the curve at every degree for the 180°curve. Once this was created the points were shifted in order to become tangent with the two tangent road profiles that were created. A screen shot of the constant radius path is shown below in Figure A.24.

As shown the path is two straight road segments that are tangent to the constant radius curve, this method was used over a complete circular path due to the orientation in which TruckSim would begin each maneuver. Many iterations and differing attempts were used to get the LCV to orient on the 8°banking and on the correct heading but none proved correct. Therefor the solution was reached that the vehicle was to start out on a flat straight road that would twist from 0°banking to 8°banking over a span of 100 m. a graphical representation
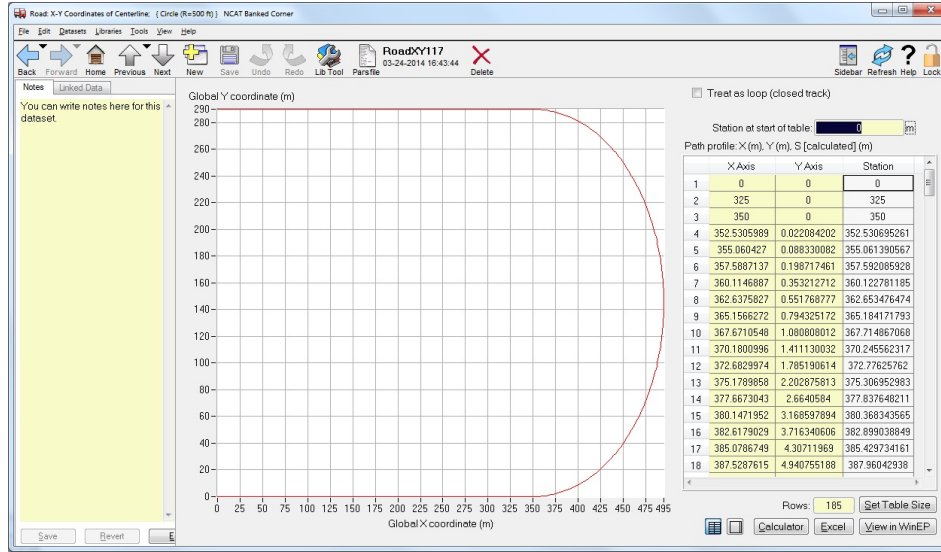
Figure A.24: Constant Radius Path

of the twist is shown in Figure A.25. The actual data points that were used for the twist are shown in Figure A.26.

A.4.2 The Single Lane Change Maneuver

TruckSim came pre-packaged with the single lane change maneuver, this was used as the base point to create the new maneuver. The points were generated to match the intended path outlined in Section 3.3. The resulting driver input path is shown in Figure A.27. The aim of the path was to travel down the centerline of the right lane and once through the first gate steer into the left lane.

In parallel with adjusting the default driver input path for the single lane change, the animation needed to be altered to match the desired path. This was done in a similar fashion that the driver path was determined. The difference is that the points needed to represent the edges of the road instead of the centerline. Four sets of cones where placed to represent the maneuver, the middle two being the most crucial as the spacing had to match what was prescribed in Section 3.3. The resulting cone positions along with a graphical representation of the cones is shown in Figure A.28.
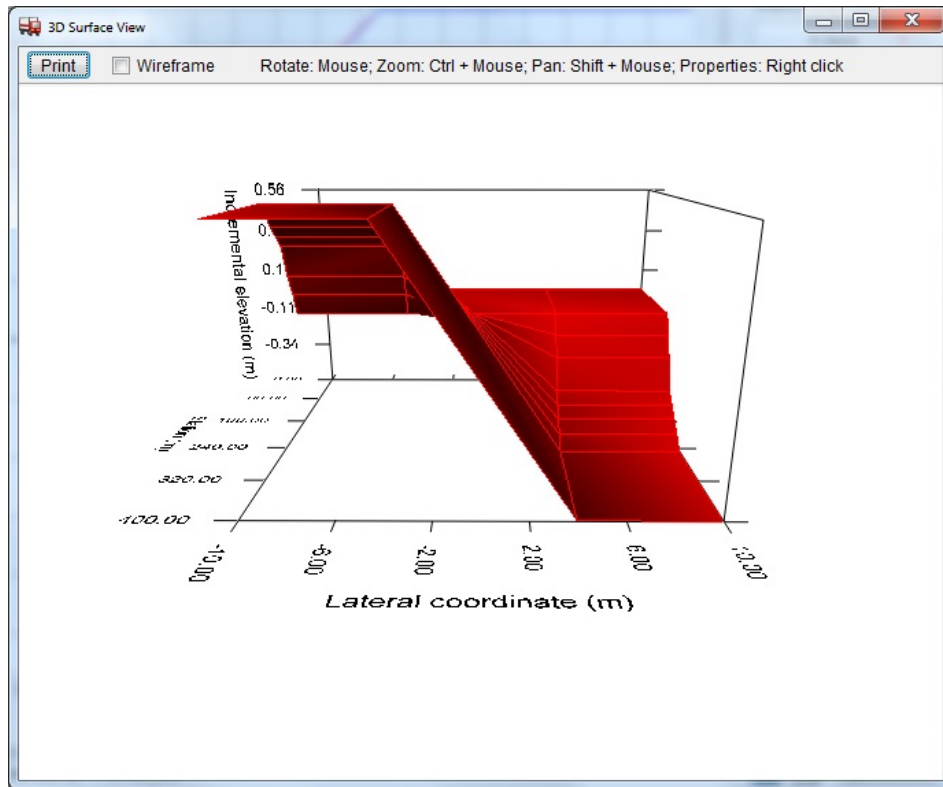
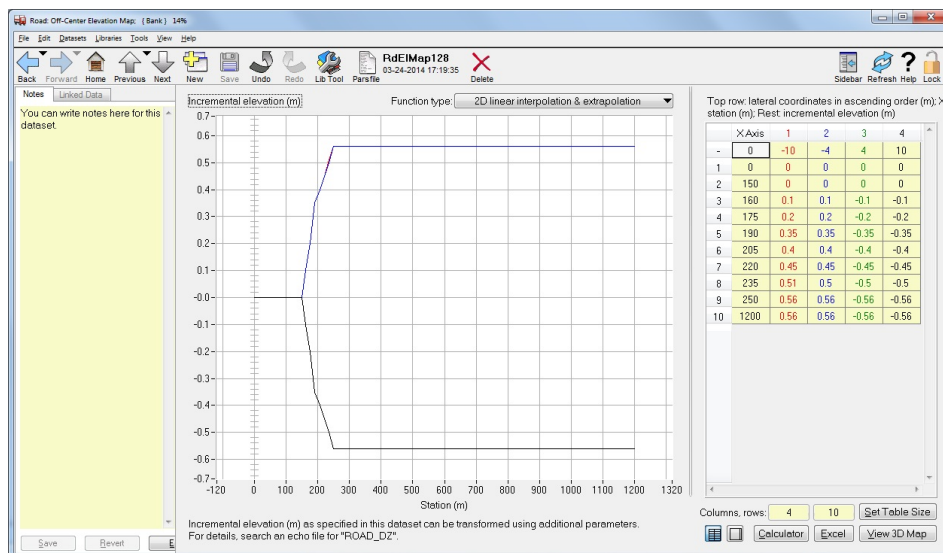Figure A.25: 3D Representation of Gradual Lane Twist
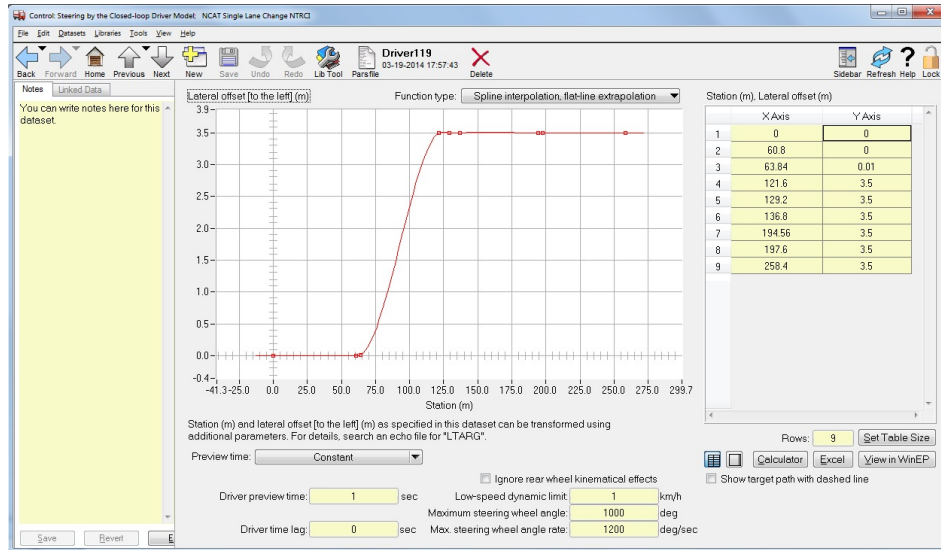

Figure A.26: Gradual Lane Twist
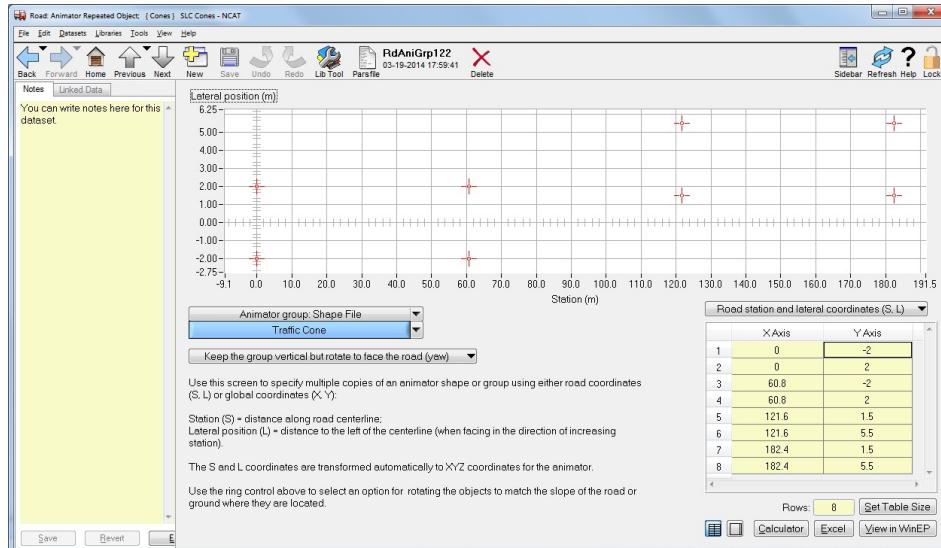
Figure A.27: Single Lane Change Driver Input

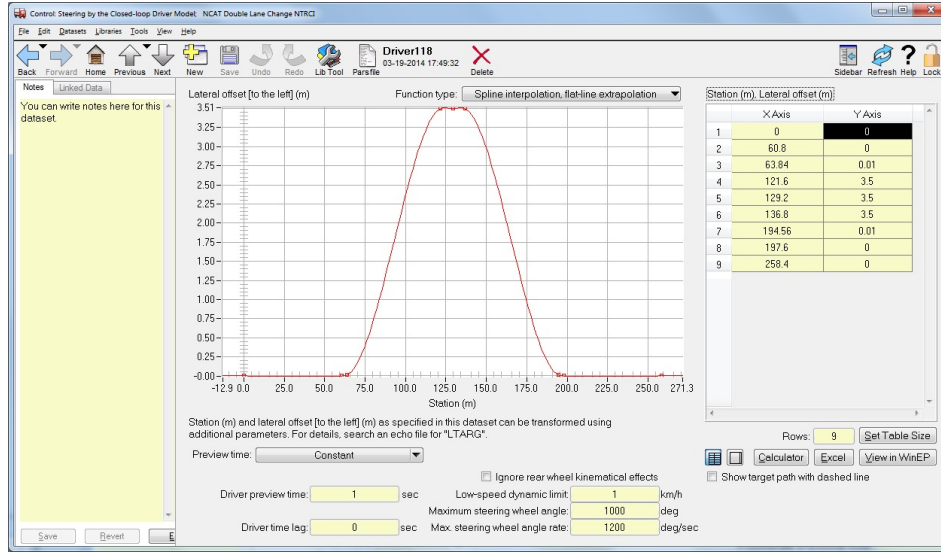Figure A.28: Single Lane Change Cone Positions

Figure A.29: Double Lane Change Driver Input

A.4.3 The Double Lane Change Maneuver

Similar to the single lane change, TruckSim already had a double lane change maneuver defined so again it was modified to match the maneuver that was performed during the experimental phase. As detailed in Section 3.3, the driver was to steer back into the right lane after traveling through the second gate in the left lane. The same method that was used for defining the single lane change path was used for the double lane change. The resulting driver input path is shown in Figure A.29.

Again, the simulation cone positions had to be adjusted in order to match the newly defined maneuver. The same cone positions where used from the single lane change however, there were two more sets of cones positioned in the right lane to represent the second lane change in the double lane change maneuver. In the case of the double lane change, the middle four sets of cones were critical as so to match the desired spacing of the gates outlined in Section 3.3. The resulting cone positions along with a graphical representation of the cones is shown in Figure A.30.
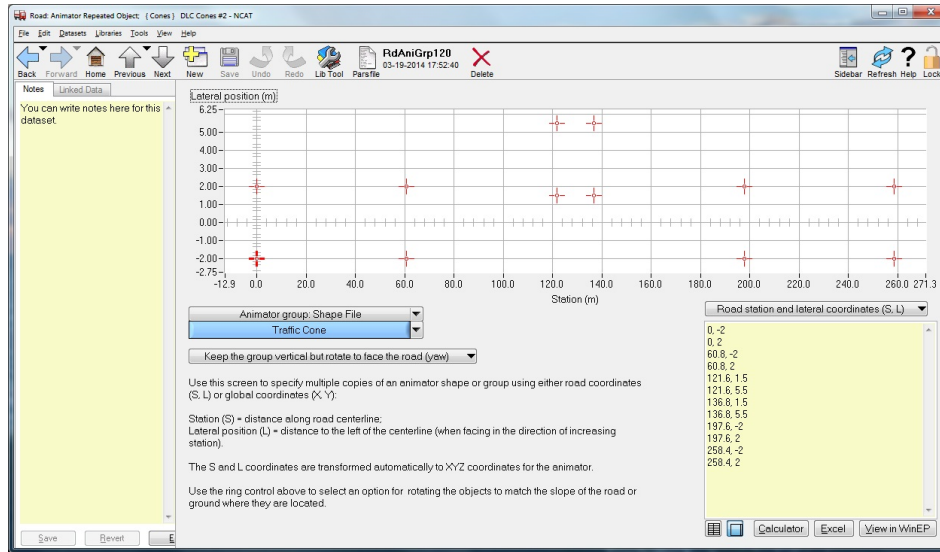
Figure A.30: Double Lane Change Cone Positions

A.4.4   Future Potential Improvements for TruckSim® Model

As with any simulation, there is always room to improve upon it. This simulation is no different as there were several different areas in which the model was lacking to some extent. The most critical area in which the fidelity can be improved upon is the tire data. The tires for the simulation were left as packaged from TruckSim. If the model is to be improved, the first step suggested would be to obtain more accurate tire data and insert that data into the simulation. In addition to the tire data, more knowledge about the suspension kinematics would help serve the simulation. The data was also limited to what could be obtained by hand without the use large test equipment specifically engineered to characterize heavy trucks. Some examples of such equipment would be a tilt table to better locate the CG of the units and a Kinematics and Compliance (K&C) measurement machine to better characterize the suspension.