NTRCI
NATIONAL TRANSPORTATION RESEARCH CENTER, INCORPORATED

HEAVY VEHICLE RESEARCH CENTER

Truck Rollover Characterization for Class-8 Tractor-Trailers Utilizing Standard Dual Tires and New-Generation Single Tires

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TRUCK ROLLOVER CHARACTERIZATION FOR CLASS-8 TRACTOR-TRAILERS UTILIZING STANDARD DUAL TIRES AND NEW-GENERATION SINGLE TIRES

A Final Report on a Test-Track-Based Study for the National Transportation Research Center, Inc. (NTRCI) Conducted by the Oak Ridge National Laboratory (ORNL), in Partnership with Dana Corporation, Michelin Americas Research and Development Corp., and Clemson University

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The authors wish to gratefully acknowledge the contributions of Mr. Doug Pape of Battelle Memorial Institute (BMI) for his contributions to this project. Mr. Pape actively participated in defining truck rollover maneuvers and shared valuable technical insights regarding vehicle dynamics and truck rollover.

EXECUTIVE SUMMARY

The Heavy Truck Rollover Characterization Project is a major research effort conducted by the National Transportation Research Center, Inc. (NTRCI) in partnership with Oak Ridge National Laboratory (ORNL), Dana Corporation (Dana), Michelin Americas Research and Development Corporation (Michelin) and Clemson University (Clemson), under the NTRCI's Heavy Vehicle Safety Research Center (HVSRC) for the Federal Highway Administration (FHWA). ORNL provided the day-to-day management of the project. The expertise mix of this team coupled with complementary research needs and interests, and a positive "can-do" attitude provided an extremely positive experimental research opportunity for all involved. Furthermore, this team supplied significant and valuable resources that provided a strong positive benchmark regarding the ability to conduct research within a public-private partnership. The work conducted by this team focused on initial efforts to generate data and information on heavy truck rollover not currently available in the industry. It reflects efforts within Phases 1 and 2 of a longer-term four-phase research program.

A 1999 Peterbilt 379 class-8 tractor and 2004 Wabash dry freight van trailer were the test vehicles utilized in this effort. Both were instrumented with a number of sensors to capture the dynamics of the tractor and trailer as it engaged in various testing maneuvers that included: an evasive maneuver, swept sine, constant radius, and a run-off-the-road maneuver. The run-off-the-road maneuver was discontinued because the test track could not safety accommodate such a maneuver. These maneuvers were carried out utilizing both standard dual tires and new-generation dual tires in six test series. Two test series also included the use of a wider-slider suspension. Outriggers were placed on the test vehicle to assure that an actual rollover would not occur, however, the tests were designed to generate lift-off of tires during the tests. One of the main objectives of the tests that are a part of this study was to understand how different elements (e.g., dual tires and wide-base, new-generation single tires, different trailer suspension types, etc.) affect the overall vehicle roll stability. Tilt-table tests were also performed to characterize the static rollover propensity if the tractor trailer.

For all of the tests, the vehicle was loaded with ballast for a gross vehicle weight rating of 79,000 lbs., and the speeds were gradually increased so that wheel lift-off was experienced both visually and via instrumentation. A significant amount of data was collected on all maneuvers performed (1.2 Gigabytes of data from 45 data channels sampled at 0.01 sec) and information was also captured via videotaping (one camera inside the cabin and three others outside; plus one off-board camera). Due to a number of issues related to the sensors, and idiosyncrasies in the data itself, a statistically meaningful data set was not possible. However sufficient data was collected to demonstrate the trends and patterns in the heavy truck rollover phenomenon.

Analyses of the data were performed by the partners. ORNL analyzed the evasive maneuver and constant radius data. Although the lack of data did not allow for the performance of statistical tests over the data collected, the results of both tests analyzed seem to indicate that the tractor-trailer tire configurations that included the new-generation single tire consistently performed better (except for one case involving a constant radius test) than the standard layout (both tractor and trailer with dual tires). The results also indicate that for the tests that included the use of a wider-slider for the trailer, improved stability and increased effective stiffness of the trailer were experienced.

Dana also analyzed the evasive maneuver using a different analysis methodology. Their analysis indicated that for those tests run with new-generation single tires on the trailer (and dual tires on the tractor in one case, and new-generation single tires on the tractor in another), when the results are compared to standard dual tires on the tractor and trailer, a clear improvement in vehicle stability could be seen. Dana also found large contributions to increasing roll stability by using the wider-slider trailer suspension.

Michelin analyzed the data from swept sine maneuver. Michelin computed six frequency response functions (FRFs) to include an analysis of the coherent frequency range of each of the six test series. The swept sine test can be used, for example, to calculate yaw rate to steering wheel angle and lateral acceleration-to-steering wheel angle. In general, Michelin found that differences between the test series for the swept sine maneuver were small with the exception of those cases in which the wider-slider configuration was used. The estimated trailer roll gain was noticeably lower with the wider-slider configuration.

Clemson University conducted the analysis of the constant radius maneuvers conducted at radii of 150ft and 400ft. Different variables were analyzed including Trailer Roll Gradient (deg/G), Fifth Wheel Roll Moment Sensitivity, and Axle 5 Absolute Roll Angle Sensitivities. For the Trailer Roll Gradient analysis, the data indicated that for the case with new-generation single tires on the tractor and trailer (with a wider-slider suspension), the test vehicle rolled less per unit g than the other series. This was followed closely by the case of standard duals on the tractor and new-generation singles on the trailer (with a wider-slider suspension), (similar to the results found by ORNL for this maneuver). In Clemson's analysis of the Fifth Wheel Roll Moment Sensitivity, results of the analysis indicated that new-generation tires on the tractor and trailer (with the wider slider suspension) gave the best overall performance in terms of roll moment generation, followed somewhat closely by the case of standard duals on the tractor and new-generation singles on the trailer (with a wider-slider suspension). A similar result was obtained in Clemson's analysis of understeer gradient and lateral acceleration. Lastly, Clemson investigated, analytically, which design and loading variables had the largest impact in minimizing rollover propensity. They accomplished this via a computer program which was written to study the effect of these variables on the rollover propensity. The design variables that were found to be most influential on rollover were identified and include: payload placement, roll bump stop clearance, payload distribution, track width, and torsional stiffness of the tractor sprung mass.

Overall, for this study, it was concluded that the use of next-generation single tires and wider-slider suspensions seem to provide improved roll stability for class-8 tractor-trailers. Further quantification of this effect should be conducted through additional research, and similar studies should be conducted on flat-bed trailers and tankers. Lastly, other technologies exist and are emerging that could also contribute to improved roll stability. Future research involving public-private partnerships that reflect a vested interest on the part of all partners may be the key toward the accomplishment of this important and costly research.

1. INTRODUCTION/BACKGROUND/OVERVIEW

1.1 INTRODUCTION

The Heavy Truck Rollover Characterization Project is a major research effort conducted by the National Transportation Research Center, Inc. (NTRCI) in partnership with the Oak Ridge National Laboratory (ORNL), Dana Corporation (Dana), Michelin Americas Research and Development Corporation (Michelin) and Clemson University (Clemson), under the NTRCI'S Heavy Vehicle Safety Research Center (HVSRC). Since 2003, NTRCI's efforts under the HVSRC has been funded by the Federal Highway Administration (FHWA) and the National Highway Traffic Safety Administration (NHTSA), and carried out by ORNL, Battelle Memorial Institute (BMI), and the University of Tennessee (UT). In addition to this heavy truck rollover characterization project, NTRCI has supported HVSRC research in the following areas:

- Finite Element Modeling of Selected Single Unit Truck - Infrastructure Crashes,
- Evacuation Modeling with Emphasis on Heavy Truck Movement,
- Improvement of the TruckSim Brake Module,
- Brake Material Characterization with a Subscale Brake-Tester (SSBT),
- Evaluation of a Multi-Plate Performance-Based Brake Tester,
- Study of Long-Phosphoring Paint Pigments to Enhance Truck Conspicuity,
- Development and Evaluation of a Pulsed Ultra-Violet Headlight for Truck Safety,
- Evaluation of a Wireless Brake Status, Health Monitoring and Communication System, and
- Correlation of Brake Performance in the Laboratory, Test-Track and Field Operational Test.

A primary goal of the NTRCI is to facilitate the collaboration and partnership of private industry with research entities such as ORNL, BMI and UT on research areas of national importance. Such partnerships have been successfully put in place with Dana, Michelin, and Volvo Group (Volvo), and have allowed research needs of common interest to be addressed through leveraged federal and private resources.

Consistent with its role, NTRCI for this project created the teaming relationship, provided overall contract management (using subcontracts with all participants) and served as overall project manager, providing advice, guidance, assistance and oversight to the team throughout the project. ORNL, as the lead partner, was responsible for the day-to-day management and direction of the Heavy Truck Rollover Characterization Project, to include coordinating and integrating the efforts of the other partners, and preparing this report.

1.2 BACKGROUND

Heavy truck rollover crashes are not frequent occurrences. They represent approximately three percent of all crashes for combination trucks. Although this percentage is low, fatalities associated with heavy truck rollovers are inordinately high. Truck rollover is a factor in about 13 percent of all fatal crashes of combination trucks (http://www-nrd.nhtsa.dot.gov/departments/nrd-01/summaries/ITS_10_2.html). In addition, it is not unusual for the economic losses of the payload and other associated insurance costs to be in the millions-of-dollars per crash.

Understanding the interactions of vehicle load, tires, suspensions, vehicle types, vehicle stiffness (tractor and trailer), and roadway surfaces/tire interface on truck rollover events can contribute significantly to improving heavy truck safety. Such understanding can be applied to support the design and evaluation of new technologies such as wider axles, new-generation single tires, adaptive suspension systems, rollover warning systems, etc. It can also contribute to improving roadway design to minimize the potential for truck rollover stemming from vehicle-highway interactions, and can contribute to more effective regulation aimed at reducing truck rollovers. Additionally, such understanding is essential for development of a next generation heavy vehicle dynamics model. Such a model would be a valuable tool for evaluating new product innovation, and for the assessment of the interactions associated with complex vehicle dynamics. Although there have been a number of heavy truck rollover tests conducted in the past, there are almost no publicly available databases on heavy truck rollover of sufficient granularity to support development of a robust vehicle dynamics model.

Understanding the dynamics and characteristics of heavy truck rollovers is complex, and cannot be achieved thoroughly without the conduct of test-track-based vehicle testing. Such testing encompasses the collection of vehicle dynamics data and information on truck rollover performance involving various types of driving and braking scenarios. Additionally, data from a tilt-table is important for determining the static characteristics of the subject vehicle to be utilized at the test track.

1.3 OVERVIEW

The work conducted in this project focused on initial efforts to generate data and information on heavy truck rollover not currently available in the industry. This work is expected to provide a deeper understanding of heavy truck rollover characteristics and will contribute toward achievement of a heavy vehicle dynamics model.

Because of the complexity of this research, the high costs involved with test-track and field-testing, and limited funding, a long-term, four-phase Program was conceived. The research conducted in this project addressed Phases 1 and 2. Phases 3 and 4 will be conducted in follow-on research efforts. The four phases are:

Phase 1: Baseline Data Collection
Phase 2: Tractor/Box-Trailer Testing
Phase 3: Tractor/Flatbed/Tanker Testing
Phase 4: Customized Tractor-Trailer with Low Rollover Propensity

These Phases involve the following:

Phase 1: Testing involved a class-8 over-the-road tractor-trailer with dual tires on the tractor drive axles and on the trailer axles. Candidate maneuvers considered for this project were derived by examining various vehicle dynamics sources including ISO standards, SAE papers, and work instructions. Maneuvers selected for execution included Swept-Sine, Evasive Lane Change, Constant Radius, and Run-off-the-Road. The tractor and trailer were both equipped with rear air suspensions. Such testing was conducted in order to generate controlled baseline data that will be used for comparison with all future testing in this program. Phase 1 testing (a combination vehicle with dual tires) encompasses the majority of class-8 over-the-road combinations now in service on U.S. roadways. The tractor-trailer and specialized test-equipment (e.g., a pair of wheel-end force transducers) were provided for use within this project by Dana as part of a cost-sharing agreement. Additional specialized test equipment and data acquisition hardware/software were provided by Michelin.

Phase 2: Testing involved the same maneuvers as conducted in Phase 1, but included the use of new-generation single tires on the tractor, on the trailer, or both; and involved testing with a van type trailer, with and without a wider-slider suspension. Table 1.3.1 provides a listing of the vehicle tire configurations for Phase 1 and 2 testing. As in Phase 1, the tractor and trailer were both equipped with rear air suspensions. Phase 2 coupled with Phase 1 covers all of the current vehicle/tire combinations for van type tractor-trailer combinations.

Table 1.3.1 Vehicle Tire Configurations for Phase 1 and Phase 2 Testing.

Test Series	Phase	Tractor	Trailer Suspension Type	
			Standard (48 in Box Width)	**Wider-Slider (54 in Box Width)**
1	Phase 1	dual	dual	*not used*
2	Phase 2	new-generation single	dual	*not used*
3	Phase 2	new-generation single	new-generation single	*not used*
4	Phase 2	dual	new-generation single	*not used*
5	Phase 2	new-generation single	*not used*	new-generation single
6	Phase 2	dual	*not used*	new-generation single

Phase 3 - Phase 3 testing will involve a dry box van trailer, a flatbed trailer, a tanker trailer, and a standard frame class-8 tractor. Baseline rollover data will be gathered on the flatbed trailer and the tanker trailer to compliment the data gathered in Phases 1 and 2. Additionally, torsional stiffness data will be measured for all platforms.

Testing of the flatbed and tanker trailers will be performed with new-generation single tires and dual tires. Kinematics and Compliance (K&C) characterization will be done on these trailers along with a new procedure to evaluate torsional stiffness. A Finite Element Analysis (FEA) of the trailers will be done and compared to K&C results.

The data gathered during this testing will be used along with the data gathered in Phases 1 and 2 to model and simulate potential changes to currently existing axles, frames and suspensions. Simulation of the tests will be performed with a TruckSim or ADAMS model. From this modeling and simulation effort, recommendations of actual hardware changes will be identified in order to optimize these vehicle systems and components to take better advantage of the new-generation single tires. These hardware changes will be implemented in Phase 4. FEA analysis of the modification will be done to quantify the gain in stiffness. Likewise, simulations in Trucks/ADAMS will quantify the gain in rollover threshold. The project partners will work from basic principles, i.e., "from a clean sheet of paper," to define the critical vehicle (tractor and trailer) parameters to maximize the rollover threshold, handling, and ride comfort without significantly compromising vehicle durability or other important factors such as fuel economy.

Phase 3 testing will involve Dana, Michelin, and possibly a flatbed trailer manufacturer, a tanker manufacture, a tanker fleet operator, and an insurance underwriter.

Phase 4 - Phase 4 testing will involve a modified class-8 tractor with widened frame rails and axles along with a redesigned suspension and new-generation single tires. It is expected that these modifications may involve adding new rails along side of the existing rails and adding needed cross-member support to increase torsional stiffness. These modifications will mimic, to a large extent, a production tractor with wider frame rails. FEA analysis and vehicle dynamics simulations will be done on the tractor to verify gains in stiffness and rollover threshold.

The trailers will undergo similar modifications to improve roll performance and in the case of the tanker, to lower the overall effective center of gravity of the vehicle. This will be done by lowering the tanker into the space made available by the new-generation single tires and the wider frame rails.

Flatbed trailer torsional stiffness may be increased by widening the frame rails or modifying the suspension to take advantage of the extra space provided by the new-generation single tires.

These "optimized" platforms will be tested again and comparisons will be made with the baseline data to assess the effectiveness of the modifications including roll propensity and torsional stiffness. Upon completion of the testing and analysis, additional modeling and simulation will be conducted to identify recommendations of "advanced" changes for future testing not defined in this document.

Phase 4 testing will involve a tire manufacturer, a suspension manufacturer, an axle manufacture and may involve a flatbed trailer manufacturer, a tanker manufacture, a tractor manufacture and an insurance underwriter. The completion of Phase 4 testing will include all currently existing or planned vehicle configurations and combinations for standard class-8 over-the-road tractor-trailers.

Products resulting from Phase 1 and 2 efforts were as follows:

- Data and information on heavy vehicle suspensions were generated that can contribute to better understanding of suspension roll stability and roll characteristics.
- Test development to be able to differentiate between different vehicle design parameters as related to rollover and handling
- Understanding the effects that suspension roll characteristics have on overall vehicle roll stability was facilitated.
- Data and information on the characteristics of dual tires and new-generation single tires in rollover events were generated.
- Understanding of roll stability and handling differences between dual tires and new-generation single tires, with emphasis on their effect on tractor-trailer dynamics, was facilitated.
- Vehicle dynamics data for truck rollover events, with emphasis on dynamics associated with a tractor-trailer's fifth wheel were generated.
- Insights for improving torsional stiffness in an integrated suspension were gained. Based on the modified trailer test results, which includes a wider-slider, it was shown that widening the frame of the trailer increased roll stiffness and consequently rollover threshold. The same concept can be applied to the tractor by widening the frame rail to take advantage of the extra space that is provided by the new-generation wide single tire and a similar improvement in rollover threshold is expected.
- Building and putting together an expert and diverse group to provide and test the latest market innovations in heavy truck handling and rollover improvements.

2. PROJECT DESCRIPTION

2.1 PROJECT OVERVIEW

The Heavy Truck Rollover Characterization Project was led by ORNL for NTRCI in partnership with Dana and Michelin. Clemson also participated as a partner in this effort. Both Dana and Michelin provided significant in-kind contributions in the form of equipment and staffing to support the conduct of this research. In addition to staffing, their in-kind contributions involved the use of a class-8 tractor, a box-trailer, wheel-end torque sensors and on-board data acquisition systems (DASs). More details of these contributions are provided later in this report. It is clear that without such industry participation, cooperation and collaboration, rollover tests like those conducted in this project would be difficult to organize, and would likely require significantly more resources and time to accomplish. In addition to these industry partners BMI supported this project by providing staff with prior and significant truck rollover experience.

ORNL was responsible for the following activities in this project (Responsibilities of other partners are provided in subsequent sections):

- Truck Rollover Program Management,
- Development of a Truck Rollover Test Plan,
- Identification and Procurement of Testing Instrumentation,
- Support for Instrumentation of the Test Tractor-Trailer,
- Support for the Conduct of Rollover Testing,
- Data Analyses, and
- Final Report Preparation.

Some of these activities are highlighted below.

2.1.1 Truck Rollover Test Plan

ORNL, with input from Dana, Michelin, BMI and NTRCI developed a test plan for Phases 1 and 2 that was consistent with accepted rollover testing practices and of prior work in this area. ORNL worked with all participating partners to ensure that the agreed upon test expectations of all partners would be met. The plan called out the types of tests to be preformed, number of tests, goals of each test, participants, location, individual participant responsibility, and data collection protocols. Additionally, an equipment scheduling matrix was developed that optimized the transfer of test instrumentation to each test vehicle in order to minimize the number of transfers between test vehicles and locations. A more detailed discussion of the Test Plan is provided later in this report.

2.1.2 Identification and Procurement of Test Equipment

ORNL worked with participating partners to identify needed equipment for the rollover testing effort and to determine if suitable instrumentation and cabling existed within their companies. ORNL also determined test equipment to be purchased based on needed equipment vs. existing equipment. A list of needed equipment was developed and prioritized by absolute need and cost. ORNL assisted NTRCI in the procurement of needed equipment and miscellaneous accessories. More details on the test equipment are provided later in this report.

2.1.3 Support for Instrumentation of the Test Tractor-Trailer

Primary instrumentation of the test tractor and trailer was accomplished by Dana staff with support by Michigan Scientific of Charlevoix, MI. This effort was completed prior to the arrival of the test vehicle at the Transportation Research Center (TRC) Inc., in East Liberty, Ohio. During the test events conducted at TRC and the University of Michigan Transportation Research Institute (UMTRI), ORNL assisted in the installation and removal of dual tires, new-generation single tires, wheel-force transducers, the steering robot, and the outrigger-mounted cameras as required by the test plan.

2.1.4 Support for the Conduct of Rollover Testing

Rollover testing was conducted by the staff of TRC, Inc., with oversight provided by ORNL and Dana. The tests included tilt-table testing conducted at the tilt-table test facility at UMTRI, and test-track testing that included the following maneuvers: Swept Sine, Highway Evasive Maneuver, Constant Radius, and Step Functions. Some initial data was collected on the step function but testing was discontinued for this maneuver due to safety, equipment and test-track concerns. ORNL was responsible for test plan adherence. A description of all of the maneuvers is provided later in this report along with more details of the tilt-table testing and test track testing. An overview of the data collected is also subsequently provided.

2.1.5 Data Analysis

ORNL, Dana, Michelin, and Clemson conducted data analyses on the data collected at the test-track. UMTRI provided a summary of the results of the tilt-table testing. ORNL led the analysis of the highway evasive maneuver, Michelin and Clemson led the analysis of the Swept Sine maneuver, and ORNL and DANA led the analysis of the Constant Radius maneuver. The partners provided conclusions based on the data, made recommendations for future research, and compiled lessons learned to optimize future data collection efforts. Details of the data analyses, results, conclusions, recommendations and lessons learned are provided later in this report.

2.2 PARTNER ROLES

The Heavy Truck Rollover Characterization Project relied-on and received considerable industry Partner support. The primary partners were Dana and Michelin.

2.2.1 Dana Corporation Support

Dana provided the following support to the project:

- Assumed the lead in acquiring the necessary test equipment to perform the evaluations by supplying a Peterbilt 379 class-8 tractor, a dry van trailer (with and without a wide slider suspension system), and provided a large portion of the vehicle dynamics instrumentation used in the project. This included the DAS, vehicle speed sensor, multiple accelerometers, a dynamic measurement system, string potentiometers, and two wheel force transducers.
- Provided a test engineer and technician to set up the instrumentation and troubleshoot the system prior to its arrival at the test track.
- Validated the test vehicle and its related sensors and equipment as well as the chosen vehicle maneuvers. This validation was conducted at Dana's Commercial Vehicle Systems Technology Center in Kalamazoo, Michigan.
- Played a key role in administering and executing the test plan by providing the test director and data collection engineer during the vehicle testing.
- Collected and distributed the test data. The raw data was archived and distributed to the team for their respective analyses.

- Provided data analysis of the evasive maneuver. A report was provided with numerical data, graphs, charts, conclusions, etc.

2.2.2 Michelin Americas Research and Development Corporation Support

Michelin provided the following support to the project:

- Tire characterization
  - Identified all of the tire types that would be used in the study (dual, single, steer, drive, etc.).
  - Identified all test conditions (load, slip angle, camber angle, etc.).
  - Submitted tires to flat track testing.
  - Processed data for different model inputs.
- Vehicle characterization
  - Identified vehicle for Kinematics and Compliance (K&C) characterization.
  - Performed K&C characterization test.
- Modeling simulation and comparison
  - Performed modeling simulation with different test scenarios.
  - Compared different modeling results and inputs from Flat track vs. instrumented hub.
- Optimization of vehicle dynamic response and rollover resistance
  - Utilized the existing model and simulation as a basis for developing an optimization methodology that may be used in preliminary design stages to maximize rollover threshold.
  - Extended the model and the simulation to include effects of torsional flexibility of the tractor and trailer frames.
  - Implemented the extended model in the optimization routine developed in the first phase.
  - Utilized the optimization simulations to explore a limited number of advanced design concepts.
- On vehicle testing
  - Supported vehicle instrumentation.
  - Conducted data analysis.

3. TESTING

3.1 SUMMARY OF TEST TRACK TESTING

The following series of five test maneuvers were selected to maximize the desired data acquisition levels while minimizing testing time and resources. The data acquired from the following events were used to correlate with virtual simulation model results.

3.1.1 Evasive Lane Change Maneuver

Background: This maneuver and associated evaluation was conducted to determine a vehicle's transient response when subjected to a sudden lane change. The resulting data was used to study the transient roll control characteristics of vehicle attitude and rollover/understeer.

Setup: The Single Lane Change Course (Evasive Maneuver) was setup with pylons as shown in Figure 3.1. It was setup on the Vehicle Dynamics Area (VDA) at TRC. A level asphalt area of sufficient size (50 sq acres) to accommodate safe entry and exit of the course for the size and weight vehicle being tested.

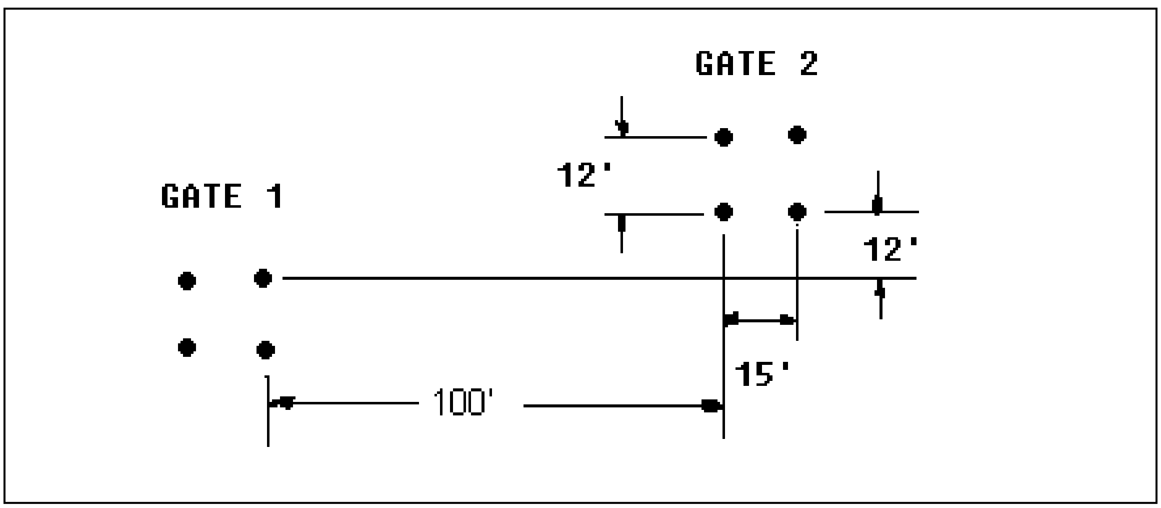


Figure 3.1.1 Evasive Maneuver Pylon Layout.

Ballasting: The gross vehicle weight rating (GVWR) was approximately 79,000 lbs. Its unladened vehicle weight (UVW) was approximately 38,950 lbs.

Vehicle Control: Professional Driver.

Procedure: The test consisted of negotiating a left-hand lane change. Gate 1 was entered at a constant speed. While maintaining speed, an abrupt reverse-ramp steer was executed upon exiting gate 1. The steer input provided by the driver was sufficient to traverse the centerline and gain a position for a straight entry into gate 2. As gate 2 was being traversed, the driver maintained his initial speed until exiting gate 2. Initial efforts involved negotiating the course at 41 mph. Subsequent efforts increased the speed by 2 mph until incipient rollover as indicated by outrigger contact with the ground. Once the rollover threshold speed was determined, the test was repeated three times, and verification was made that sufficient data had been obtained.

Results: The following variables were examined:

- vehicle speed at wheel lift,
- lateral acceleration of the trailer CG at wheel lift,
- combined lateral acceleration of the tractor CG and trailer CG at wheel lift
- fifth wheel roll moment.

3.1.2 Swept Sine Maneuver

Background: The Swept Sine test provides complementary information regarding sensitivity between, for example, the steering wheel input and resulting yaw rate and lateral acceleration of the vehicle system as a function of frequency. This test thus provides information relating to the vehicle frequency response.

Setup: This test required a sufficiently large area to operate the test vehicle at a constant speed of 50 mph for approximately 25 sec, with room to attain test speed and to decelerate at the end of the test. It was desirable to position a camera inside the vehicle to record the steering wheel movement during this test.

Ballasting: The GVWR was approximately 79,000 lbs. Its UVW was approximately 38,950 lbs.

Vehicle Control: Professional Driver.

Procedure: The vehicle should maintain a constant speed of 50 mph throughout the maneuver. Beginning with a sinusoidal steering rate of 0.2 Hz, the driver must determine the steering angle required to generate (at 0.2 Hz) approximately +/- 0.2 g peak lateral acceleration[1] as measured at or near the tractor CG. The steering amplitude may change somewhat when using different tires. The initial steering direction should remain consistent. An example is shown in Figure 3.1.2.

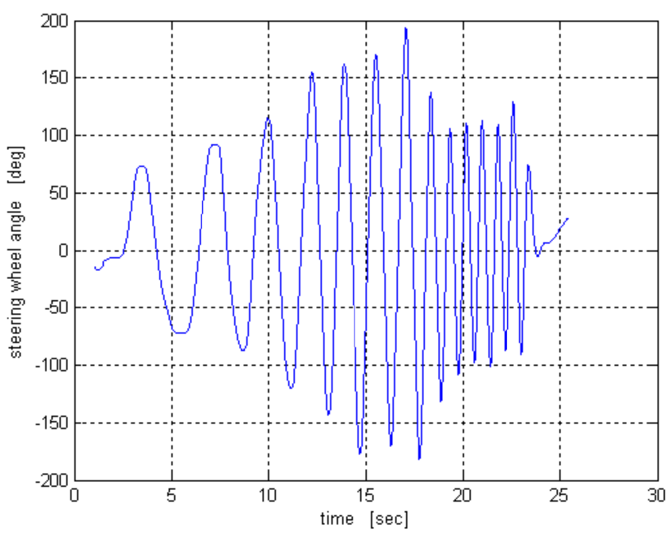


Figure 3.1.2 Example of Swept Sine Steering Wheel Angle.

The driver is charged to perform a swept sine steering input, increasing the steering frequency uniformly from 0.2 Hz to about 2 Hz by the end of the 25 sec interval. The peak steering wheel input

[1] The roll stability of the test vehicle should also be considered when selecting this value, i.e. in some cases, lower values of lateral acceleration might be required.

can drop appreciably at the higher frequencies in order to avoid acceleration levels becoming too high. An example of lateral acceleration output is shown in Figure 3.1.3.

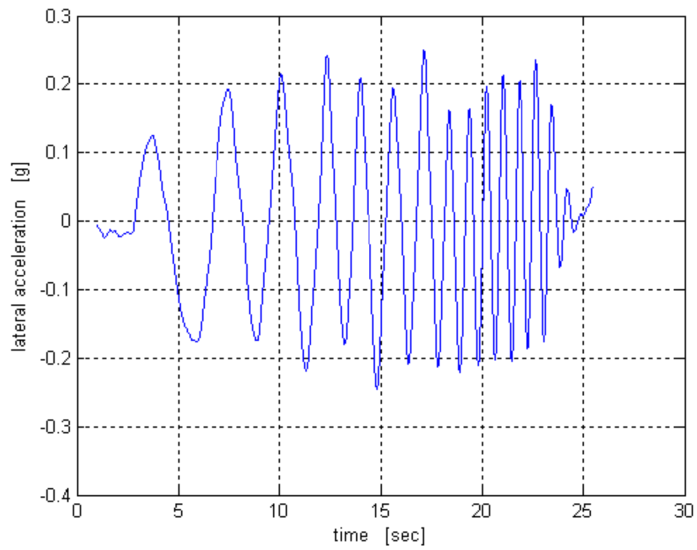


Figure 3.1.3 Example of Swept Sine Lateral Acceleration.

The maneuver should be practiced a number of times until the driver feels comfortable with the procedure (for safety, the driver could start by running at lower acceleration levels, and then increase initial levels, up to 0.2 g at 0.2 Hz in this case - as proficiency develops). The steering amplitude should be regulated by the driver so as not to exceed safe acceleration levels at any time during the test.

The test procedure should be run at 50 mph, approximately 25 sec in duration with at least 0.5 sec straight line at the beginning to establish zeros. Eight passes should be completed with a minimum sampling rate of 50 Hz.

Results: The following relationships were examined:

- Tractor yaw rate to steering wheel angle,
- Tractor lateral acceleration to steering wheel angle,
- Tractor roll rate to tractor lateral acceleration,
- Trailer roll to trailer lateral acceleration,
- Trailer yaw rate to steering wheel angle, and
- Trailer lateral acceleration to steering wheel angle.

3.1.3 Steady State Constant Radius Turn - 150 ft Radius

Background: Steady state maximum lateral acceleration tests were conducted to determine the maximum lateral acceleration that could be achieved by a vehicle under steady state cornering conditions. The test consisted of negotiating a circular path until the maximum achievable steady state speed was attained and held for at least one complete lap. The cornering ability of a vehicle was quantified by the level of lateral acceleration that could be sustained in a stable condition.

Setup: This procedure utilized the 150 ft constant radius paved circle on the VDA.

Ballasting: The GVWR was approximately 79,000 lbs. Its UVW was approximately 38,950 lbs.

Vehicle Control: Professional Driver.

Procedure: The driver was tasked to maintain a constant circular path by varying the steer angle. Lateral acceleration was increased by 0.1 g/lap until the maximum achievable speed was attained. As soon as the vehicle was in motion, the start of the test was triggered. This was done in order to establish the relationship between increased speed and lateral acceleration or roll. Vehicle speed was increased at a steady, consistent level while the driver continued to stay on the path. The test was suspended when the maximum lateral acceleration or rollover threshold was achieved. The test was also repeated in the opposite direction (counter-clockwise [CCW]).

3.1.4 Steady State Constant Radius Turn – 400 ft Radius

Background: Steady state maximum lateral acceleration tests were conducted to determine the maximum lateral acceleration that can be achieved by a vehicle under steady state cornering conditions. The test consisted of negotiating a circular path until the maximum achievable steady state speed was attained and held for at least one complete lap. The cornering ability of a vehicle was quantified by the level of lateral acceleration that could be sustained in a stable condition.

Setup: This procedure utilize the 400 ft constant radius paved circle of the VDA.

Ballasting: The GVWR was approximately 79,000 lbs. Its UVW was approximately 38,950 lbs.

Vehicle Control: Professional Driver.

Procedure: The driver was tasked to maintain a constant circular path by varying the steer angle. Beginning from a static position, vehicle speed was increased at a linear rate of 2.5 mph every 15 sec. As soon as the vehicle was in motion, the start of the test was triggered. This was done in order to establish the relationship between increased speed and lateral acceleration or roll. After the maximum achievable speed was reached, the driver slowly decreased the vehicle speed at a constant rate (2.5 mph/15 sec) until the vehicle stopped. The test was also repeated in the opposite direction (CCW).

3.1.5 Straight-Line Road Edge Rollover - Step Function

Background: This test was to be conducted in order to evaluate whether a rollover occurs when the driver simply goes over the edge of the road and encounters a step function between the pavement and the shoulder. Furthermore, this test was intended to look at overcorrection effects relative to bringing the vehicle back to the roadway. It should be noted that this test was not completed because of concerns for safety. The test track was not appropriately configured to conduct this test safely and it was therefore aborted after an initial trial.

Setup: A step function curb was constructed along the left side of the test lane. The height of the step function was to be about 3 inches, and the length was to be approximately 800 ft.

Ballasting: The GVWR was approximately 79,000 lbs. Its UVW was approximately 38,950 lbs.

Vehicle Control: Professional Driver.

Procedure: The driver was tasked to travel at a constant speed of 35 mph. He was to allow the vehicle to drift left at a defined yaw angle until the left tires crossed the road edge. Data was to be taken to quantify the effects on vehicle stability for this part of the event.

Following this, the driver was to engage in an aggressive right steer over-correction to direct the vehicle back onto the pavement. A pylon was positioned to provide a target for the driver to re-enter the road surface. However, it was noted that the path of the vehicle was subject to the response of the tires on the unimproved surface. The maneuver was to have been repeated at 40 mph.

3.2 SUMMARY OF TILT-TABLE TESTING

Tilt-table testing was conducted by placing the vehicle on a heavy vehicle tilt-table and slowly rotating this configuration about a longitudinal axis. Restraint straps were used to prevent the vehicle from rolling off the table when it reached its rollover threshold. These straps were fitted to the wheels and axles of the vehicle and had enough slack to permit roll freedom of the vehicle slightly beyond its roll stability limit. As this was reached, and after pausing to let the vehicle stop rocking against the restraint straps, the table slowly returned to the level position. This testing performed in this project involved tilting the tractor-trailer combination to one side only. The test configurations were as follows:

- Peterbilt 379 class 8 tractor with dual tires, 53 ft Wabash dry van trailer (air suspension) with dual tires,
- Peterbilt 379 class 8 tractor with new-generation single tires, 53 ft Wabash dry van trailer (air suspension) with new-generation single tires, and
- Peterbilt 379 class 8 tractor with new-generation single tires, 53 ft Wabash dry van trailer (air suspension) with new-generation single tires and wider-slider suspension.

Each test configuration was repeated three times with the expectation of 0.003 to 0.005 g variation. Tests were conducted by UMTRI staff at the UMTRI facilities.

The relationship between the Load Transfer Ratio (LTR) for a given axle and the Equivalent Lateral Acceleration (ELA) was evaluated. The LTR is a measure defined as the difference between the low-side and high-side wheel loads on an axle group divided by the total load carried by the axle group. An LTR of zero corresponds to an axle on which the load is uniformly divided between the left and the right, whereas an LTR of 1.0 (unity) indicates an axle in which the load is entirely concentrated on one side or the other. Figures 3.2.1 and 3.2.2 show the test vehicle on the tilt-table and the trailer at wheel lift-off.

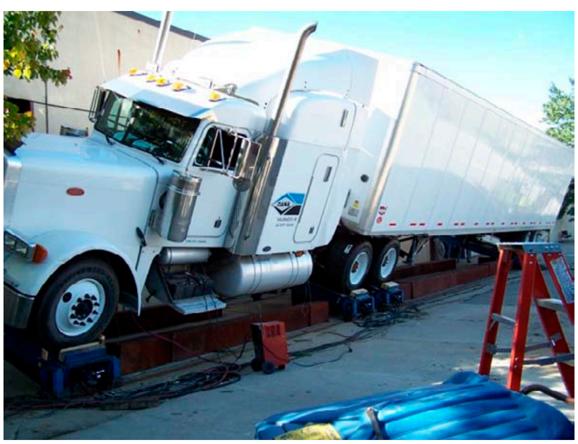


Figure 3.2.1 Test Vehicle on Tilt-Table.

Figure 3.2.2 Trailer Axle 4 at Liftoff.

3.3 BALLASTING

The ballast for the rollover testing consisted of 4,000 lbs, 3,200 lbs, and 2,850 lbs concrete blocks provided by TRC, Inc. All vehicle/tire configurations were tested in a “fully loaded” condition (i.e., as close to 80,000 lbs as possible). The series of tests called out in section 3.1 did not require changes to the ballast in the test vehicles. All ballast was secured via a load frame and binders to prevent load shifting during roll event, hard braking, and evasive maneuvers. No ballast was attached to the tractor for any part of this testing. Table 3.3.1 shows the axle weight and total weight of the test vehicle during each series of testing.

Table 3.3.1 Axle Weight (lbs) per Test Series.

	SERIES 1	**SERIES 2**	**SERIES 3**	**SERIES 4**	**SERIES 5**	**SERIES 6**
Steer	11,300	11,270	11,370	11,190	11,430	11,410
Drive	33,980	33,520	33,720	33,820	33,700	34,130
Trailer	33,980	33,960	33,560	33,600	33,630	33,650
TOTAL	79,260	78,750	78,650	78,610	78,760	79,190

Note: Weight includes driver and passenger

The total ballast added to the trailer was 39,350 lbs with 18,000 lbs added to the nose of the trailer and 21,350 lbs added to the rear of the trailer. Figure 3.8 shows the placement of the ballast in the trailer. The center of gravity (CG) of the test vehicle (after loading) was 299.3 in behind the front wall of the trailer, 51.0 in from the driver's side of the trailer, and 18.3 in above the trailer floor as shown in Figure 3.3.1.

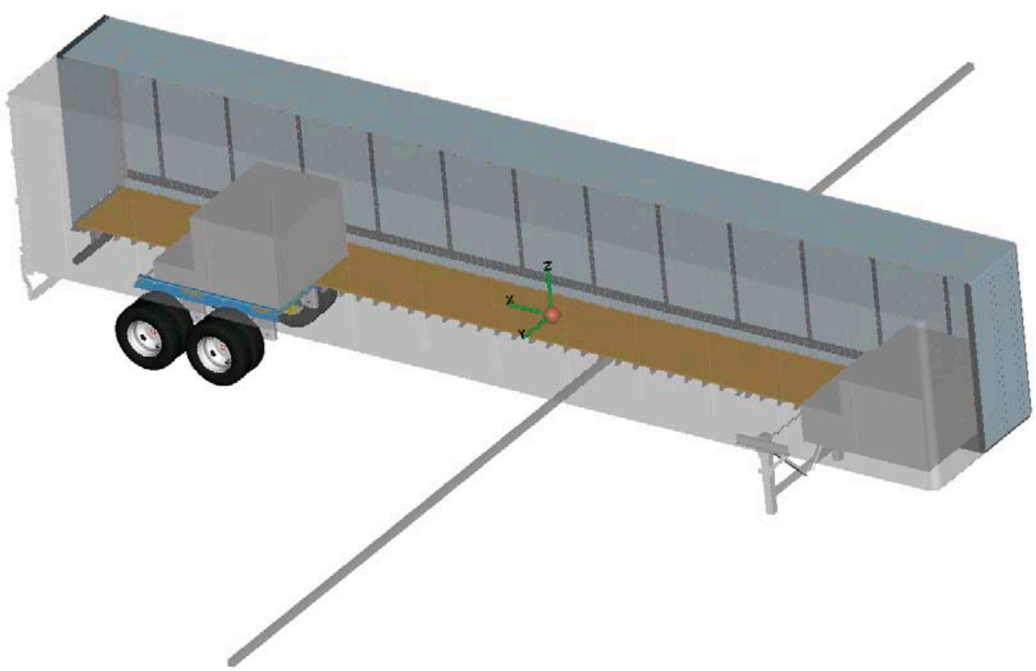


Figure 3.3.1 Load Placement.

3.4 TEST VEHICLE AND INSTRUMENTATION SUMMARY

The vehicle configuration was selected based on three primary factors: accessibility, OEM affiliation, and market data. Accordingly, the research partners chose a 1999 Peterbilt 379 tractor (Figure 3.4.1) and a 2004 Wabash dry freight van trailer (Figure 3.4.2) as the test vehicle combination.

The Peterbilt 379 is a conventional 6x4 tractor that is famous for classic long-nose styling and a balance of performance and reliability. As Peterbilt's most popular truck, the model 379 can be seen nearly everywhere on the interstate. The Peterbilt 379 used in the rollover test was powered by a Caterpillar 3406E engine. According to industry sources, van trailers will account for 78 percent of the total trailer shipments in 2005. Hence, an understanding of the roll characteristics associated with van trailers was critical to the overall evaluation of a tractor-trailer combination. Wabash National Corporation is a leading manufacturer of dry van trailers. A new 53 ft Wabash van trailer was procured by Dana for the sole purpose of this rollover evaluation.

Figure 3.4.1 Peterbilt 379 Tractor.

Figure 3.4.2 Wabash Van Trailer.

The high-tech instrumentation selected by the research partners offered unique insight into the rollover characteristics of the test vehicles. Vehicle speed was monitored with a Datron DLS optical speed sensor. The Watson DMS-E604 was fixed near the tractor CG to dynamically measure lateral acceleration, roll angle, and angular rates. Likewise, the Oxford RT3100 measured similar parameters at the trailer CG. PCB accelerometers assessed the lateral accelerations at the rear drive and rear trailer axles.

MTS-SWIFT 50T wheel force transducers (Figure 3.4.3) were installed at the right rear drive axle and right rear trailer axle wheels. Along with tri-axial (longitudinal, lateral, and vertical) wheel forces, these valuable transducers measured wheel angle and overturning, braking, and steering moments. A new SEA steering controller was used to perform robotic steer maneuvers and steering wheel position. A fifth wheel load transducer, leased from UMTRI, measured all four primary loads transmitted between the tractor and trailer by the fifth wheel coupling: longitudinal force, lateral force, vertical force, and roll moment. Finally, string potentiometers were located on the both sides of the vehicle to determine the roll angle between the axles and the sprung mass.

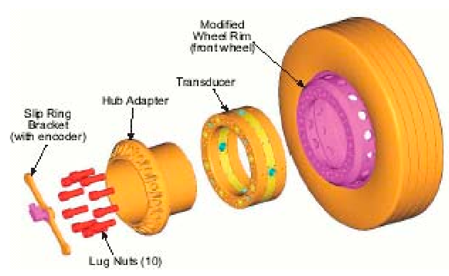


Figure 3.4.3 Wheel Force Transducer.

3.5 OVERVIEW OF DATA COLLECTION

The central DAS used for the rollover testing was a Megadac 6510DC. The programmable cards (channels 16-23 and 40-47) were set at 33 Hz (eight pole filter). The eight channel cards were set at 21 Hz (three pole Butterworth filter). The sampling rate was 100 scans per sec.

Michigan Scientific (www.michsci.com) was contracted for instrumentation support and data acquisition expertise. They helped address the challenge of instrumenting the vehicle with numerous sensors as well as acquiring, storing, and transferring data. The data acquisition setup involved designing and fabricating custom brackets and interfaces, physically connecting cables to the Megadac, and checking the validity of sensor signals. Instrumenting the vehicle with the sensor suite and data acquisition equipment was a 2-to-3 week process.

A data acquisition engineer accompanied the driver during each test event to monitor the equipment and sensor output. Initialization and termination of each data set was controlled with a hand trigger. Test data from the Megadac RAM was originally archived to the host computer before being transferred to CD. Data acquisition files were made available in ASCII, Optim TCS, and MatLab format. The research partners received as many as eight CD's of test data.

Communication between test personnel at the proving grounds was aided by handheld two-way radios. One person was designated to videotape each event, while another recorded the test parameters, monitored track conditions, and logged the data sets on a laptop spreadsheet.

3.5.1 Lessons Learned – Positive Impact

A number of things were found to positively affect the efficiency and effectiveness of the testing. They were as follows:

- *Day-to-Day Test Schedule*. In order to optimize the test-track and test-track resources, a day-to-day Test Schedule was developed early in the testing at TRC. This provided the ability to "look ahead" and convey this information to the staff at TRC for their test-track usage forecasting. This was especially helpful on the two occasions when the team traveled to UMTRI for tilt-table testing.
- *Michigan Scientific*. An engineer from Michigan Scientific was assigned to the data collection effort during all vehicle testing. Additionally, Michigan Scientific supplied the DAS and data collection hardware and software. This reduced the overall capital equipment cost and provided additional expertise.
- *Locally Purchase Materials and Supplies*. Tables, chairs, DC power packs, AC inverters, and two-way radios were purchased to allow for efficient, safe, and continuous testing.
- *Video Markers*. While not used for this testing, video markers should be used at the beginning of each test series. These markers should indicate the date, times, test series, and vehicle configuration. This would greatly reduce the confusion when sorting through video data. These markers could be used for on-board and off-board recordings.
- *Pre-Mounting Wheels and Tires*. An equal number of wheel and tires were purchased and pre-mounted to allow for fast configuration of the Test Vehicle from configuration-to-configuration.

3.5.2 Lessons Learned – Negative Impact

Throughout the testing process, various circumstances led to delays, loss of data, and changes to the schedule. These circumstances are being presented so that in future tests, they can be accounted for, planned for, and/or corrected to increase the efficiency and effectiveness of those tests. The following were considered to be noteworthy:

- *Steering Controller.* The team had multiple technical issues with the SEA steering controller. Its functionality was limited to providing steering wheel angle. An SEA employee was on-site at TRC three separate days to assist with troubleshooting the device. There were repeated difficulties in establishing communication between the software and the steering robot. Rather than spending additional time troubleshooting the device, the team decided to proceed with the testing using full manual control for all passes. There is a pressing need for such a device for future rollover testing to account for driver correction and driver variability from pass-to-pass. Further evaluation of the steering controller is required to work out the bugs in the system.
- *TRC Track Access.* Weather, priority, and scheduling conflicts at the TRC facility lead to periodic downtime for the team. While this is very difficult to control, it needs to be factored into the schedule of future testing.
- *Demand for Outriggers.* The outriggers used by the heavy truck rollover team were in high demand. Concessions were made in the test schedule to allow other groups to use the outriggers. The time spent removing the outriggers and waiting for them to be installed again delayed the program by several days. Consideration needs to be given to the purchase of a dedicated set of outriggers for future phases of testing.
- *Rigidity of the Outriggers.* The outriggers that were used could not be "folded for travel." They therefore had to be removed in order to travel to UMTRI for the tilt-table testing. The installation and removal of the outriggers was very time consuming, and the team's priority to use them was lost once they were removed. Future Phases of this program would be well served by the purchase of retractable outriggers that would allow for travel on public roadways.
- *Demand for Wheel Force Transducers.* The heavy demand for wheel force transducers at Dana and the special mounting brackets required for their use on the test truck delayed the start of the test program by about two weeks. The cost to duplicate this instrumentation is prohibitive; however consideration should be given in advance to the availability of the transducers for future phases of testing.
- *Fifth Wheel Fz (force) & Mx (moment) Equations.* The data, as distributed for two derived components of the fifth wheel load transducer, was erroneous. The errors were identified when data analysis yielded suspect results. Better interrogation test equipment is required to mitigate erroneous data for future testing.
- *Watson Box.* The lateral acceleration and roll signals provided by the Watson box gyro/accelerometers were often faulty. There was a high degree of drift, offset, and measurement uncertainty. A Crossbow accelerometer was positioned at the tractor CG to provide lateral acceleration in lieu of the Watson Box. However, the Crossbow lateral acceleration is not corrected for roll. This equipment will be replaced in future phases of testing.
- *High Frequency PCB Accelerometers.* Two channels used high-frequency PCB accelerometers that were not particularly useful for measuring steady state lateral acceleration on the axles. Some of the data for these channels was of poor quality. There are many low-frequency accelerometers that would be more appropriate for this application.
- *Sensor Orientation.* There were many questions regarding the orientation of the sensors. Wherever applicable, the sensors were positioned +X aft, +Y right, and +Z up. Some of the signal signs were inadvertently reversed for the data sets after the sensors were removed and reinstalled. Care should be taken that all sensors are aligned properly in a common orientation.
- *Sensor Offset.* Occasionally, signals such as roll angle were offset from zero at the start of an event. This may have resulted from the difference in the slope of the pavement between the

dynamic test area and the "flat" location where the sensors were balanced/zeroed. Sensor output should be reviewed prior to the start of each event to verify that the offset is acceptable.

- *Datron Speed Sensor.* The Datron Speed Sensor was erratic at times and failed to operate at a critical time during testing causing a major delay. This device will be replaced in future testing and a backup device will be available.
- *Vehicle Center of Gravity (CG).* A higher vehicle CG would help accentuate roll characteristics. To maximize the CG, an ideal load would fill the volume of the trailer and reach legal gross weight. This will be addressed in future testing by redesigning the load frames to allow “higher” stacking of the ballast.
- *Evasive Maneuver Procedure.* The evasive maneuver should be performed with the automated steering controller to increase the consistency of the steering input. The path should be allowed to vary if necessary, as long as the two gates are crossed (see Figure 3.1.1). Evasive maneuvers should be performed within a wide velocity range in small intervals regardless of wheel lift threshold (passes that did not produce wheel lift are just as important as the passes that did). A minimum of ten data sets should be obtained. Ten is sufficient to provide enough resolution in determining the point of wheel lift and provide a high sample to account for driver variations.
- *Test Road Surface.* The surface of the road should be swept prior to testing to minimize sliding due to grit on gravel. To ensure a clean surface for every test series, sweeping should become a standard practice. Any disparity in surface cleanliness between test series is unknown.
- *Run-Off-the-Road Event.* A significant amount of practice time was given to the road-edge recovery maneuvers. The team was not able to simulate a cornering event where the trailer dropped off the edge of the road. The TRC road-edge event was not sufficient to meet the original intent of the maneuver. The soft sand and dirt in the off-road area prevented repeatability from one test series to the next. Later, rain turned the road recovery area into a shoulder of thick mud. The test was not conducted because of these concerns, and because of safety concerns.

4. OVERVIEW OF DATA

The data collection effort for this project was extensive and generated a rich database of diverse information on truck (tractor and trailer) performance under different maneuvers for different configurations of wheels and tires. The information gathered included not only the variables used in the analyses presented in this report, but also many other important variables that will allow future investigation of other aspects of truck performance not covered in this study. This information is discussed in the next sub-section.

As described earlier in this report, six wheel-tire configurations were tested for ten different maneuvers. Forty-five different variables, measured through a variety of sensors, were recorded every 0.01 sec and 1.2 GB of data was generated. Information was also acquired by videotaping, with one camera inside the cabin and three other outside; plus one off-board camera.

The next sub-section presents a summary of the information gathered during these tests, including a detailed description of the data acquisition channels. Subsequently, issues related to the data that was collected and used in the analyses presented in this report are addressed. The final sub-section discusses in some detail, the steps that were taken to prepare the raw data for the analyses presented in this study.

4.1 SUMMARY OF DATA COLLECTED

One of the main objectives of the tests that are part of this study was to understand how different elements (e.g., dual tires and wide-base, new-generation single tires, different trailer suspension types, etc.) affect the overall vehicle roll stability. Additional goals included acquiring actual rollover data to calibrate and expand simulation models, improving virtual proving ground testing capabilities, and determining predictive indicators of roll that can be used to alert drivers and prevent rollover accidents.

To achieve these objectives and goals, five different tests were designed (see Sections 2 and 3), and large amounts of data were collected during each one of them. The tractor and trailer used in this study were instrumented with an extensive array of sensors that measured those variables judged as the most relevant in characterizing the required rollover evaluations and analyses. Table 4.1 presents a detailed list of all the sensors, including video feeds, deployed for the track tests (i.e., dynamic tests), with a description of each one of the variables measured. The 45 variables were sampled at 0.01-sec intervals, which provided a very high resolution of the information collected.

In addition to the track tests conducted at TRC, a series of tilt-table tests were performed at UMTRI. Those tests were designed to determine the exact roll angle of a static vehicle combination relative to tire combinations, and complement the dynamic information that the TRC tests produced. All of the variables presented in Table 4.1.1 were sampled during these static tests with the exception of Vehicle Speed, Lateral Acceleration, Yaw Angle, Roll Rate, Pitch Rate, Yaw Rate, Slip Angle, and Steering Wheel Position. Sampling was done every 0.1 sec.

Table 4.1.1 Data Acquisition Channels.

Megadac Channel Number	Measurement	Units	Sensor	Recommended Location	Comments
0	Vehicle Speed	mph	Datron DLS Optical		
1	Lateral Acceleration	g	Watson DMS-E604	Close to Tractor CG Inside Cab	
2	Roll Angle	deg			
3	Yaw Angle	deg			
4	Roll Rate	deg/s			
5	Pitch Rate	deg/s			
6	Yaw Rate	deg/s			
7	X Acceleration	G's			
8	Lateral Acceleration	g	Oxford RT3100	Close to Trailer CG Inside Van Trailer	
9	Roll Angle	deg			
10	Yaw Angle	deg			
11	Roll Rate	deg/s			
12	Pitch Rate	deg/s			
13	Yaw Rate	deg/s			
14	Lateral Acceleration	g	PCB Accelerometer	Axle 3 Top Center	Localized lateral acceleration of unsprung mass
15	Lateral Acceleration	g		Axle 5 Top Center	
16	Slip Angle	deg	Oxford RT3100	Close to Trailer Van Trailer CG	
17	Longitudinal Force	lbf	MTS SWIFT50-T	Axle 3 Inside Wheel	
18	Lateral Force	lbf			
19	Vertical Force	lbf			Determination of wheel lift off
20	Overturning Moment	lbf-in			
21	Driving/Braking Moment	lbf-in			
22	Steering Moment	lbf-in			
23	Wheel Angle	deg			
24	Longitudinal Force	lbf	MTS SWIFT50-T	Axle 5 Inside Wheel	
25	Lateral Force	lbf			
26	Vertical Force	lbf			Determination of wheel lift off
27	Overturning Moment	lbf-in			
28	Driving/Braking Moment	lbf-in			
29	Steering Moment	lbf-in			
30	Wheel Angle	deg			
31	Steering Wheel Position	deg	SEA Steering Controller		Sensitivity is 100 deg/V
32	XL[1]	lbf	Fifth Wheel Load Transducer (Left)	Fifth Wheel	
33	YL[1]	lbf			
34	ZRL[1]	lbf			Determination of the onset of fifth wheel separation
35	ZLL[1]	lbf			Important for model validation
36	XR[1]	lbf	Fifth Wheel Load Transducer (Right)	Fifth Wheel	
37	YR[1]	lbf			
38	ZRR[1]	lbf			Determination of the onset of fifth wheel separation
39	ZLR[1]	lbf			Important for model validation
40	Displacement	in	String Pot SN:5654	Left Side of Axle 1	Determination of the roll angle between axle and sprung mass
41	Displacement	in	String Pot SN: 5623	Right Side of Axle 1	
42	Displacement	in	String Pot SN: 5621	Right Side of Axle 3	
43	Displacement	in	String Pot SN: 5622	Left Side of Axle 3	
44	Displacement	in	String Pot SN: 0002-11637	Right Side of Axle 5	
45	Displacement	in	String Pot SN: 9911-11115	Left Side of Axle 5	
Video Recorder					
GV-D900	Wheel Lift Off	N/A	Video Camera	Axle 3	Determination of wheel lift off
GV-D900	Wheel Lift Off	N/A	Video Camera	Axle 4	Determination of wheel lift off

Table 4.1.1 Data Acquisition Channels (Continued)

Megadac Channel Number	Measurement	Units	Sensor	Recommended Location	Comments
GV-D900	Wheel Lift Off	N/A	Video Camera	Axle 5	Determination of wheel lift off
GV-D900	Steering Wheel Movement	N/A	Video Camera	Cab	Driver's view and steering wheel movement

[1] Channels 40-43 are the left chair (a fifth wheel "chair" mounts to a truck frame and sits beneath the fifth wheel coupler "plate") and channels 44-47 are the right chair. X, Y, ZR, and ZL are matrix components for calculating the overall X, Y, and Z loads and roll moment at the fifth wheel.

A total of six different configurations of tractor-trailer wheels and tires (labeled Series 1 to 6; see Table 1.3.1) were subjected to four different tests. Tests involving off-road maneuvers (i.e., Off-Road, Straight-Line Road Edge Rollover, and Curved-Line Road Edge Rollover) were only performed for a few cases and discontinued due to safety and data inconsistency concerns. The 200 ft and 300 ft Constant Radius Turns were only carried out for Series 3 to aid in determining the appropriate radius for testing. Tilt-table tests were conducted only on configurations (Series) 1, 3, and 5.

Table 4.1.2 presents a summary of the tests that were conducted for each Series. Under the column labeled "Tests," the table entry indicates for a particular Series (column header), the number of runs that were conducted for that specific test type (row header); while the column labeled "MB" shows the size of the data files containing the information gathered (in megabytes). Consider, for example, Series 1. Two runs were conducted for that series for the 150 ft Constant Radius Turn maneuver (one in a clockwise [CW] direction and another one in a CCW direction). During these tests, the sensors collected a total of 31.23 MB of information resulting from the 0.01-sec sampling of the 53 variables described in Table 4.1. Two tests were conducted for this Series for the 400 ft Constant Radius Turn maneuver (116.71 MB of data were collected), eight for the Highway Evasive maneuver (7.48 MB), four for the Off-Road test (6.21 MB), eight for the Swept Sine maneuver (20.39 MB), and five tests (i.e., three rollover runs and two low-angle runs) on the tilt-table (29.52 MB). No tests were conducted for the 200 ft and 300 ft Constant Radius Turn maneuvers, or the Straight- and Curved-Line Road Edge Rollover maneuvers. The totals for Series 1 were 29 tests performed and 211.54 MB of collected information, while for the entire battery of tests for all series these figures were 171 tests and 1,199.66 MB, respectively.

Besides collecting information directly from the sensors mounted on the tractor and the trailer, video images were also gathered for the tests. Three video cameras were set to view axles 3, 4, and 5, (i.e., rear drive axle [aft view], left trailer tandem axle wheels, right trailer tandem axle wheels) and the images collected from these cameras were synchronized with various sensor data to identify wheel lift off. A fourth camera was located inside the cabin to record the driver's view and steering wheel movement for the Swept Sine maneuver. In addition to these four onboard cameras, one off-board camera was used to record the vehicle's path during the test maneuvers. Four X10 Anaconda wired outdoor color video cameras and a Lorex Color Quad Multiplexer (which recorded the video feeds to a Sony model GV-D900 Digital Video Cassette Recorder) were used during the tests. Ten hours of video information was collected during all the tests and archived on ten 1-hr mini-DV cassette tapes (this includes videos from TRC and UMTRI).

Table 4.1.2 Summary of Data Collected (MB).

Test Type	Series 1		Series 2		Series 3		Series 4		Series 5		Series 6		Total	
	Tests	MB	Tests	MB	Tests	MB	Tests	MB	Tests	MB	Tests	MB	Tests	MB
Constant Radius Turn – 150 ft	2	31.23	2	29.17	2	30.90	2	28.82	2	31.44	2	33.65	12	185.20
Constant Radius Turn – 200 ft					1	20.90							1	20.90
Constant Radius Turn – 300 ft					1	20.71							1	20.71
Constant Radius Turn – 400 ft	2	116.71	2	108.16	2	95.91	2	119.72	2	114.79	2	116.50	12	671.78
Highway Evasive Maneuver	8	7.48	8	5.53	12	16.54	7	5.60	11	12.67	9	7.91	55	55.73
Off-Road	4	6.21	1	1.59	10	12.96							15	20.76
Straight-Line Rd Edge Rollover					3	5.54							3	5.54
Curved-Line Rd Edge Rollover					8	10.30							8	10.30
Swept Sine	8	20.39	8	20.10	8	26.04	11	29.06	8	20.17	8	16.66	51	132.42
Tilt-Table Testing	5	29.52			4	19.31			4	27.47			13	76.30
Totals	29	211.54	21	164.55	51	259.11	22	183.20	27	206.54	21	174.72	171	1,199.66

4.2 DATA ISSUES

The intense data collection regimen described previously involved the use of many different sensors (see Table 4.1), some of which were delicate instruments that sometimes malfunctioned. Fortunately, in most of these cases a graphical inspection of the data collected was enough to determine its invalidity. However, and due to the very large amount of data gathered in this study (1.2 GB), it was not feasible to conduct graphical analyses of the data immediately after it was collected[2], and therefore no adjustments were made to correct these malfunctioning sensors in successive tests.

Figure 4.2.1 shows an example of this type of issue. The figure illustrates the measurement of the Cabin Rollover Angle (Watson DMS-E604 sensor) as a function of time for the six Series during the CCW Constant Radius maneuver. It is evident from the graph that during the Series 5 test, that the sensor malfunctioned and collected erroneous information. However, this problem is almost impossible to identify by just looking at the data file generated during the test. Figure 4.2.2 shows just three data collection points, out of a total of 11,493 data sampling points, from all the detectors at 30.00, 30.01, and 30.02 sec. Unless there is an obvious problem, e.g., a sensor always giving the same reading, it is very difficult to realize that a specific sensor is collecting data outside its normal range by looking at the numerical stream of data.

A somewhat more common issue with the data was related to initial offsets. At the beginning of each test, some measurements should have initial values of zero (e.g., lateral acceleration, rollover angle, speed, etc.) unless the vehicle was already moving when the data collection started. This problem can be, and was, easily corrected by shifting the data stream for that particular sensor in the vertical direction (assuming sensor raw data vs. time) to eliminate the initial offset. Of course, this could only be done when it was known that the offset was the result of sensor balancing and not due to any other problems.

[2] Inspections of the data collected were performed. However, it was very difficult to identify problems just by looking at the numbers provided by the sensors, especially when the problems may be in the middle of very long streams of data (e.g., in some tests, sensors generated over 55,000 data points for each variable measured).

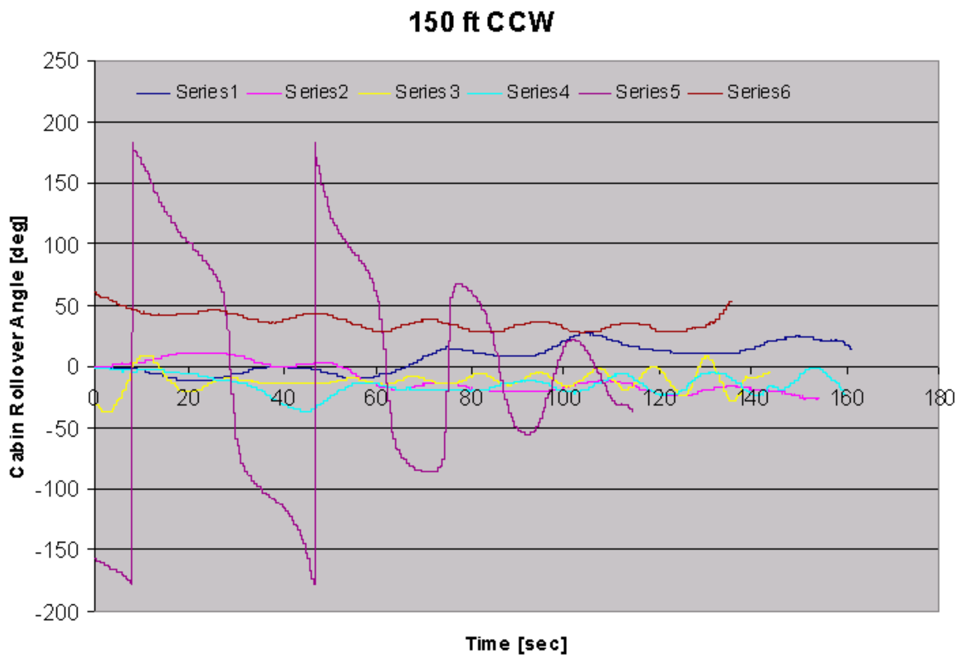


Figure 4.2.1 Cabin Rollover Angle (deg) vs. Time (sec) During the 150 ft CCW Constant Radius Maneuver, by Series.

3.00000000E+01	1.69155000E+01	-7.65625000E-01	-5.63735030E+01	-1.44911250E+02	-5.08125000E+00
1.90000000E+00	-8.91562500E+00	5.31250000E-02	-1.11762690E-01	1.08750000E+00	-1.40495630E+02
-8.43750000E-02	-6.56250000E-02	-9.73437500E+00	-4.99002000E-02	0.00000000E+00	-2.21480580E+01
5.46116500E+00	4.24757280E+00	-4.40950920E-01	7.69552800E+00	-1.58505660E+02	-7.46805500E+01
1.11258780E+02	-6.63937500E+00	-3.21425000E+02	-1.86092250E+03	1.14105880E+04	-6.45480240E+03
1.60712500E+02	-4.97853000E+02	1.34662500E+02	4.29596880E+02	-1.80331750E+03	1.12236050E+04
-6.05029690E+03	-2.08591190E+02	-2.07438750E+02	2.84714998E+02	3.18781250E+02	9.12678890E+02
6.28912640E+02	3.80795450E+03	6.25405290E+03	-1.08395850E+03	3.02896710E+03	1.17879250E+04
2.85728640E+03	2.43807290E-01	-2.06752290E-01	-3.16653960E-01	4.28734760E-02	3.99000300E+00
6.51508930E+00	1.05912770E+01	-2.84917630E+01	7.52264180E+01	-8.21190070E+02	6.62415620E+01
1.18782140E+02	-2.00067090E+02	1.96290860E+03	-5.35028150E+03	-6.88360610E+01	-2.28652890E+02
3.66348980E+03	2.47940870E+04	-1.66153520E+04			
3.00100000E+01	1.69312500E+01	-7.61875000E-01	-5.66429640E+01	-1.45158750E+02	-4.95625000E+00
2.00000000E+00	-8.88125000E+00	5.00000000E-02	-1.28711880E-01	1.08937500E+00	-1.40580000E+02
-4.68750000E-02	-2.59375000E-01	-9.62187500E+00	-6.23752500E-02	-3.72023810E-02	-2.42718450E+01
5.46116500E+00	5.46116500E+00	-4.50536810E-01	3.07821120E+00	-1.61553840E+02	-7.92528290E+01
1.03638310E+02	-6.63750000E+00	-4.83682810E+02	-1.84265750E+03	1.12838720E+04	-6.32803430E+03
2.02435940E+02	-7.87114810E+02	1.43527500E+02	3.56967190E+02	-1.87497250E+03	1.14445840E+04
-6.36030260E+03	-1.64798560E+02	-1.24463250E+02	2.93490005E+02	3.18781250E+02	1.01029160E+03
5.82669060E+02	3.79467090E+03	6.33720680E+03	-1.21649480E+03	2.96705430E+03	1.16914820E+04
2.79676900E+03	2.52950070E-01	-2.00671340E-01	-3.10525170E-01	4.42345380E-02	4.00036420E+00
6.52269230E+00	1.16190730E+01	-3.04297530E+01	9.02731660E+01	-8.74167170E+02	6.75000000E+01
1.11014440E+02	-2.02460010E+02	1.68955930E+03	-5.50035380E+03	-6.88237600E+01	-2.63237600E+02
3.55414750E+03	2.47074180E+04	-1.61874730E+04			
3.00200000E+01	1.69391250E+01	-7.51250000E-01	-5.69348800E+01	-1.45400620E+02	-4.75000000E+00
2.15937500E+00	-8.95312500E+00	3.78125000E-02	-1.42156530E-01	1.08937500E+00	-1.40692500E+02
-6.25000000E-02	-2.15625000E-01	-9.68125000E+00	-4.36626750E-02	-2.48015870E-02	-2.33616500E+01
5.15776700E+00	6.06796120E+00	-4.55010220E-01	1.38519500E+01	-1.50885190E+02	-6.70600860E+01
1.09734690E+02	-6.64875000E+00	-5.77946870E+02	-1.78435000E+03	1.10288950E+04	-6.03416280E+03
2.36432810E+02	-9.55370690E+02	1.52505000E+02	1.40623440E+02	-1.94662750E+03	1.16222950E+04
-6.65763140E+03	-1.04871810E+02	-2.58146000E+02	3.02400000E+02	3.18812500E+02	1.23968150E+03
5.41049850E+02	3.80352660E+03	6.47725550E+03	-1.25909570E+03	2.88609140E+03	1.16607960E+04
2.72328350E+03	2.49902480E-01	-2.06752290E-01	-3.10525170E-01	4.35540070E-02	4.00632970E+00
6.52712730E+00	1.15296970E+01	-2.88233860E+01	1.02434840E+02	-8.23111590E+02	6.84139840E+01
1.17556880E+02	-1.89697280E+02	2.02047500E+03	-5.02676850E+03	-6.91811770E+01	-7.65065140E+01
3.43032590E+03	2.47542150E+04	-1.57880780E+04			

Figure 4.2.2 Data Collected from All Sensors at 30.00, 30.01, and 30.02 sec During the 150 ft CCW Constant Radius Maneuver for Series 5.

An example of the offset problem can be observed in Figure 4.2.3, which shows Speed vs. Time for the CW Constant Radius maneuver. The speed measurements for Series 4 do not start at 0 mph for time 0.00 sec, but at about 12 mph. This seems to indicate either a speed sensor calibration problem, or simply that data collection started after the vehicle was already moving. However, when readings from other sensors are considered, it is possible to have a better understanding of the source of the problem. Consider Figure 4.2.4 which shows the Trailer Rollover Angle as a function of time, for the same tests. For Series 4 at time 0.00 sec, the rollover angle is almost zero, which could indicate an offset problem with the speed sensor. This is because for this test (i.e., constant turn) even a small speed would generate a rollover angle with values different from zero. It is also possible that the roll sensor had a positive bias while at rest, which caused it to read 0 at low speeds (a more probable explanation, since the speed sensors are less likely to present calibration problems). For the same reasons (i.e., for test speeds close to zero, rollover angles different from zero cannot be generated), the Trailer Rollover Angle data for Series 2, 3, and 6 had an offset problem. On the other hand, Series 1 and 5 show examples of data collection starting after the vehicle was moving (e.g., both Speed and Trailer Roll Angle provide values different from zero at time 0.00), and therefore do not require any initial offset correction.

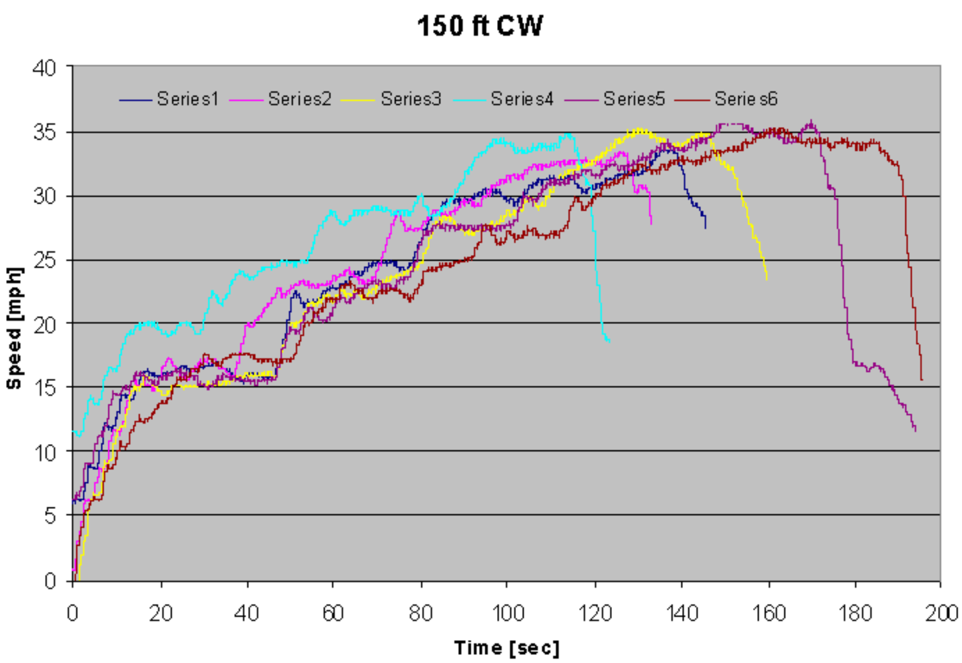


Figure 4.2.3 Speed (mph) vs. Time (sec) During the 150 ft CW Constant Radius Maneuver, by Series.

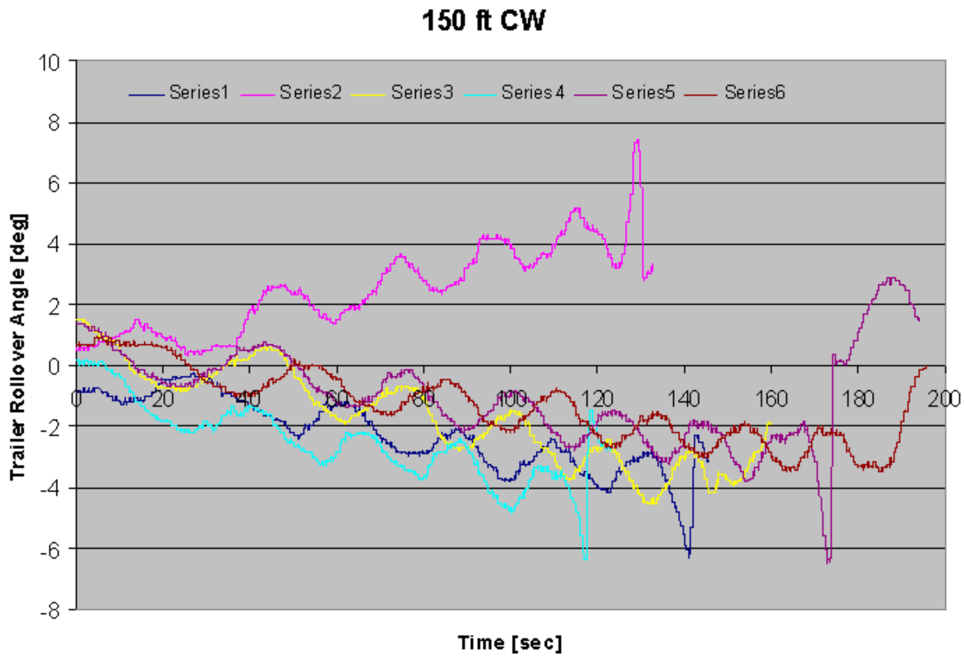


Figure 4.2.4 Trailer Rollover Angle (deg) vs. Time (sec) During the 150 ft CW Constant Radius Maneuver, by Series.

Figure 4.2.4 points to another type of data problem. Series 2 in Figure 4.2.4 shows positive values for the Trailer Rollover Angle, while all the other Series show negative angles (the correct sign for the CW turning maneuver). In this case, the problem was not a data collection issue, but a mislabeling of the data file. This problem was easily identified as a mislabeling issue by looking at other variables for Series 2 during this test, particularly the vertical force on the fifth axle; i.e., because of the position of the sensor (i.e., driver side wheel), the value should have decreased during the test. The mislabeling problem was only observed for this Series during this test (of course, the data file for the Series 2 150 ft CCW Constant Radius maneuver was also mislabeled).

There were other minor problems with the data, which were easily solved by looking at a graphical representation of the information. One example of such problems was encountered during the analysis of the data from the Evasive Maneuver in which the numerical analysis of the results showed a strange behavior of one of the Series (i.e., no wheel liftoff at speeds considerably higher than any other Series). A graphical representation of the data showed that this particular run involved an aborted test maneuver, and in consequence, it was eliminated from the data set for the analysis (see the analysis included in Section 5 of this report).

4.3 DATA PREPARATION FOR ANALYSES

A number of data preparation steps were engaged in prior to performing the data analyses for this study. The first step was to eliminate and correct the problems identified and described in the previous subsection. In many cases, it was also necessary to filter the data to smooth out variations and reduce noise. In other cases the analyses required fitting the data to first- or second-order curves to simplify the analysis.

Although a more detailed discussion of the data preparation for the different analytical methodologies used in this study is presented in the next Section, below is presented a summary of those tasks by test. Notice that the data collected in each test was analyzed by one or more of the partners participating in this study, although in almost all the cases the analyses were performed using different methodologies. In consequence, the data preparation tasks summarized below may not have been applied to all the analyses for that particular test.

Evasive Maneuver

- Out of 55 observations, 16 were eliminated from the analysis (15 because they did not produce wheel liftoff, and one because the data collection run was aborted).
- Lateral acceleration was measured by the Oxford box at the trailer CG and by Crossbow/Watson sensors at the tractor CG.
- Lateral acceleration and vertical load signals were processed through a 3.0 Hz, 2nd-order low-pass filter to eliminate higher frequency noise.
- Wheel lift-off of the right rear trailer axle wheel was determined by the vertical wheel force. The wheel was off the ground when there was no positive vertical load measured by the SWIFT 50T.
- The analysis required the computation of the intervals of time that elapsed between the moment the maximum lateral acceleration was registered and the instant at which liftoff and the maximum roll angle were observed.
- Roll stiffness [deg per g]; i.e., the ratio between the maximum roll angle and the maximum lateral acceleration, was calculated and used in the analysis.

Constant Radius Maneuver

- To evaluate the data, a low-pass filter was applied to reduce the noise in the raw data (the cut-off was 0.1 Hz, using functions built into Matlab).
- The lateral acceleration was modified with a 2nd-order curve fit to reduce small variations in the data.
- The roll moment data was converted to Newton-meters to allow for comparison to simulation data.
- The lateral forces for each series for both Axles 3 and 5 were taken from the wheel transducers and plotted against both time and lateral acceleration.
- The string pots that were on the axles were used to determine the absolute roll angle of Axle 5.
- The absolute roll angle for Axle 5 was calculated, filtered, and then fitted with a 1st-order curve against a set of lateral acceleration data that had been both filtered and fitted with a 2nd-order curve. The fits were adjusted to have an intercept of zero to facilitate visual comparison.
- The fifth wheel loads were calculated using algorithms provided by Dana.
- The absolute roll angle for axle 5 was determined using the recorded string pot data and the absolute trailer roll angle.

Swept Sine Maneuver

- The following frequency response functions (FRF's) were examined using the data that was collected:
    - Tractor yaw rate-to-steering wheel angle,
    - Tractor lateral acceleration-to-steering wheel angle,
    - Tractor roll rate-to-tractor lateral acceleration,
    - Trailer roll-to-trailer lateral acceleration,
    - Trailer yaw rate-to-steering wheel angle, and
    - Trailer lateral acceleration-to-steering wheel angle.
- Tractor lateral acceleration was not roll-corrected.
- The frequency range of interest for this maneuver - *from the tire perspective* - for heavy trucks is between approximately 0.2 Hz and 2.0 Hz.

4.4 COMPARISON OF TIRE FORCE FROM FLAT TRACK AND WHEEL FORCE TRANSDUCER MEASUREMENTS

Tire forces and moments are typically measure using a flat track and are used as inputs to perform vehicle handling simulations using codes such as ADAMS or TruckSim. However, very little is known about on vehicle tire forces and moments, especially during handling maneuver. The dynamic hub that was provided by the truck rollover characterization team, allowed for capturing actual tire force during vehicle maneuver.

This is an analysis of data received from the Michelin Proving Ground dynametric hub tests. The hub was installed on the right side of axle 3 of a Peterbilt 6x4 with semi trailer. The total vehicle load was 79,051 lbs. The test results were compared to simulation results by TruckSim based on tire forces and moments from flat track testing.

Four tests were run on a 400 ft constant radius skidpad. Each test represented a unique combination of steer and drive axle tires. The speed was ramped from 3 mph to 50 mph over a period of approximately five minutes. Each test was run in the clockwise and counterclockwise directions.

Typical lateral force results are given in Figure 4.4.1. The lateral force is plotted as a function of lateral acceleration for both test directions. The CCW forces are larger than the CW forces as the CCW data represents the outside wheel in the turn. The raw data are represented by the individual data points, and characterized by relatively little noise. The red curves represent polynomial fits to the raw data. Both CW and CCW data were corrected for zero offset in Figure 4.4.1.

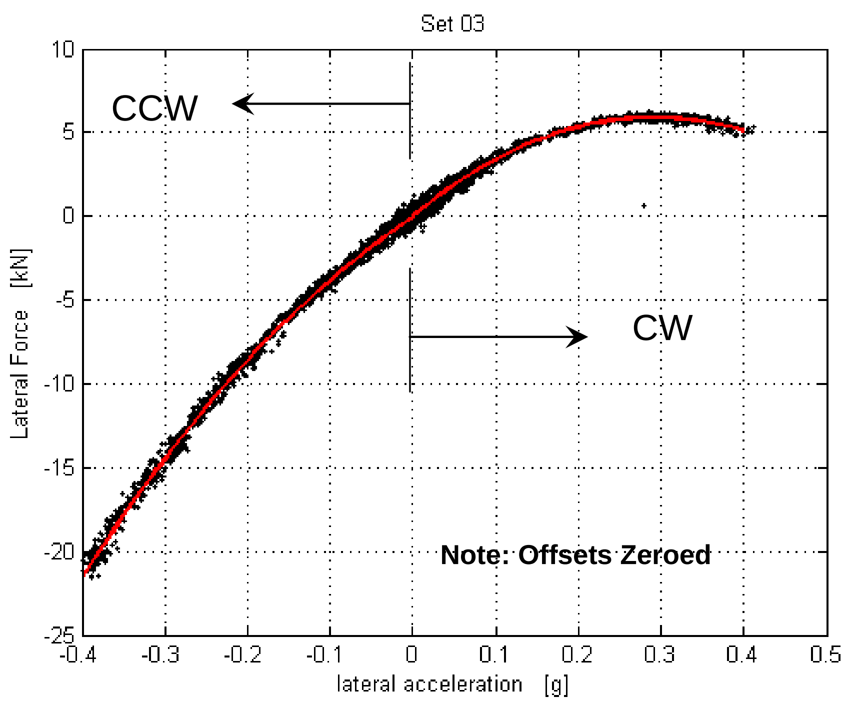


Figure 4.4.1

Lateral Force (kN) as a Function of Lateral Acceleration (g) for Both Test Directions.

In Figure 4.4.2(a), the CCW lateral force data from Figure 4.4.1 is transposed to represent an approximation to what the results would have been had the test been run in the CW direction and there were dynametric hubs at both the left and right wheel positions. This was done in order to compare directly with data obtained from a simulation that shows the left and right wheel positions.

The simulation results for lateral force are shown in shown in Figure 2(b). It is noted that the simulation was run over an 80 sec period from 5 mph to 50 mph.

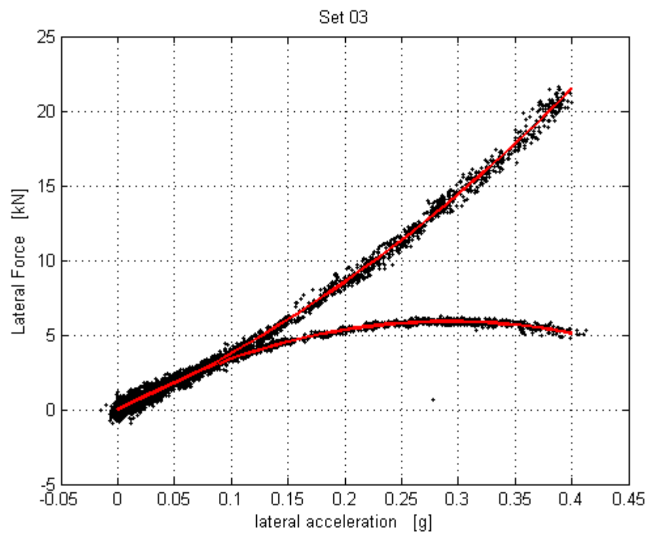


Figure 4.4.2(a) Transposed CCW Lateral Force Data

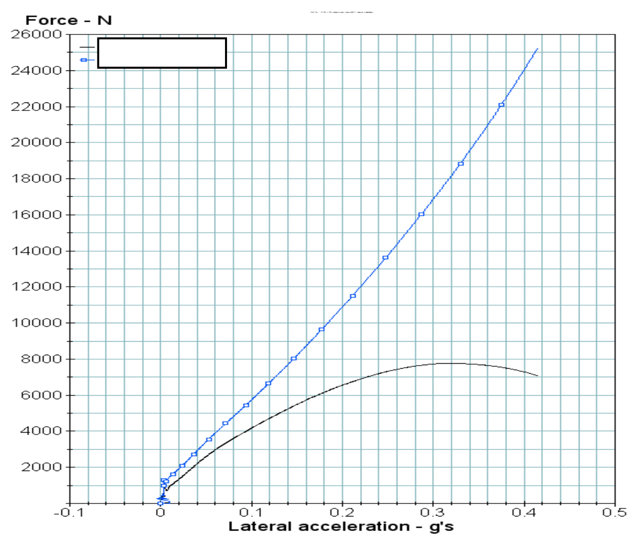


Figure 4.4.2(b) Simulation Results for the Lateral Force

Measured lateral force data, evaluated at ± 0.3g for the four tire sets, are shown in Table 4.4.1. The results show reasonably consistent values with the exception of Set 01 CW.

Table 4.4.1 Lateral Force @ ±0.3g

Set	Fy_CCW @ (-) 0.3g	Fy_CW @ 0.3g
01	-14.7	8.93
02	-13.9	5.98
03	-14.4	5.89
04	-14.5	5.6

An example of measured vertical wheel force data is shown in Figure 4.4.3 for both CW and CCW directions. Again, dispersion of data is very small. Offsets at zero-g were averaged in this example. Typically, the difference in offsets ranged from approximately 1.0 to 3.0 kN

The gradient of vertical load to lateral acceleration at zero-g was calculated for all four tire sets with the results presented in Table 4.4.2. Results were relatively consistent with the exception of Set 01 counterclockwise.

Table 4.4.2 Wheel Force Gradients @ zero-g

Set	CCW [kN/g]	CW [kN/g]
01	-54.7	-60.2
02	-62.4	-64.2
03	-61.8	-60.6
04	-60.3	-60.9

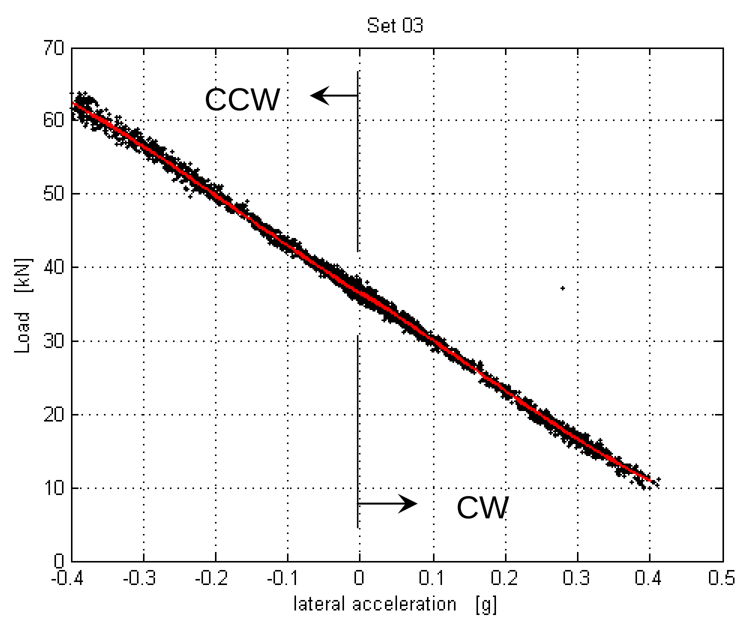


Figure 4.4.3 Measured Vertical Wheel Force Data for Both CW and CCW Directions.

In summary, the data appeared to be stable and relatively noise free. The results showed the modeled lateral force to be typically higher than that which were measured. Recommended additional tests should include testing for repeatability (between dismounting and mounting hub). Also, the frequency response of this transducer should be obtained from the manufacturer in order to determine suitability for other types of tests.

5. DATA ANALYSES

5.1 ORNL ANALYSIS OF EVASIVE MANEUVER AND CONSTANT RADIUS MANEUVER

This part of the report was prepared by Oscar Franzese and Bill Knee of the Oak Ridge National Laboratory.

5.1.1 Evasive Maneuver

5.1.1.1 Description

The purpose of this test was to evaluate a vehicle's roll characteristics and overall transient response when subjected to a sudden lane change. The set up for the evasive maneuver consisted of two gates delimited by four pylons on a level asphalt area of sufficient size to accommodate safe entry and exit of the course for the size and weight vehicle being tested. Gate 2 was located 100 ft downstream of gate 1, and 12 ft to the left (i.e., gate 1 mimicked a rightmost lane on a three-lane freeway, with gate 2 representing the leftmost lane). The test consisted of negotiating a left-hand lane change by entering gate 1 at constant speed, making an abrupt steer upon exiting gate 1, gaining position for straight entry to gate 2, and maintaining the initial speed until exiting gate 2. The test, in general, started at 41 mph and the speed was increased by 2 mph until the rollover threshold was observed. Once the rollover threshold speed was determined, the test was repeated three times.

5.1.1.2 Results

Table 5.1.1 presents a summary of the evasive maneuver tests. Fifty-five tests at different speeds were conducted for this maneuver, for all the six series. For each series (column) in Table 5.1.1, an entry in a given row (speed at which the test was conducted) indicates the test date, time, and run number in parenthesis. Empty cells in the table indicate that there were no evasive maneuver tests conducted for that series at that speed, while cells highlighted in gray indicate tests that did not show a liftoff of the trailer[3]. For example, for Series 2 (i.e., tractor with single tires and trailer with dual tires), evasive maneuver tests were conducted at 43, 45, 47, 49, 51, and 53 mph; all of them on September 29th, 2004 between 6:16 PM and 6:27 PM. For that series, tests at 43 and 45 mph did not produce a liftoff of the trailer. The first test that produced a liftoff (determined with instrumentation) occurred at 47 mph; however, the test was not stopped at that point because at the testing site liftoff was determined visually (i.e., wheel liftoff was first visible at 53 mph, at which point the test was repeated twice to confirm the observation).

[3] Wheel liftoff was determined by checking whether the vertical-force transducer mounted on the trailer's rear axle showed a null or negative force (i.e., value of variable mts5vert<=0 in the test data set).

Table 5.1.1 Summary of Evasive Maneuver Tests by Series and Speed.

	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6	Number of Tests
37 mph			09-24 11:08 (8)				1
39 mph			09-24 11:10 (9)				1
41 mph			09-24 11:12 (10)	09-30 12:44 (13)	10-21 15:49 (9)	10-14 14:55 (8)	4
43 mph	09-28 14:48 (8)	09-29 18:16 (8)	09-24 11:13 (11)	09-30 12:45 (14)	10-21 15:51 (10)	10-14 14:57 (9)	6
45 mph		09-29 18:17 (9)	09-24 11:15 (12) 09-27 15:12 (8)	09-30 12:47 (15)	10-21 15:52 (11)	10-14 15:01 (10)	6
47 mph		09-29 18:19 (10)	09-24 11:17 (13)	09-30 12:48 (16)	10-21 15:53 (12)	10-14 15:03 (11)	5
48 mph	09-28 14:50 (9)						1
49 mph	09-28 14:51 (10) 09-28 14:53 (11) 09-28 14:54 (12) 09-28 15:03 (15) 09-28 15:05 (16)	09-29 18:20 (11)	09-27 15:14 (9)	09-30 12:49 (17) 09-30 12:51 (18) 09-30 12:52 (19)	10-21 15:55 (13) 10-21 16:29 (14)	10-14 15:04 (12)	13
51 mph	09-28 14:56 (13)	09-29 18:22 (12)	09-27 15:18 (10) 09-27 15:20 (11) 09-27 15:23 (12) 09-27 15:25 (13)		10-21 16:30 (15)	10-14 15:06 (13)	8
53 mph		09-29 18:23 (13) 09-29 18:25 (14) 09-29 18:27 (15)			10-21 16:32 (16) 10-21 16:33 (17) 10-21 16:34 (18)	10-14 17:18 (14) 10-14 17:19 (15)	8
55 mph					10-21 16:36 (19)	10-14 17:21 (16)	2
Number of Tests	8	8	12	7	11	9	55

Table 5.1.1 indicates that the first tests in the sequence corresponded to Series 3 (i.e., tractor and trailer with single tires). Probably because of the driver's lack of practice with the maneuver and perhaps due to his unfamiliarity with the tire handling for this series, these tests were also the ones with the overall minimum speed of the evasive maneuver (i.e., 37 and 39 mph). Subsequently, and for the other five series, the tests always started at a minimum of 41 mph for settings with single tires for the trailer and at 43 mph for those with dual tires. Notice that Series 2 to 6 achieved trailer liftoff at maneuver speeds that were lower than that of Series 1 (dual tires on both the tractor and the trailer). This was particularly noticeable for Series 5, which has single tires on both the tractor and the trailer, combined with a wider-slider suspension for the latter. In this case, an evasive maneuver taken at 43 mph reflects a liftoff of the trailer.

On the other hand, Table 5.1.1 shows that test run 13 for Series 5 did not produce a liftoff of the trailer. Moreover, this run is the one with the highest maneuver speed in the entire sequence for which no liftoff of the trailer was observed. This fact warranted a closer look at the data. Figure 5.1.1 shows the value of variable mts5vert (i.e., vertical force on the fifth axle) as a function of time for runs 13 and 14 of Series 5; both at 49 mph. Notice that while run 14 shows the typical, and expected, evolution of the vertical force as the maneuver progresses (i.e., truck turning to the left and then to the right, with vertical forces on the fifth axle on the driver side increasing and then decreasing), the diagram for run 13 does not. This indicates that run 13 was a failed run, in which the maneuver was not completed as specified (e.g., the driver may have aborted the maneuver because the first gate in the maneuver may have been missed) and therefore this run was eliminated from the data set.

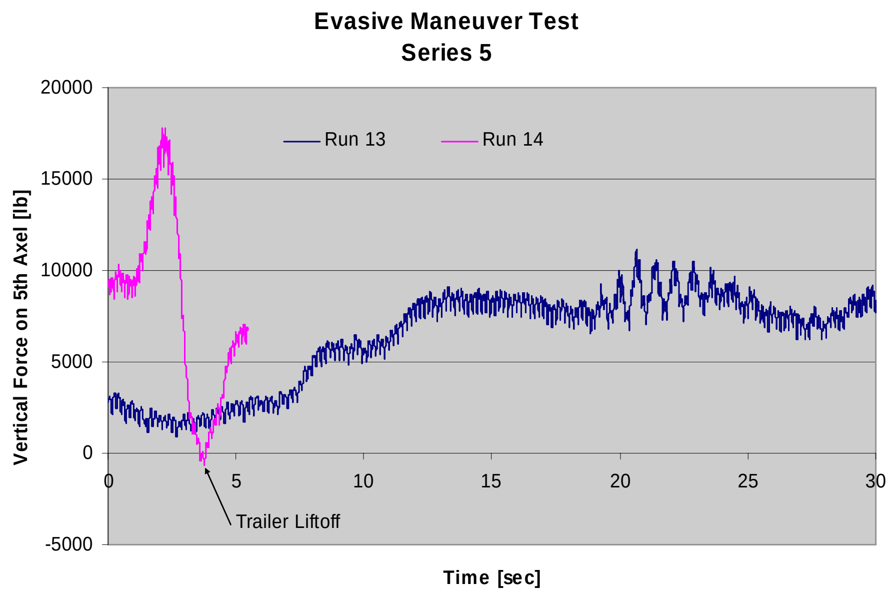


Figure 5.1.1 Series 5 Evasive Maneuver Test (Runs 13 and 14).

This leaves Series 1 (dual tires on the tractor and trailer, the most typical truck tire layout used on highways in the US) as the one with the highest evasive maneuver speed (i.e., 48 mph) for which no trailer liftoff was observed. To certify that this was the case, the data collected for Series 1 run 9 was closely analyzed. Figure 5.1.2 represents the value of variable mts5vert as a function of time for run 9 of Series 1. As opposed to Series 5 run 13, Series 1 run 9 shows the typical shape of the vertical force diagram as the maneuver progresses, with mts5vert getting very close to 0 (i.e., 176.17 lb) but never becoming negative or zero during the maneuver. All of the other runs that were identified as “non-liftoff runs” were also checked in the same way as Series 5 runs 13 and 14, and Series 1 run 9; none of them were discarded from the dataset. Table 5.1.2 presents the minimum value of the vertical force on the fifth axle for these runs.

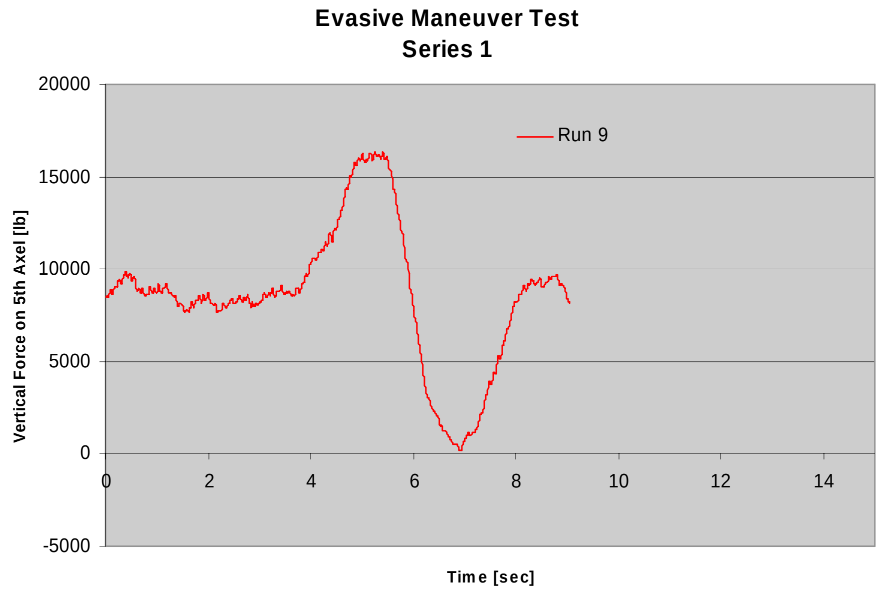


Figure 5.1.2 Series 1 Evasive Maneuver Test (Run 9).

Table 5.1.2 Fifth Axle Minimum Vertical Force (lbf), by Series and Speed for the Evasive Maneuver Test.

	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6	Number of Tests
37 mph			4,007.00				1
39 mph			3,044.27				1
41 mph			2,334.97	1,336.70	2,297.88	2,597.67	4
43 mph	2,640.94	2,688.84	1,523.68	959.64	-44.81	710.84	6
45 mph		1,503.59	384.78 84.99	-290.52	-706.21	262.70	6
47 mph		-349.24	-460.50	-466.68	-486.77	-364.69	5
48 mph	176.17						1
49 mph	-564.04 -655.21 -412.60 -602.67 -199.35	-593.40	-452.78	-475.96 -526.95 -465.14	N/A -633.58	-548.59	13
51 mph	-718.57	-764.93	-506.86 -509.95 -474.41 -449.69		-764.93	-557.86	8
53 mph		-752.57 -695.39 -635.12			-840.65 -747.93 -814.38	-420.33 -800.47	8
55 mph					-870.01	-295.15	2
Number of Tests	8	8	12	7	11	9	55

In order to study the stability of each of the six configurations, it is necessary to identify the maximum roll angle registered in each test and the lateral acceleration that caused that angle. Because of inertia and the fact that the system (i.e., trailer) was not absolutely rigid, there is a time difference between the instant at which the maximum lateral acceleration is observed and the moment at which the maximum (in absolute value) roll angle is registered. This time lag is illustrated in Figure 5.1.3. During the first second of the test, the tractor-trailer moved in a straight line (i.e., constant lateral acceleration, constant vertical force, and insignificant roll angle). At about 1.0 sec, the driver started to turn the vehicle to the left and then began to turn to the right at about 2.0 sec. At 3.27 sec the maximum lateral acceleration of this run was registered (the driver gave a sudden jolt to the steering wheel to make corrections to the truck path and guide it through the second gate of this maneuver)[4]. This sudden jolt produced a liftoff of the fifth axle at 3.60 sec and also resulted in the maximum (in absolute value) observed roll angle for this test at 3.65 sec (i.e., 0.38 sec after the maximum lateral acceleration was observed).

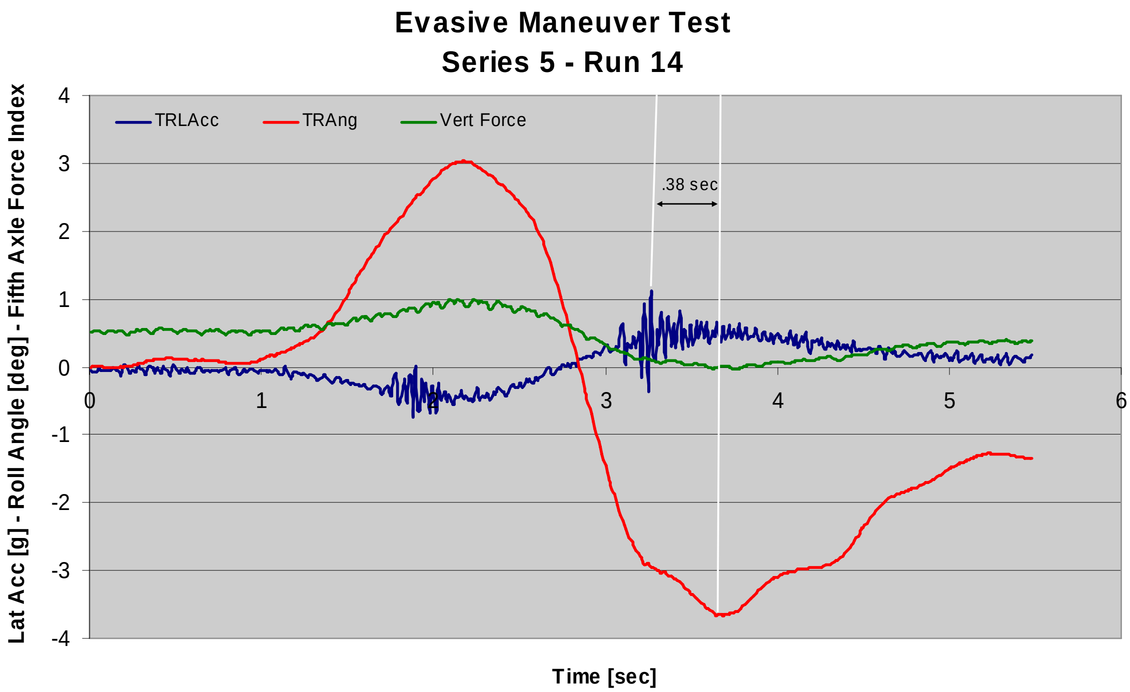


Figure 5.1.3 Trailer Lateral Acceleration (g), Roll Angle (deg), and Fifth Axle Vertical Force Index (=Vertical Force/Max Vertical Force) vs. Time (sec) for Series 5 Evasive Maneuver Test (Run 14).

Table 5.1.3 presents the maximum roll angle and the maximum lateral acceleration for each test run that resulted in a liftoff situation; while Table 5.1.4 shows the times at which the maximum lateral acceleration, liftoff, and maximum roll angle occurred. Notice that in all cases, the sequence of observed events was maximum acceleration, liftoff, and maximum roll angle.

Table 5.1.3 suggests that there is no correlation between the size of the maximum lateral acceleration observed and the resulting maximum roll angle; since similar maximum lateral accelerations resulted in very different maximum roll angles. Consider, for example, Series 5 runs 14 (49 mph) and 19 (55 mph) which registered maximum lateral accelerations of 1.091g and 1.039g, respectively. Although these values were very similar, the resulting maximum roll angles were considerably different with respective values of -3.66 deg and -8.46 deg for runs 14 and 19. The main reason for this difference appears to be related to the way the maneuver was performed in each run (i.e.; truck driver related). In Figure 5.1.3 (run 14), the maneuver clearly has two turns; one to the left and one to the right, which can be identified by following the evolution of the lateral acceleration during the test (i.e., null, negative, and positive). On the other hand, for Series 5 run 19 (see Figure 5.1.4), the maneuver required an extra turn (i.e., left turn, right turn, and left turn again, which corresponded to a negative, positive, and negative again lateral acceleration) because the truck driver overshot the path to the

[4] This analysis uses raw, unfiltered, Trailer Lateral acceleration data. The application of a 1.0-2.0 Hz low-pass filter aimed at eliminating the high frequency vibrations of the data, may reduce the lag effect somewhat.

second gate and needed to correct the truck's course[5]. As a consequence, the positive lateral acceleration was applied during a longer interval of time than in the case of run 14, which resulted in a larger maximum roll angle.

Table 5.1.3 Max Trailer Rollover Angle (deg) and Max Lateral Acceleration (g), by Series and Speed for the Evasive Maneuver Test.

	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6	Number of Tests
37 mph			N/A				1
39 mph			N/A				1
41 mph			N/A	N/A	N/A	N/A	4
43 mph	N/A	N/A	N/A	N/A	-3.42/0.996	N/A	6
45 mph		N/A	N/A N/A	-3.96/1.061	-3.60/0.983	N/A	6
47 mph		-3.85/1.17	-3.17/0.727	-4.20/0.829	-3.45/0.989	-3.66/1.149	5
48 mph	N/A						1
49 mph	-3.62/0.707 -6.51/0.663 -3.31/0.718 -3.65/0.587 -3.41/0.825	-3.87/1.102	-3.58/1.113	-7.22/0.927 -7.15/0.889 -8.12/1.011	N/A -3.66/1.091	-4.76/1.109	13
51 mph	-3.54/0.667	-4.65/0.891	-5.20/1.409 -5.20/1.107 -6.21/0.803 -3.79/1.079		-3.53/0.925	-5.66/1.225	8
53 mph		-7.10/0.765 -7.95/1.029 -5.23/0.960			-6.71/0.980 -6.68/0.894 -4.79/0.939	-3.29/1.170 -4.01/1.566	8
55 mph					-8.46/1.039	-3.34/1.358	2
No. of Tests	8	8	12	7	11	9	55

Table 5.1.4 Time (sec) at Max Lateral Acceleration (g), Liftoff, and Max Trailer Rollover Angle (deg), by Series and Speed for the Evasive Maneuver Test.

	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6	No. of Tests
37 mph			N/A				1
39 mph			N/A				1
41 mph			N/A	N/A	N/A	N/A	4
43 mph	N/A	N/A	N/A	N/A	3.64/4.20/4.20	N/A	6
45 mph		N/A	N/A N/A	4.23/4.87/4.95	3.63/3.92/4.07	N/A	6
47 mph		4.08/4.60/4.69	8.01/8.58/8.77	3.86/4.30/4.76	3.75/4.14/4.33	4.69/4.84/4.86	5
48 mph	N/A						1
49 mph	6.04/6.65/7.00 6.04/6.64/7.56 6.28/6.92/7.24 5.68/6.07/6.52 5.71/6.06/6.47	3.96/4.42/4.70	8.24/8.52/8.87	3.91/4.38/5.27 3.88/4.34/5.21 4.00/4.33/5.45	N/A 3.27/3.60/3.65	4.62/4.87/5.63	13

[5] In future studies, other variables such as steering wheel angle should be included in the analysis to have a better understanding of driver behavior and response during an evasive maneuver.

51 mph	5.28/5.45/6.03	3.67/3.96/4.60	7.83/8.50/9.15 7.75/8.25/9.04 7.72/8.36/9.06 7.76/8.32/8.86		4.30/4.79/4.90	5.18/5.34/6.19	8
53 mph		3.27/3.55/4.34 3.59/3.93/4.78 3.50/3.85/4.50			3.77/3.96/4.83 3.65/3.92/4.84 4.07/4.18/4.86	4.18/4.40/4.53 5.07/5.36/5.96	8
55 mph					3.32/3.58/4.47	4.88/5.05/5.10	2
No. of Tests	8	8	12	7	11	9	55

The same pattern can be observed in other cases, such as for example Series 2 run 11 and 14, which presented similar maximum lateral accelerations (i.e., 1.102 g and 1.029 g, respectively) but resulted in very different maximum roll angles (i.e., -3.87 deg and -7.95 deg, respectively). The maneuvers for runs 11 and 14 of Series 2 presented the same pattern as those of Series 5 runs 14 and 19. That is, while run 11 showed a lateral acceleration that went from zero to positive to negative (see Figure 5.1.5a), for run 14 (see Figure 5.1.5b), the lateral acceleration had 4 identifiable sections —i.e., null, negative, positive, and negative. Again, the extra time during which the positive lateral acceleration was applied by the driver resulted in a larger roll angle for run 14.

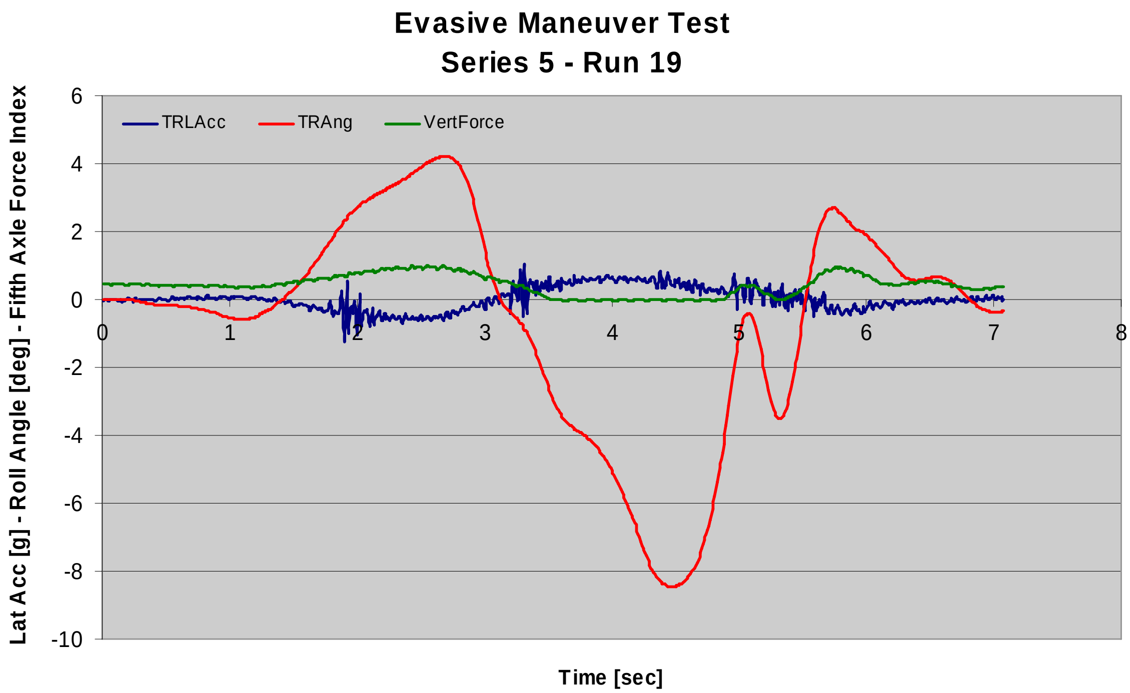


Figure 5.1.4 Trailer Lateral Acceleration (g), Roll Angle (deg), and Fifth Axle Vertical Force Index vs. Time (sec) for Series 5 Evasive Maneuver Test (Run 19).

Table 5.1.5 shows the intervals of time that elapsed between the moment the maximum lateral acceleration was registered, and the instant at which liftoff (***dTL***) and the maximum roll angle (***dTRA***) were observed. Whenever ***dTRA*** (which approximately measures half of the length of time during which a positive lateral acceleration, i.e. left turn, was applied by the driver) was larger than 1.0 sec, the maximum roll angle was considerably larger than the roll angle observed when the same maximum lateral acceleration but for a ***dTRA*** that was smaller than 1.0 sec. In other words, ***dTRA*** measures the quality of the maneuver: measurements larger than 1.0 sec indicate evasive maneuvers that required an extra correcting turn to pass through the second gate, while measurements of less than 1.0 sec indicate evasive maneuvers that were accomplished as planned (i.e., two turns). The variable ***dTRA*** was used to separate the test runs that resulted in liftoff situations into two categories (i.e., correctly and incorrectly performed evasive maneuver) and allowed the comparison of only the results of those tests in which the evasive maneuver was accomplished as planned; thus minimizing the human factor variable as much as possible.

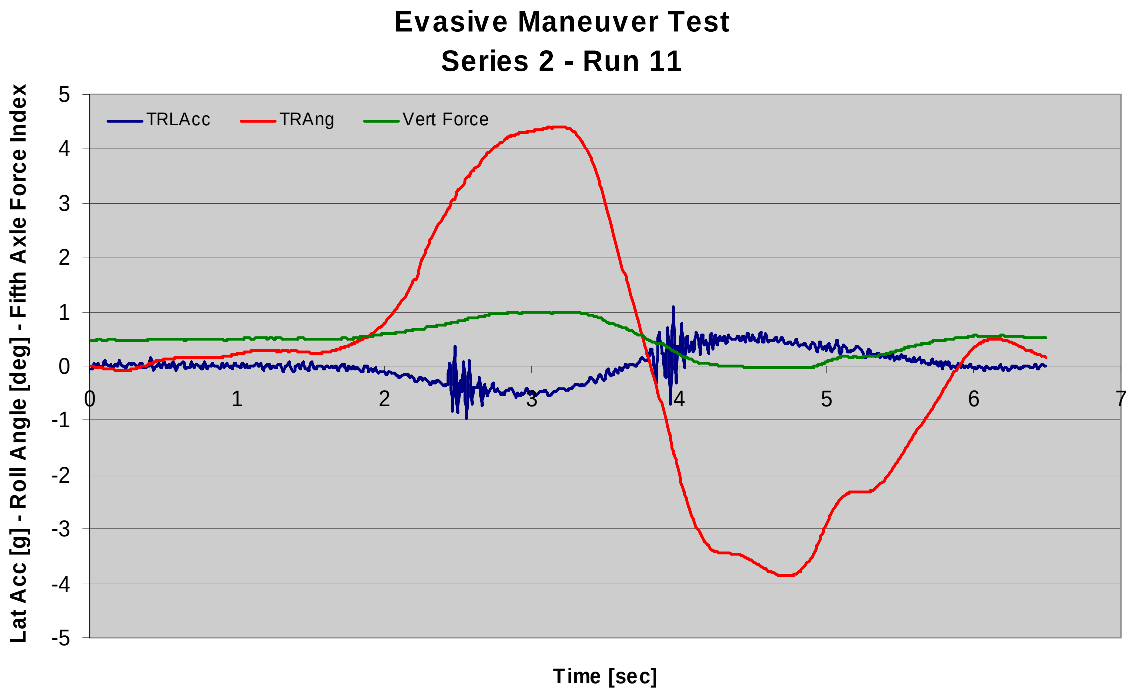


Figure 5.1.5a Trailer Lateral Acceleration (g), Roll Angle (deg), and Fifth Axle Vertical Force Index vs. Time (sec) for Series 2 Evasive Maneuver Test (Run 11).

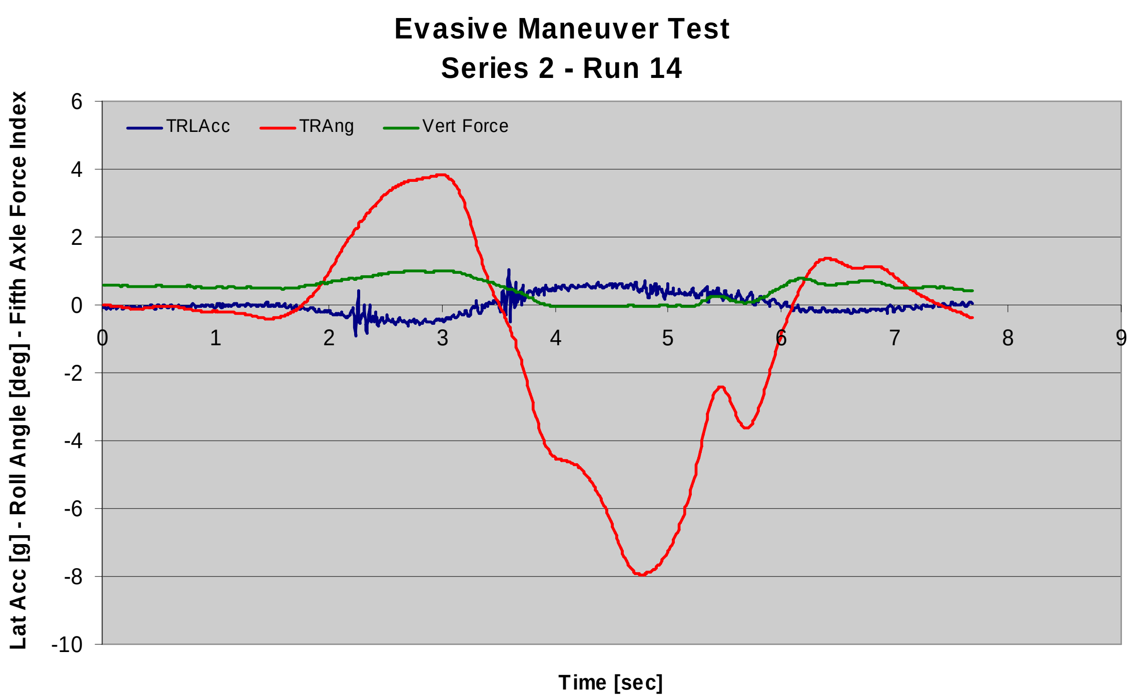


Figure 5.1.5b Trailer Lateral Acceleration (g), Roll Angle (deg), and Fifth Axle Vertical Force Index vs. Time (sec) for Series 2 Evasive Maneuver Test (Run 14).

Table 5.1.5 Delta Time (sec) between Max Lateral Acceleration (g) and Liftoff (*dTL*), and Max Lateral Acceleration (g) and Max Trailer Rollover Angle (deg) (*dTRA*), by Series and Speed for the Evasive Maneuver Test.

	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6	No. of Tests
37 mph			N/A				1
39 mph			N/A				1
41 mph			N/A	N/A	N/A	N/A	4
43 mph	N/A	N/A	N/A	N/A	0.56/0.56	N/A	6
45 mph		N/A	N/A N/A	0.64/0.72	0.29/0.44	N/A	6
47 mph		0.52/0.61	0.57/0.76	0.44/0.90	0.39/0.58	0.15/0.17	5
48 mph	N/A						1
49 mph	0.61/0.96 0.60/1.52 0.64/0.96 0.39/0.16 0.35/0.76	0.46/0.74	0.28/0.63	0.47/1.36 0.46/1.33 0.33/1.45	N/A 0.33/0.38	0.25/1.01	13
51 mph	0.17/0.75	0.29/0.93	0.67/1.32 0.50/1.29 0.64/1.34 0.56/1.10		0.49/0.60	0.16/1.01	8
53 mph		0.28/1.07 0.34/1.19 0.35/1.00			0.19/1.06 0.27/1.19 0.11/0.79	0.22/0.35 0.29/0.89	8
55 mph					0.26/1.15	0.17/0.22	2
No. of Tests	8	8	12	7	11	9	55

To compare the results of these tests, and after eliminating those with ***dTRA*** greater than or equal to 1.0 sec (runs highlighted in yellow in Table 5.1.5), the variable ***RS*** (roll stiffness) was generated by computing the ratio between the maximum roll angle and the maximum lateral acceleration. RS is a measure of the stability of each Series during the evasive maneuver (degrees per g). After computing ***RS*** for each run, the average RS for the Series was computed and compared against Series 1 (i.e., the most common configuration). The results, shown in Table 5.1.6 indicate that all of the five new configurations (i.e., Series 2 to 6) perform better than a configuration with dual tires for both the tractor and the trailer (Series 1). It should be noted, however, that because of the limited number of observations, these figures cannot be statistically tested. Nevertheless, Series 2 to 6 show improvements on the ***RS*** index (when compared to Series 1) that ranged between 13% (Series 4, single tires on trailer, dual tires on tractor) and 45% (Series 6, single tires on trailer, dual tires on tractor, and using a wider-slider for the trailer).

Table 5.1.6 Ratio Between Max Trailer Rollover Angle (deg) and Max Lateral Acceleration (g) (*RS*), for runs with *dTRA* less than 1.0 sec, by Series for the Evasive Maneuver Test.

Series	RS [deg/g]		Percent Difference
	Mean	Std Dev	
1	-5.073	0.783	---
2	-4.008	1.058	21.01
3	-3.791	0.807	25.28
4	-4.399	0.940	13.28
5	-3.809	0.658	24.93
6	-2.755	0.323	45.70

Variable ***dTRA*** also quantifies the relative roll stiffness by providing a measure of the speed at which the forces are transmitted from the CG of the trailer (lateral acceleration sensor) to its wheels (vertical force). A smaller ***dTRA*** indicates a faster (more rigid) transmission of forces. Table 5.1.7 shows the average ***dTRA*** (as well as the standard deviation) for all the series, for the evasive maneuver test which resulted in liftoff situations and which were not eliminated from the data set as described earlier. Again, due to the limited number of observations, no statistical test can be performed; however, the results seem to indicate that Series 6 and 5 (in that order) presented the most rigid configurations.

Table 5.1.7 Time Lag (dTRA) Between Max Roll Angle and Max Lat Acceleration by Series for the Evasive Maneuver Test.

Series	dTRA [sec]	
	Mean	Std Dev
1	0.854	0.103
2	0.760	0.161
3	0.695	0.092
4	0.810	0.127
5	0.558	0.143
6	0.408	0.331

5.1.2 Constant Radius Maneuver

5.1.2.1 Description

This battery of tests was conducted to determine the maximum lateral acceleration that can be achieved by a vehicle under steady state cornering conditions. The test consisted of negotiating a circular path (of 150 and 400 ft radius) until the maximum achievable steady state speed was attained. After that speed was achieved, then at least one more lap was completed. The test was suspended when the maximum lateral acceleration or the rollover threshold was achieved. Tests were conducted for both CW and CCW turns.

5.1.2.2 Results

Four different tests were conducted for this maneuver: two (CW and CCW) at a radius of 150 ft and two at a radius of 400 ft. For the purpose of this analysis, only those cases were considered in which liftoff conditions were reached. This occurred only with those tests where the constant radius was 150 ft (the 400 ft radius was too large to induce lateral accelerations that could result in a liftoff situation). Also, since the fifth axle vertical force sensor was located on the driver side, it was only possible to determine liftoff situations with the instruments (as opposed to visually) for the CW turning maneuvers. Therefore, the results of the tests analyzed here correspond only to the 150 ft constant radius CW turning maneuver.

The analysis proceeded in much the same way as for the evasive maneuver tests discussed above. That is, for each one of the six runs (one for each series) the maximum roll angle was determined once liftoff had been observed, and subsequently the maximum lateral acceleration that caused it was found. Consider, for example, Figure 5.1.6, which shows the lateral acceleration, roll angle, and fifth axle vertical force as a function of time for Series 1. Specifically, the figure shows the last 8.5 sec of the test, and that at approximately 135.7 sec, the first liftoff condition occurred and lasted until approximately 141.8 sec, at which time the driver exited the loop. An analysis of the data shows that the maximum lateral acceleration (0.564 g) occurred at 135.37 sec and the maximum roll angle (-5.47 deg) at 141.07 sec.

Similar conditions as those presented in Figure 5.1.6 were observed for the other Series (see Figures 5.1.7a to 5.1.7f). Figure 5.1.7a shows a representation of the three variables presented above. Notice, however, that the diagrams are "inverse-like" images of those of the other Figures. Specifically, notice that the vertical force looks to be increasing instead of decreasing as it should be, given the geometric conditions of the test (i.e., CW turn and vertical force sensor on the driver-side wheel). The problem was a mislabeling of the test results (i.e., for Series 2, the 150 ft CW data was labeled 150 ft CCW, and vice-versa). Figure 5.1.7b shows the correct data for Series 2, 150 ft CW turn.

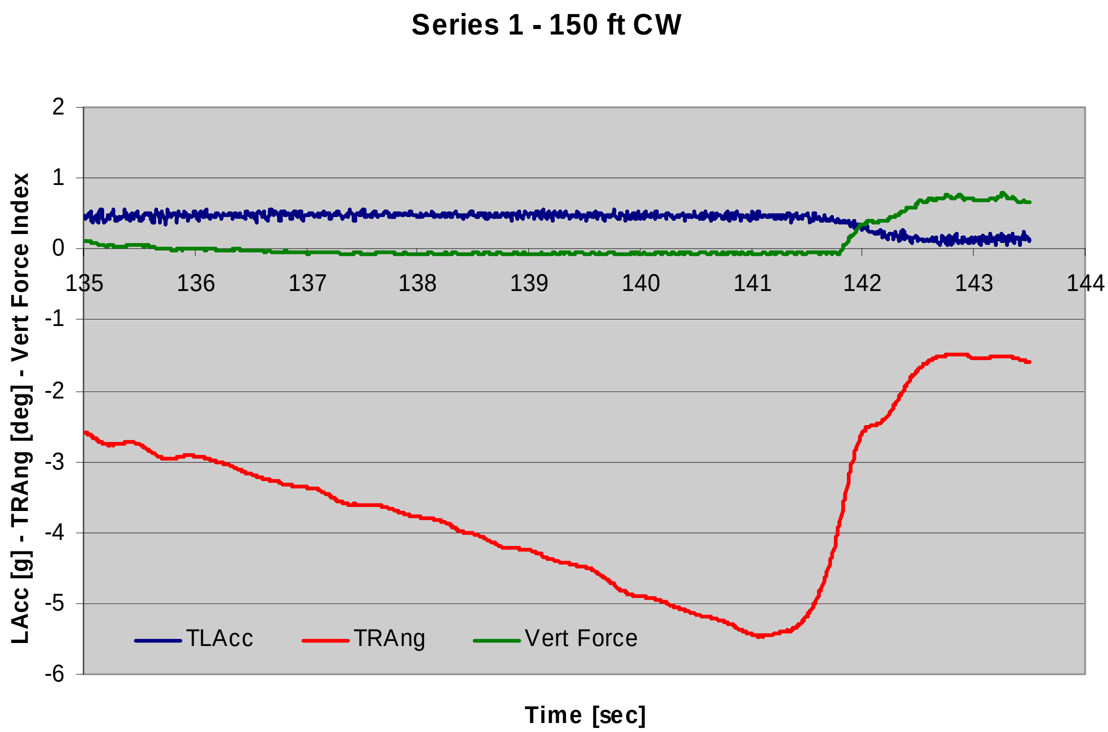


Figure 5.1.6 Trailer Lateral Acceleration (g), Roll Angle (deg), and Fifth Axle Vertical Force Index vs. Time (sec) for Series 2, Constant Radius Maneuver Test.

A summary of the information shown on the graphs is presented in Table 5.1.8. The table also includes the roll angle measured 1.0 sec after the maximum lateral acceleration before liftoff was observed (column 5). That is, to compute the variable ***RS*** (roll stiffness) as was done previously, a determination was made of the maximum lateral acceleration and the time of its occurrence (***tMLAbL***) before liftoff was first observed. As was discussed earlier, the roll angle that resulted from that lateral acceleration did not occur at the same time, but had a time lag. It was assumed that the time lag had a duration of 1.0 sec, which is a relatively conservative estimate (see Table 5.1.7). Therefore, at time ***tMLAbL + 1* sec** the roll angle (column 4) that was later used to compute variable ***RS*** was determined**.** The results of these computations are shown in Table 5.1.9.

Table 5.1.8 Summary of Parameters by Series for the 150 ft Radius CW Maneuver Tests.

Series	Max Lat Acc (g) before 1st Liftoff		Roll Angle (deg) 1.0 sec after Max Lat Acc		Roll Angle (deg) at Liftoff		Max Lateral Acceleration (g)		Max Roll Angle (deg)	
	Time	Value	Time	Value	Time	Value	Time	Value	Time	Value
1	135.37	0.564	136.37	-3.936	135.77	-2.963	135.37	0.564	141.07	-5.468
2	141.36	0.615	142.36	-3.218	141.73	-3.606	143.34	0.640	149.92	-7.928
3	125.64	0.634	126.64	-3.546	126.77	-5.094	145.59	0.642	131.57	-6.028
4	97.42	0.615	98.42	-4.669	98.29	-4.794	109.73	0.660	117.09	-6.474
5	168.55	0.573	169.55	-2.747	169.25	-3.924	171.81	0.632	172.97	-7.888
6	155.10	0.720	156.10	-2.093	156.65	-2.948	162.76	0.808	163.69	-4.262

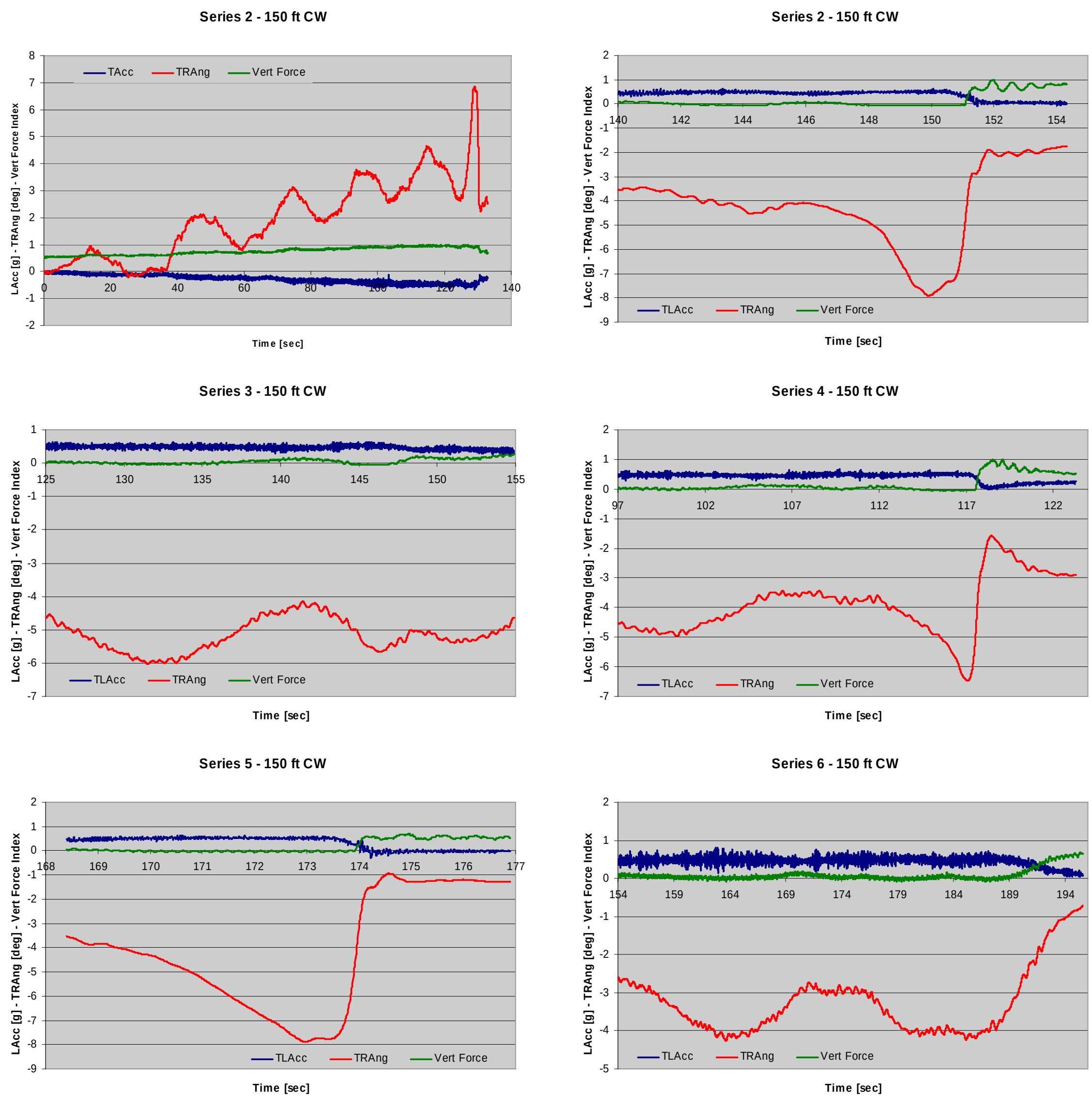


Figure 5.1.7a to 5.1.7f Trailer Lateral Acceleration (g), Roll Angle (deg), and Fifth Axle Vertical Force Index vs. Time (sec) for Series 2 to 6, Constant Radius Maneuver Test.

Similarly to the Evasive Maneuver Test, the 150 ft Radius CW Turn Test showed that Series 6 and 5 performed the best when compared to the basic case (Series 1), followed by Series 2 and 3. Series 4, on the other hand, appears to be worse than Series 1. Again, since there was only one observation per series for this test, the results could not be statistically analyzed..

Table 5.1.9 Ratio between Trailer Roll Angle (deg) and Max Lateral Acceleration (g) before Liftoff (*RS*), by Series for the 150 ft Radius CW Maneuver Test.

Series	RS [deg/g]	Percent Difference
1	-6.981	---
2	-5.229	25.09
3	-5.591	19.91
4	-7.588	-8.70
5	-4.792	31.35
6	-2.908	58.34

5.1.3 Conclusions and Future Research

Although the lack of data did not allow for the performance of statistical tests over the data collected, the results of both tests analyzed seem to indicate that the studied wheel/tire layouts (Series 2 to 6) consistently performed better (except for one case, i.e., Series 4, constant radius test) than the standard layout (Series 1, both tractor and trailer with dual tires). The results also indicate that Series 6 and 5 were the best performers of all of the six series analyzed. Both Series 5 and 6, which used a wider-slider for the trailer, improved stability and increased the effective stiffness of the trailer.

The data suggested that the truck driver played a significant role in the evasive maneuver, which affected the results of the test. Undoubtedly, it is not possible for a human being to reproduce the same path for every attempt that this maneuver is conducted (ideal situation), particularly if the wheel and tire layout are changed from test to test and there is only a short time for the driver to gain practice and a better "feeling" of the truck drivability. By carefully analyzing the data, those runs were identified in which the evasive maneuver was not performed as planned (i.e., only two turns as opposed to two turns plus a corrective maneuver), and those runs were eliminated from the analysis dataset. Unfortunately, this reduced the usable data to only a few points that could be used in the analysis.

It is proposed that this test, which proved to be very valuable in determining the performance of the different wheel and tire layouts studied, be conducted with the aid of a driving robot to keep the variability introduced by the driver to a minimum. The evasive maneuver is simple enough so that a robot can perform it with minimum difficulty. However, it is expected that for each series, the robot steering would have to be adjusted to maintain the same trajectory for all the tests (it is initially important to begin with the same trajectory for each test series to allow for equivalent comparisons). This would mimic a real-world situation in which the driver, with enough experience with each tire/wheel combination, can follow exactly the same trajectory, thus eliminating the driver factor from the analysis.

If this maneuver was performed as described, it would be possible to have a higher number of replications of the test so that the results can be statistically analyzed. A larger sample size will also help clarify some of the effects that were difficult to explain with a very small number of observations. For example, what effect do dual tires on the tractor have when combined with single tires on the trailer? Series 4 (see Table 5.1.6) indicates less stability than Series 3, but Series 6 has higher roll stiffness than Series 5. The most rigid configurations have the least compliance. Using this methodology, Series 1 has the most compliance. However, because the use of single tires is expected to yield more tire compliance than the dual tires, future research in this area is suggested.

5.2 DANA ANALYSIS OF EVASIVE MANEUVER

This part of the report was prepared by Paul Pollock and Daniel Coleman of Dana Corporation.

5.2.1 Evasive maneuver

5.2.1.1 Setup and Procedure

The highway evasive maneuver was conducted to determine the vehicle's transient response when subjected to a sudden lane change. Cones were positioned in a flat, open area of the test track as shown in Figure 3.1.

The test consisted of negotiating a left-hand lane change. The vehicle enters gate 1 at a constant speed. While maintaining speed, the driver makes an abrupt reverse-ramp steer as he exits gate 1. The driver then provides the steer input required to traverse the center line and to gain position for straight entry into gate 2. The driver was tasked to maintain his initial speed until gate 2 had been exited. In general, the test started at 41 mph and the speed was increased by 2 mph until the rollover threshold was observed. Once rollover threshold speed was determined, the test was repeated three times.

5.2.1.2 Data Analysis

Data reduction and analysis was performed using Optim dataACE V3.60. The purpose was to determine the vehicle speed and instantaneous lateral acceleration required to induce wheel lift-off.

Wheel lift-off of the right rear trailer axle wheel was determined by the vertical wheel force. The wheel was determined to be "off the ground" when there was no positive vertical load measured by the SWIFT 50T, i.e., when there was only the negative weight of the wheel. The minimum lateral acceleration for wheel lift in response to a sudden lateral force is always less than the static rollover threshold.

Lateral acceleration was measured by the Oxford box at the trailer CG and the Crossbow/Watson sensors at the tractor CG. Lateral acceleration and vertical load signals were processed through a 3.0 Hz, 2nd order low pass filter to eliminate the higher frequency noise.

Three approaches were used to evaluate transient roll control or lateral stability on the lane-change maneuver. They were:

- Vehicle speed at wheel-lift,
- Lateral acceleration of the trailer CG at wheel-lift, and
- Combined lateral acceleration of the tractor CG and trailer CG at wheel lift (note: the tractor is well past its peak lateral acceleration when the trailer reaches its maximum roll angle).

5.2.1.3 Correlation Between Vehicle Speed and Wheel Lift

As displayed in Figure 5.2.1, higher speeds generally produced wheel lift of the right rear trailer axle tire more often than lower speeds. Wheel lift occurred at a threshold of approximately 46 mph and above. The data shows that the two highest speeds that did not produce wheel lift occurred with the Series 6 configuration. Series 5 was the only other configuration that showed a run above 48 mph that did not cause the wheel to lift. This would suggest that Series 6 and Series 5 enabled the driver to pass through the maneuver at the highest speeds without experiencing wheel lift.

Figure 5.2.1 Vehicle Speed (mph) at Wheel Lift.

There are some abnormalities in the data, such as is seen in Series 6, which should be mentioned. Two Series 6 passes failed to produce wheel lift near 52 mph despite three prior occurrences of wheel lift at lower speeds. Likewise, one Series 5 pass at 44 mph caused wheel lift while another at 48.5 mph did not. One explanation may be that vehicle speed does not reflect characteristics of the steering input or the vehicle path. Therefore, higher speeds do not necessarily result in higher lateral accelerations, and speed alone is an inconclusive indicator of roll performance, i.e., it does not tell the entire story.

5.2.1.4 Correlation Between Trailer Lateral Acceleration and wheel Lift

This approach taken in this analysis considered only the data sets that exhibited wheel lift. Passes that did not produce wheel lift were ignored. Table 5.2.1 shows the instantaneous lateral acceleration of the trailer CG at the moment of wheel lift. Vehicle Configurations of higher stability can accept higher levels of lateral acceleration to produce wheel lift.

Table 5.2.1 Instantaneous Lateral Acceleration (g) of the Trailer CG at the Moment of Wheel Lift.

	SER1	SER2	SER3	SER4	SER5	SER6
	0.4926	0.5118	0.5355	0.5445	0.4801	0.5342
	0.5122	0.4448	0.5799	0.5396	0.4724	0.5430
	0.5073	0.4508	0.5464	0.5243	0.4566	0.5527
	0.5022	0.4805	0.5505		0.5628	
		0.4914	0.5401		0.4729	
AVERAGE	**0.504**	**0.476**	**0.550**	**0.536**	**0.489**	**0.543**
RANK	**4**	**6**	**1**	**3**	**5**	**2**

Series 3 required the greatest lateral acceleration to lift the rear trailer axle wheel, while Series 2 was the least stable. The data suggests that new-generation single tires on the trailer wheels (Series 3 and Series 4) increased vehicle stability compared to the baseline (Series 1). Surprisingly, the effect of the wider-slider trailer suspension (Series 5 & Series 6) seems to have a minimal impact on the results. In particular, the average lateral acceleration for Series 5 is unexpectedly low. It should be noted that the range in Series 5 data is broad compared to the other configurations indicating that there is a high degree of variation in the data. Due to this anomaly in Series 5 results, an overall trend in the data is difficult to decipher.

Since vehicle speed and lateral acceleration of the trailer did not provide clear evidence of vehicle stability, a third approach was used to consider the effect of the combined tractor and trailer lateral acceleration on wheel lift. The additive instantaneous lateral accelerations of the tractor and trailer combination at wheel lift are plotted in Figure 5.2.2. For runs that did not induce wheel lift, the peak combined lateral acceleration experienced is shown.

Figure 5.2.2 Combined Tractor and Trailer Lateral Accelerations (g) at Wheel Lift.

The graph suggests that Series 1 and 2 offer the least stability, since wheel lift occurred on every pass, with a combined lateral acceleration above 0.7 g. On the other hand, for Series 4, 5, and 6, all had two runs over 0.7 g that did not produce wheel lift. Series 5 had the best run of approximately 0.88 g with no wheel lift, but also had two runs with wheel lift near 0.7 g. Series 4, 5, and 6 clearly offer the most stability as determined by wheel lift.

5.2.1.5 Fifth Wheel Roll Moment

One of the four outputs provided by the fifth-wheel load transducer was the roll moment ($M_{x)}$. Calibrations show that the roll moment has about 2.0 percent accuracy. The roll moment is depicted in Figure 5.2.3.

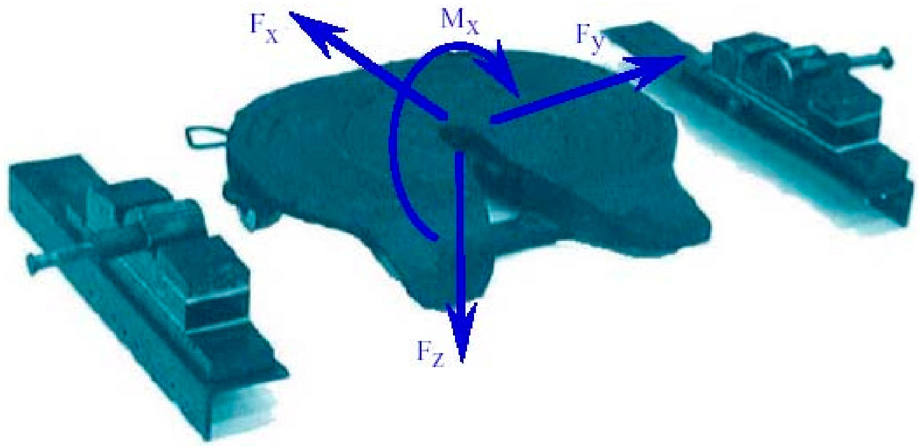


Figure 5.2.3 UMTRI Fifth-Wheel Load Transducer.

The fifth-wheel roll moment was analyzed for each test series on the 49 mph evasive maneuver. The results were expected to be comparable to those of the same maneuver at different vehicle speeds. Using Optim dataACE v.3.60, the raw trailer lateral acceleration and fifth wheel roll moment data was first plotted in the time domain in figure 5.2.4.

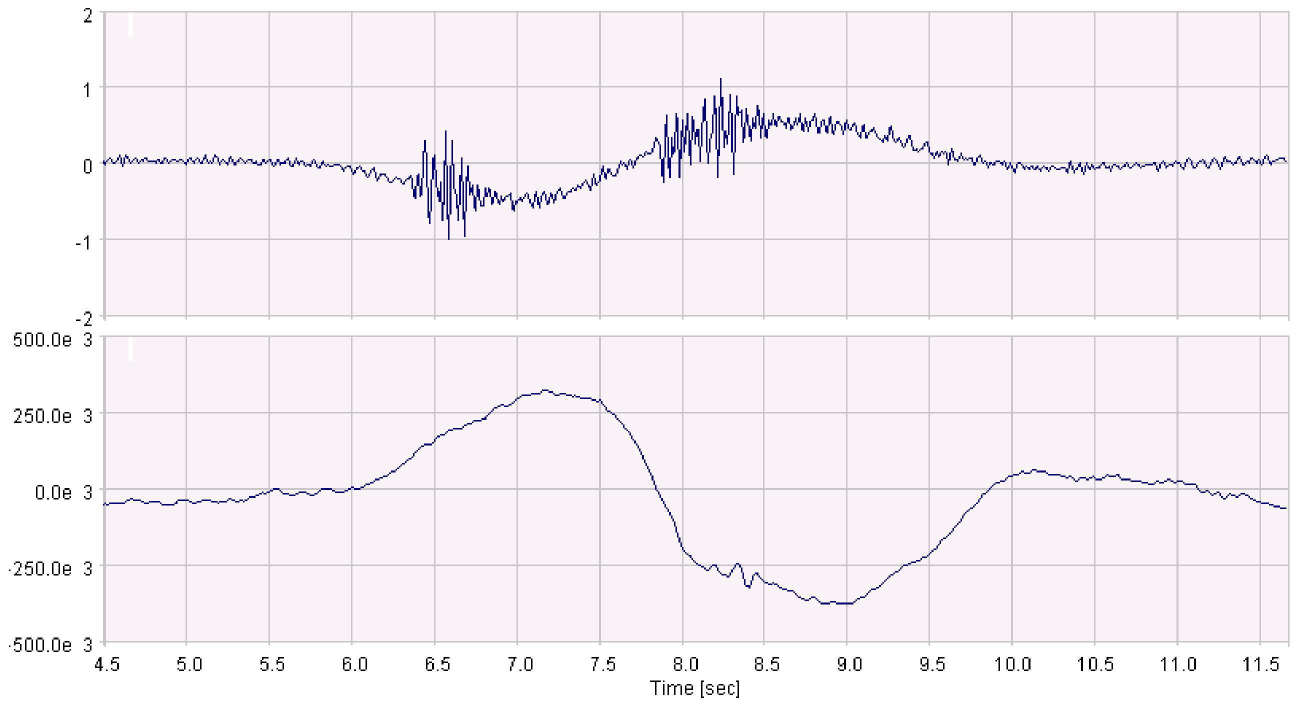


Figure 5.2.4 Series 3 Trailer Lateral Acceleration (g) and Fifth Wheel Roll Moment (ft-lbf) vs. Time (sec).

The graphs of the trailer lateral acceleration and fifth wheel roll moment were then combined into one graph and subjected to a 1.0 Hz, 2nd order low pass filter in Figure 5.2.5.

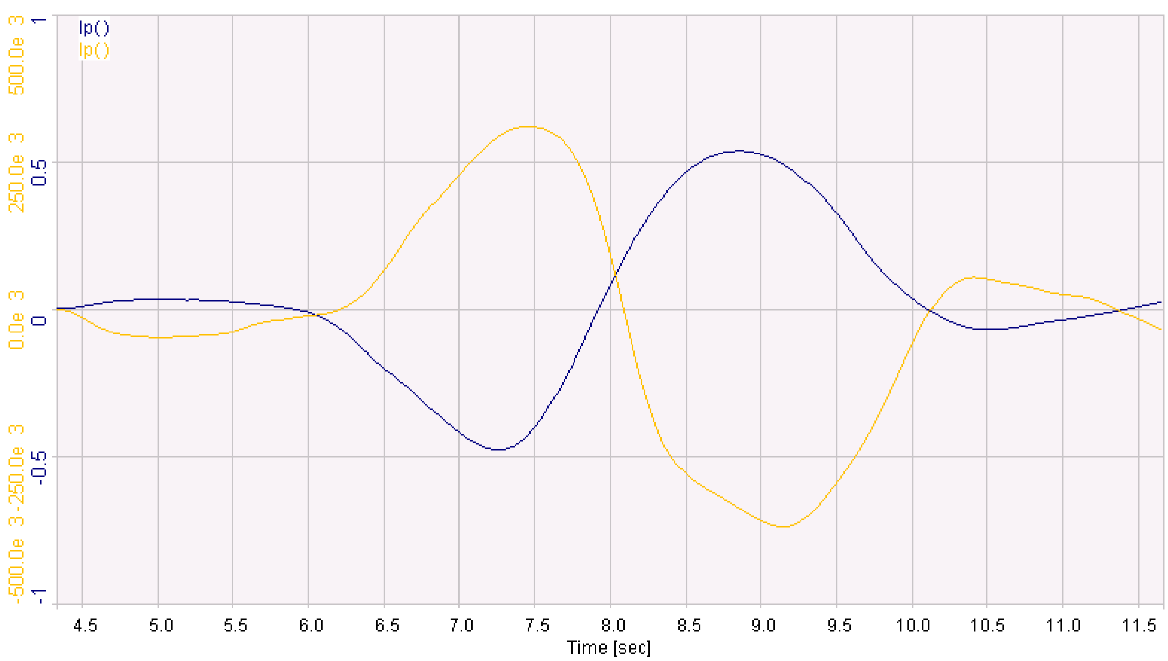


Figure 5.2.5 Series 3 Trailer Lateral Acceleration (g) and Fifth Wheel Roll Moment (ft-lbf) vs. Time (sec).

Finally, XY scatter plots were created to directly compare trailer lateral acceleration with fifth wheel roll moment in Figure 5.2.6.

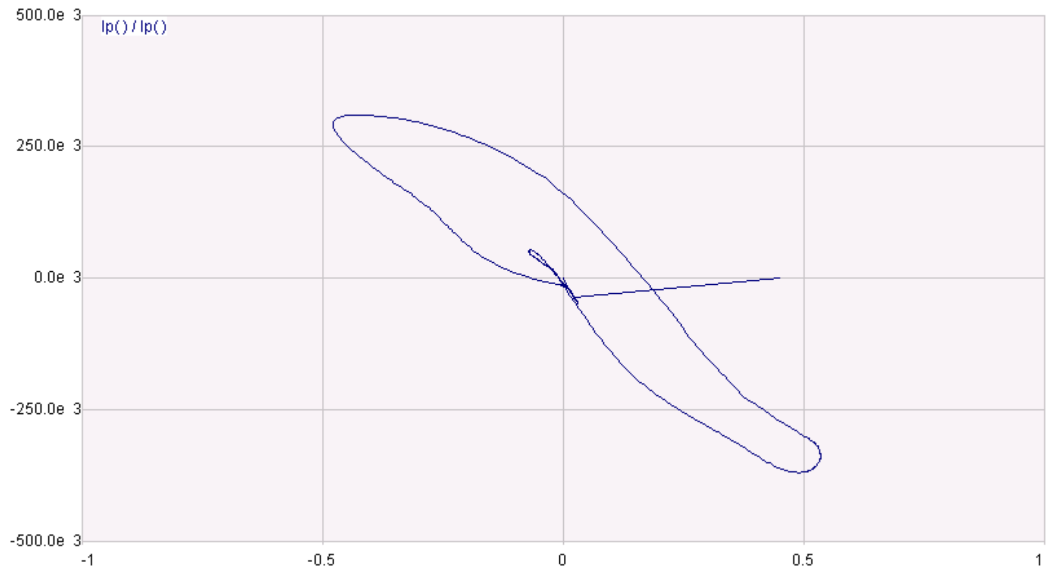


Figure 5.2.6 Series 3 Filtered Trailer Lateral Acceleration (g) vs. Filtered Fifth Wheel Roll Moment (ft-lbf).

The results of the XY plots from each test series are shown in Figure 5.2.7.

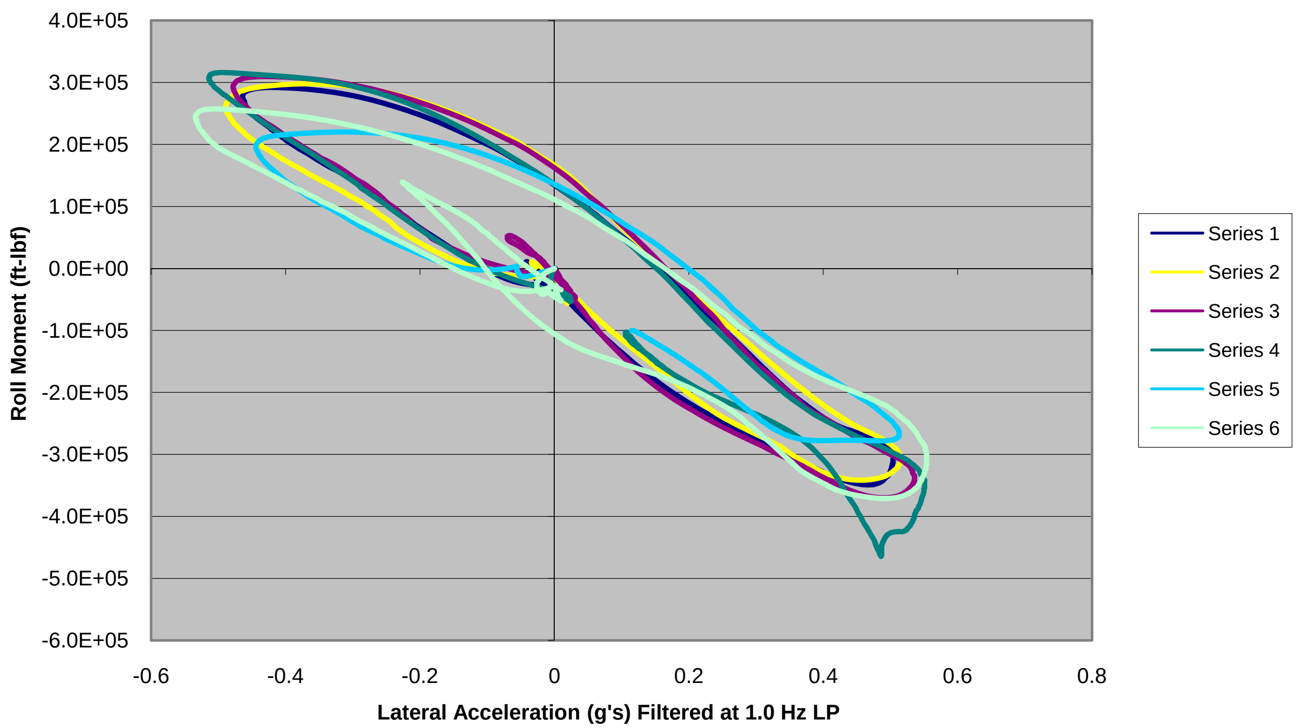


Figure 5.2.7 All Series Filtered Trailer Lateral Acceleration (g) vs. Filtered Fifth Wheel Roll Moment (ft-lbf).

To determine fifth wheel roll moment sensitivity and to clarify the results, a 1st order linear fit was applied to the data. To further facilitate easy comparison between the various series of data, the intercept of the linear fit was selected to be zero in Figure 5.2.8.

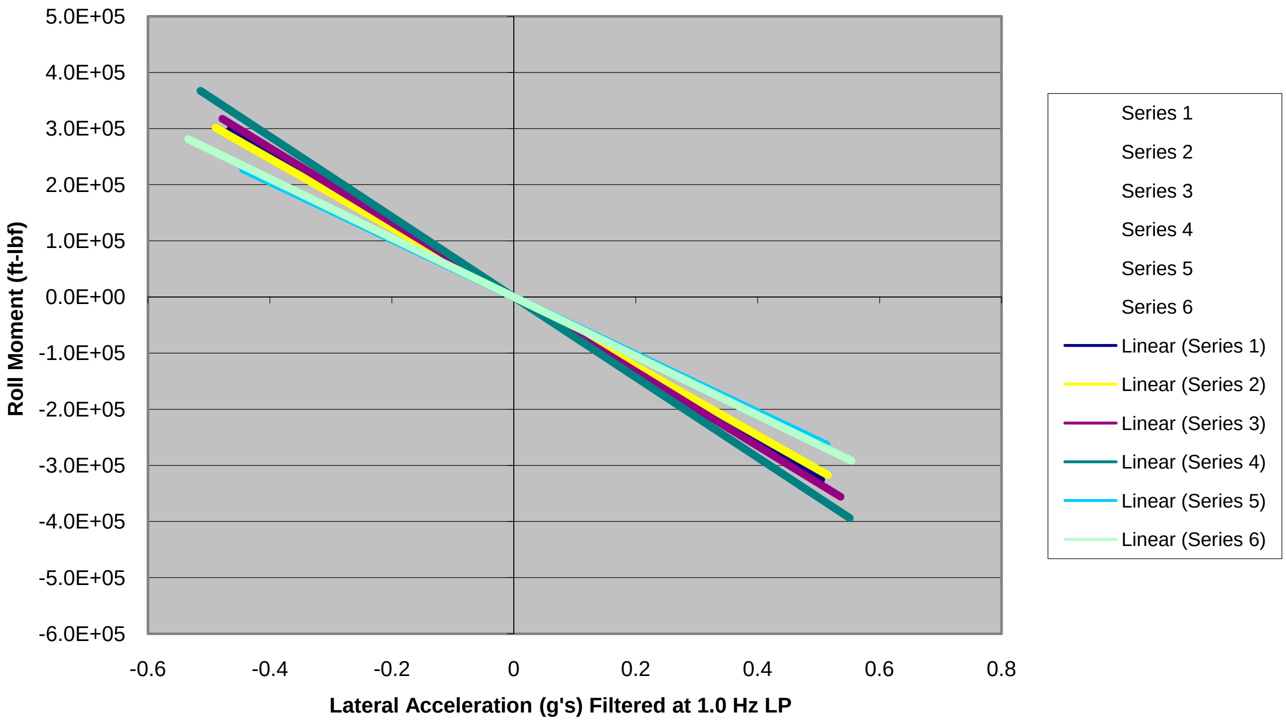


Figure 5.2.8 Linear Fit: Filtered Trailer Lateral Acceleration (g) vs. Filtered Fifth Wheel Roll Moment (ft-lbf).

The fifth wheel roll moment sensitivity values are:

Series 1: 644,686 ft-lbf/g
Series 2: 616,322 ft-lbf/g
Series 3: 663,865 ft-lbf/g
Series 4: 714,402 ft-lbf/g
Series 5: 512,937 ft-lbf/g
Series 6: 526,659 ft-lbf/g

Series 5 has the lowest roll moment sensitivity for the 49 mph evasive maneuver. A lower sensitivity indicates increased vehicle stability since there is less roll moment at the tractor-trailer connection per unit of lateral acceleration. Series 5 results represent a 20 percent improvement over the baseline Series 1. Series 6 has the second lowest roll moment sensitivity. Both Series 5 and Series 6 are configured with the wider-slider trailer suspension with new-generation single tires. Series 3 and 4 have the highest fifth wheel roll moment sensitivities. Both Series 3 and Series 4 are configured with the standard trailer suspension and new-generation single tires.

5.2.2 Conclusions

The following questions and answers reflect the conclusions of the analyses in this section.

What effect did the X-One XDA tires have on vehicle stability during the evasive maneuver?
Not surprisingly, the X-One XDA new-generation single *tractor* tires (Series 2) had little appreciable influence on *trailer* tire wheel-lift when compared to the baseline with dual drive tires (Series 1). However, the fifth wheel roll moment sensitivity was reduced by 4% when the new-generation single drive tires were added in Series 2 and by 7% when the same tires were introduced in Series 3. These results point toward a notable improvement in vehicle roll stability with the X-One XDA new-generation single tires.

What effect did the X-One XTA tires have on vehicle stability during the evasive maneuver?
The instantaneous lateral acceleration of the trailer at the moment of wheel lift was higher for every run in Series 3 and 4 when compared with the baseline runs that utilized dual trailer tires (Series 1 and 2). The combined lateral accelerations of the tractor and trailer with the X-One XTA new-generation single tire configuration also show a clear improvement in vehicle stability. This data analysis supports the conclusion that the X-One XTA new-generation single tire configuration (Series 3 and 4) provides added trailer stability over the XT1 dual tires (Series 1 and 2) for the evasive maneuver. However, this effect does not translate to the fifth-wheel, where the roll moment sensitivities for Series 3 and 4 are the highest of any configuration.

What effect did the wider slider trailer suspension with X-One XTA new-generation single tires have on vehicle stability during the evasive maneuver?
Widening the track of the vehicle in Series 5 and 6 increased the stabilizing moment available from side-to-side load transfer. Despite the increased track width, analysis of trailer wheel lift does not clearly indicate a stability improvement over the standard trailer suspension width in Series 3 and 4. Some of this inconclusiveness may be attributable to data scatter and inconsistencies within the maneuver. However, an analysis of fifth-wheel roll moment on the 49 mph evasive maneuver reveals a large 23% sensitivity reduction in Series 5 (vs. Series 3) and a 26% improvement in Series 6 (vs. Series 4). This data testifies to the large contribution to increasing roll stability by the wider-slider trailer suspension with X-One XTA tires.

5.2.3 Lessons Learned

The following is a compilation of the lessons learned from the conduct of the evasive maneuver test.

- The evasive maneuver should be performed with the automated steering controller to increase the consistency of the steering input. The path followed by the vehicle should be allowed to vary if necessary.
- Evasive maneuvers should be performed within a wide velocity range in small intervals regardless of wheel lift threshold. A minimum of ten data sets should be obtained.
- The surface of the road should be swept prior to testing to minimize sliding.

5.3 DATA ANALYSIS OF PHASE 1 AND 2 SWEPT SINE TESTS

This part of the report was prepared by Steven L. Haas of Michelin Americas Research and Development Corporation (MARC).

5.3.1 Overview of the Analysis

This is an analysis of test data received from Dana Corporation for swept sine tests conducted as part of the Phase 1 and 2 test plan developed for this project. Six test series were run consisting of unique tire or vehicle configurations. Six frequency response functions (FRFs) were computed to include an analysis of the coherent frequency range of each.

The swept sine test can be used, for example, to calculate yaw rate to steering wheel angle and lateral acceleration-to-steering wheel angle FRFs. Inputs are kept relatively low to approximate linear behavior required for the FRF analysis. It is noted that some of the additional frequency response functions analyzed here, may, in some cases, not be as linear. Accordingly, such results should be used to indicate approximate behavior or trends, and not necessarily taken in an absolute quantitative sense.

5.3.2 Introduction

Two FRFs are typically obtained from the swept sine tests. They are: 1) a yaw rate-to-steering wheel angle frequency response function, and 2) a lateral acceleration-to-steering wheel angle frequency response function. The yaw rate frequency response can be related to the driver's visual perception during the maneuver, and the lateral acceleration frequency response can be related to feedback cues the driver receives from the vehicle.

The term "Swept Sine" relates to an approximation of a relatively broad frequency input using a swept sine steering input. However, the frequency range is necessarily limited by the test speed and length of the test track, and the maximum steering rate possible or desired.

FRFs are associated with a magnitude (or gain) and a phase (related to lag, or delay), both of which are functions of frequency. Measured results depend upon both the tire and the vehicle. An important tool for evaluating FRFs is the coherence function, which provides a relative indication of the relationship of the output to the input signal.

The FRF *H(f)* can be defined as the complex ratio of the system output to the system input (as a function of frequency), and can be shown to be equal to the ratio of: the cross spectrum F_{xy} between the input and the output, and the power spectrum F_{xx} of the input[6].

$$H(f) = \frac{F_{xy}(f)}{F_{xx}(f)}$$

The FRF can be expressed as a complex number, which is a function of frequency. The magnitude and phase of *H* are determined from the relationship of the real and imaginary components. Thus, *H(f)* can be converted from its complex form, into magnitude and phase spectra.

The spacing or resolution of frequency data is determined from the length of time of the test duration. For example, if the test time *T* is 25 sec, then Δf *(in Hz)* is:

$$\Delta f = \frac{1}{T} = \frac{1}{25} = 0.04$$

Coherence is an indication of the quality of the relationship between output and input. The coherence function can be expressed as:

$$\gamma_{xy}^2(f) = \frac{\left|F_{xy}(f)\right|^2}{F_{xx}(f)F_{yy}(f)}$$

[6] For a more rigorous treatment of transfer function theory, the reader may refer, for example, to *Application of B&K Equipment to Frequency Analysis* (published by Bruel & Kjaer) or *Engineering Applications of Correlation and Spectral Analysis* by J. S. Bendat and A. G. Piersol.

where F_{xx} and F_{xy} are as previously defined and F_{yy} is the power spectrum of the output.

The associated spectra are averaged over a number of data records, giving results in the range of:

$$0 \le \gamma^2{}_{xy}(f) \le 1$$

where perfect coherence would be 1.0.

When the coherence function is less than unity, this could indicate, for example, noise present in the measured data, non linearity between input and output, or the presence of additional inputs.

For a testing duration of approximately 25 sec, input frequencies below 0.2 Hz are difficult to realize. For vehicles such as the current vehicle system, frequencies above approximately 2.0 Hz will typically exhibit reduced coherence between the steering wheel input and the yaw rate output, and the steering wheel input and lateral acceleration output for the tractor.

This test was added to the test set in order to provide some basic information pertaining to tire/vehicle frequency response. It is meant to complement the other tests and to potentially determine if there is some correlation between rollover stability and low input level frequency response.

5.3.3 Data Processing

Typically, all data files should be acquired at the same length to facilitate FRF processing, however this was not the case with this data. Accordingly, program *dt12pad_v5.m* was written to read in each of the eight passes of each series and pad all but the longest of the eight passes with the mean value of each (measured) channel (the data were not padded with zeros because of dc-offsets which were typically present). While this approach appeared to provide a reasonable approximation to the frequency response of the unpadded data, future testing should be obtained at constant time intervals. Note that each series, having some difference in the number of data points per pass, will therefore have a slightly different frequency spacing. This should not interfere with the present analysis.

A program entitled *Rsteer_trc_v4.m* was written for Matlab to calculate the FRFs. Additional FRFs were calculated in addition to the yaw rate/steering wheel angle and lateral acceleration/steering wheel angle responses. These additional FRFs were:

- Tractor Roll Rate-to-Tractor Lateral Acceleration,
- Trailer Roll-to-Trailer lateral Acceleration,
- Trailer Yaw Rate-to-Steering Wheel Angle, and
- Trailer Lateral Acceleration-to-Steering Wheel Angle.

It is noted that the tractor lateral acceleration measurements were not roll corrected. In addition, based on linearity assumptions[7], coherence, padding and other factors, the results should not be taken

[7] Inputs are kept relatively low to approximate linear behavior required for the analysis. It is noted that some of the additional frequency response functions analyzed here (particularly between the tractor and the semitrailer) may not be as linear. Accordingly, the results should be used to indicate approximate behavior or trends, and not in an absolute quantitative sense.

in an absolute sense, but rather used to determine relative or qualitative differences in tire and vehicle conditions.

5.3.4 Tractor Yaw Rate to Steering Wheel Angle

The coherence and FRFs are given in Figures 5.3.1 to 5.3.3. In the legend, the color codes are given for each series. Note that for Series 6, file number 045 is not included due to problems associated with that pass.

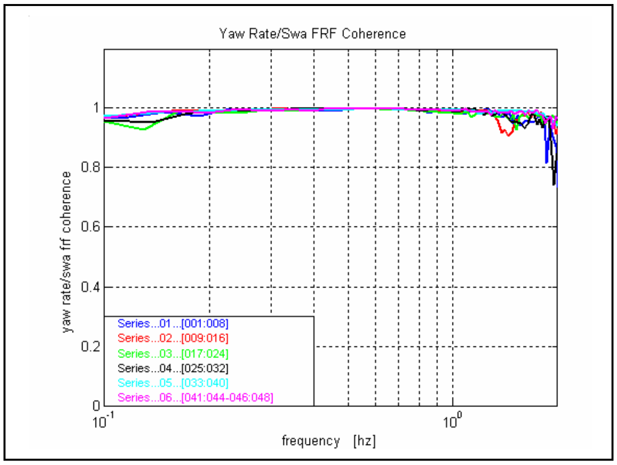


Figure 5.3.1 Yaw Rate/Steering Wheel Angle FRF Coherence.

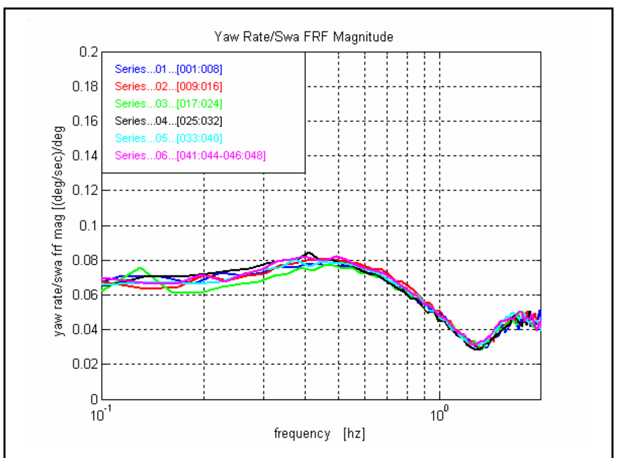


Figure 5.3.2 Yaw Rate/Steering Wheel Angle FRF Magnitude.

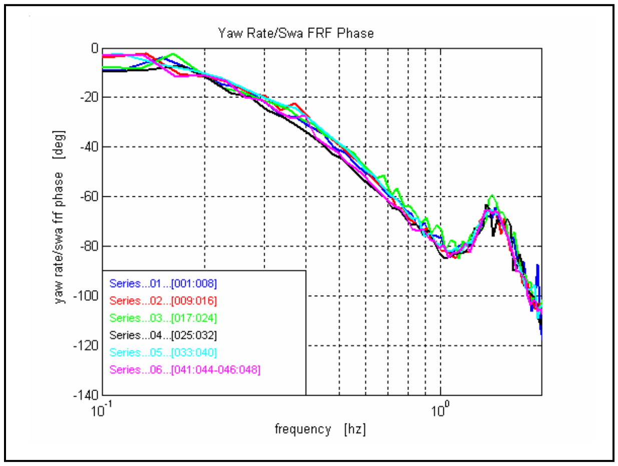


Figure 5.3.3 Yaw Rate/ Steering Wheel Angle FRF Phase.

The coherence looks reasonably good between 0.2 and nearly 2.0 Hz. No apparently significant differences are noted between series within the coherent range, with the possible exception of Series 3 which has somewhat of a lower yaw rate gain in the 0.2 to 0.4 Hz range.

Typical performance is characterized by an initially increasing yaw rate gain starting at about 0.2 Hz and reaching a maximum between 0.4 and 0.5 Hz. The phase lag, Figure 5.3.3 increases[8] from approximately 10.0 deg or less at 0.2 Hz to approximately 80.0 deg at 1.0 Hz. Within this frequency interval the trend is monotonic.

5.3.5 Tractor Lateral Acceleration-to-Steering Wheel Angle

The coherence and FRFs are given in Figures 5.3.4 to 5.3.6. The coherence is very good between 0.2 Hz and approximately 1.3 Hz. Note that Series 5 data is not included in this analysis due to problems with lateral acceleration measurements for this series.

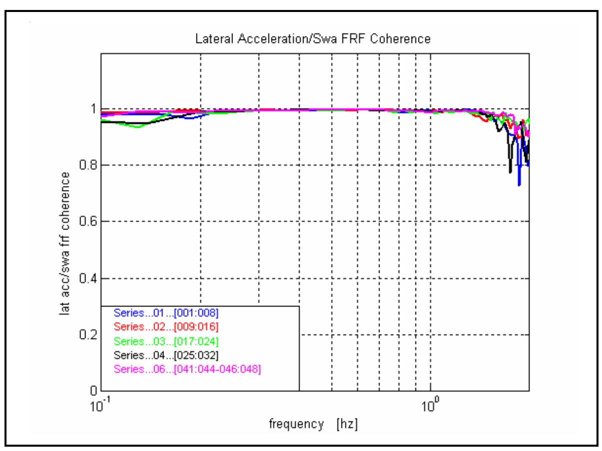


Figure 5.3.4 Lateral Acceleration/ Steering Wheel Angle FRF Coherence (Series 5 not included).

[8] When referring to the measured phase angle it is decreasing, as shown on the plot. However, when referring to the phase angle as a lag, then in this case the lag is increasing.

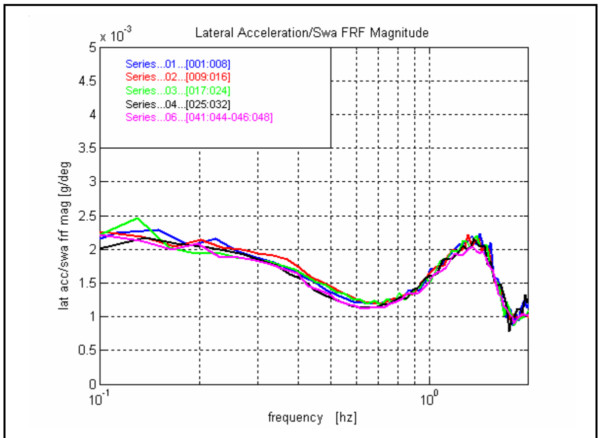


Figure 5.3.5 Lateral Acceleration/ Steering Wheel Angle FRF Magnitude (Series 5 not included).

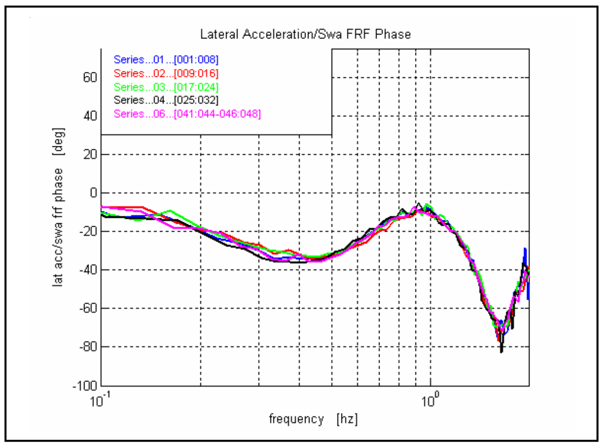


Figure 5.3.6 Lateral Acceleration/ Steering Wheel Angle FRF Phase (Series 5 not included).

No appreciable differences are noted between series for either magnitude or phase. The gain is characterized by decreasing values down to about 0.6 to 0.7 Hz and then increasing to a frequency above 1.0 Hz. A minimum phase lag (below 1.0 Hz) is reached at approximately 0.4 Hz.

5.3.6 Tractor Roll Rate to Tractor Lateral Acceleration

The coherence and frequency response functions are given in Figures 5.3.7 to 5.3.9. Roll rate was used rather than roll because of measurement problems with the tractor roll sensor. Tractor lateral acceleration was taken as the input. Again, Series 5 data could not be included due to problems as mentioned earlier.

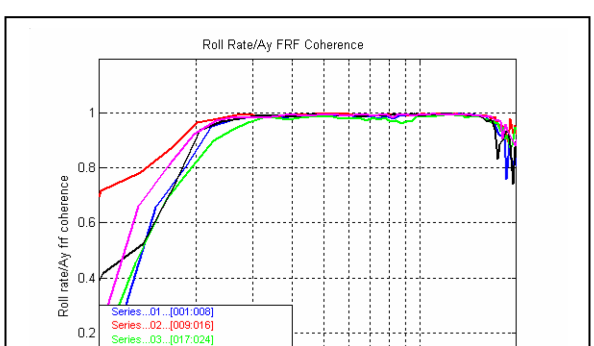


Figure 5.3.7 Roll Rate/Lateral Acceleration FRF Coherence (Series 5 not included).

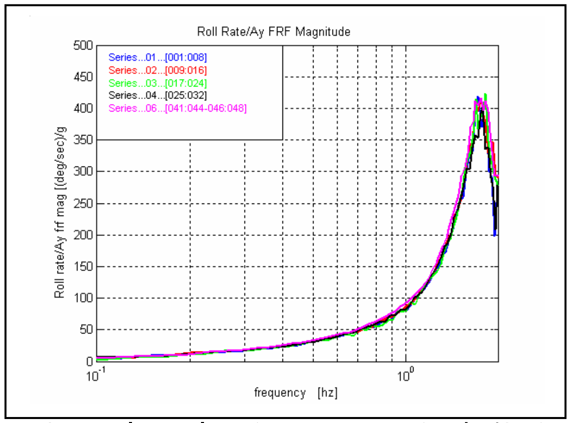


Figure 5.3.8 Roll Rate/Lateral Acceleration FRF Magnitude (Series 5 not included).

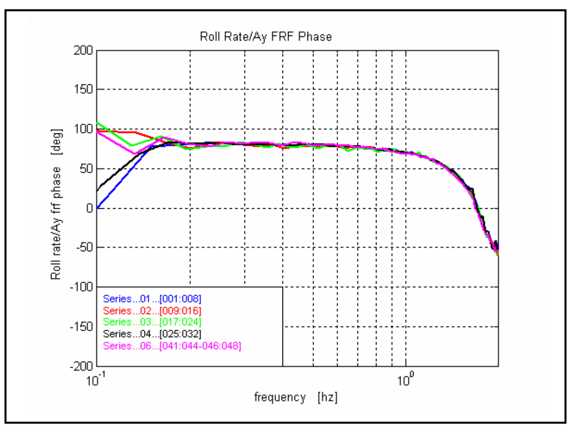


Figure 5.3.9 Roll Rate/Lateral Acceleration FRF Phase (Series 5 not included).

Relatively poor coherence below 0.3 Hz is noted here. The estimated roll rate gain (relative to lateral acceleration) in the frequency range of interest, reaches a maximum below 2.0 Hz. The phase response exhibits a small decrease between 0.2 and 1.0 Hz, and then begins to decrease at a faster rate.

5.3.7 Trailer Roll-to-Trailer Lateral Acceleration

The coherence and frequency response functions are given in Figures 5.3.10 to 5.3.12. Highest coherence values are limited here to the 0.2 to 0.7 Hz frequency range. However, within this range some distinct behavior between series may be noted in the magnitude FRF, particularly for Series 5 and 6 which use the wider-slider configuration on the trailer. The estimated roll gain (in deg per g) is clearly less for the two wider-slider series. No appreciable difference in phase lag is noted within the frequency range of interest.

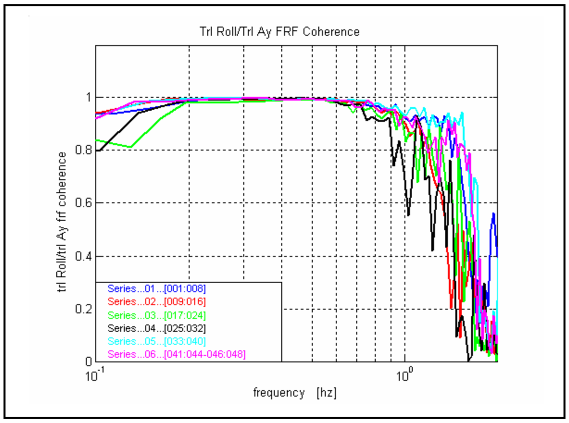


Figure 5.3.10 Trailer Roll/Trailer Lateral Acceleration FRF Coherence.

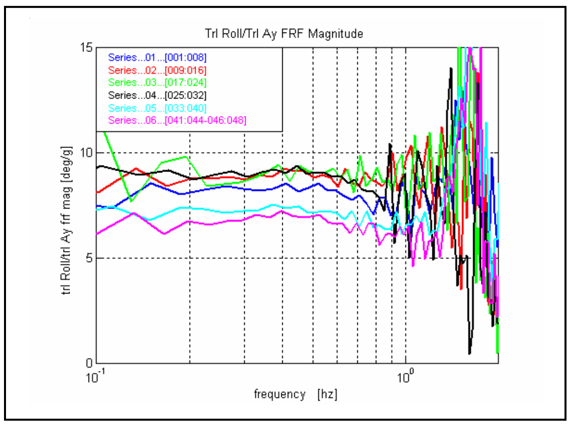


Figure 5.3.11 Trailer Roll/Trailer Lateral Acceleration FRF Magnitude.

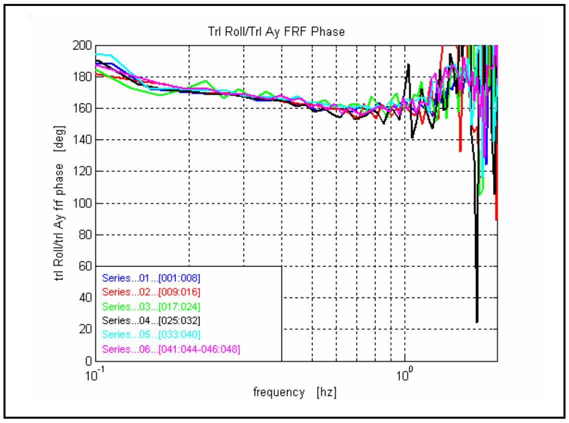


Figure 5.3.12 Trailer Roll/Trailer Lateral Acceleration FRF Phase.

5.3.8 Trailer Yaw Rate-to-Steering Wheel Angle

The coherence and frequency response functions are given in Figures 5.3.13 to 5.3.15. The coherence remains fairly high between about 0.2 and 0.7 Hz.

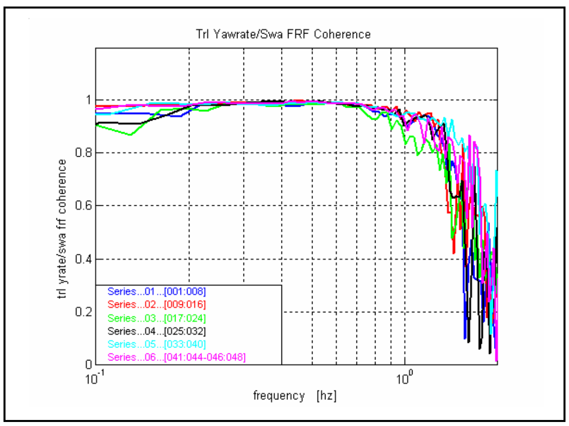


Figure 5.3.13 Trailer Yawrate/ Steering Wheel Angle FRF Coherence.

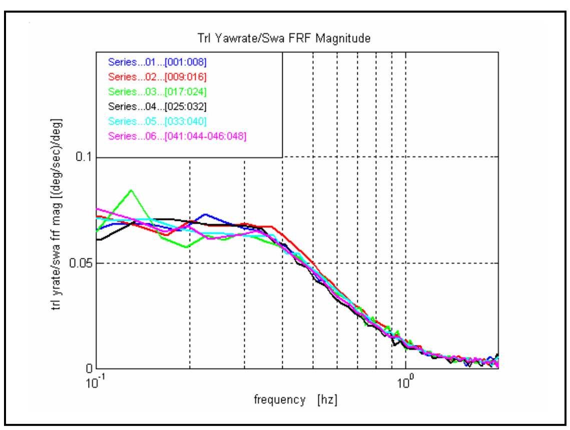


Figure 5.3.14 Trailer Yawrate/ Steering Wheel Angle FRF Magnitude.

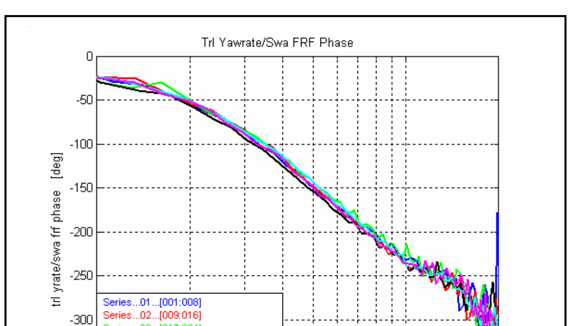


Figure 5.3.15 Trailer Yawrate/ Steering Wheel Angle FRF Phase.

The gain remains reasonably consistent up to approximately 0.35 Hz and then begins to decrease becoming very small by 2.0 Hz. The phase lag (approximately 50 deg at 0.2 Hz and approximately 235 deg at 1.0 Hz) is seen to be considerably larger than that for the tractor.

5.3.9 Trailer lateral Acceleration to steering Wheel Angle

The coherence and frequency response functions are given in Figures 5.3.16 to 5.3.18. The highest coherence values are limited to the 0.2 to 0.7 Hz frequency range, similar to the previous FRF.

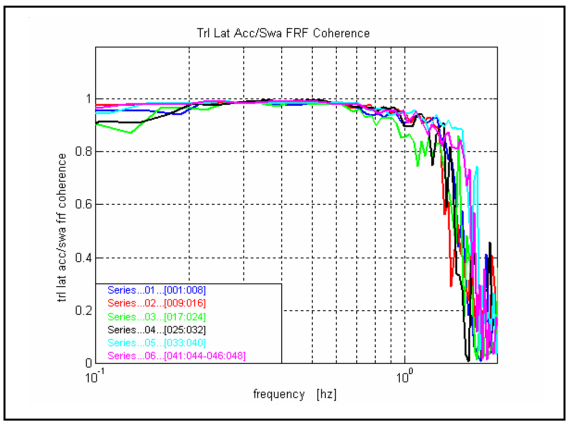


Figure 5.3.16 Trailer Lateral Acceleration/ Steering Wheel Angle FRF Coherence.

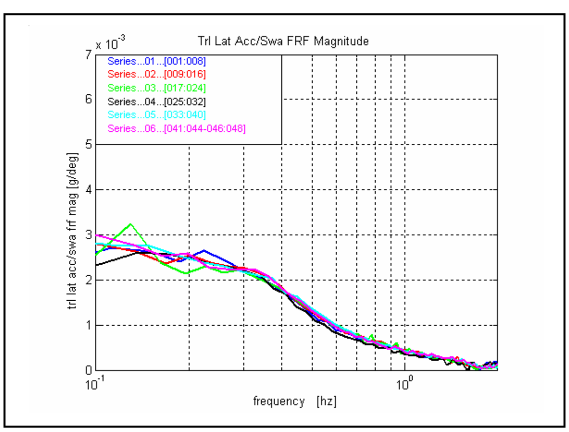


Figure 5.3.17 Trailer Lateral Acceleration/ Steering Wheel Angle FRF Magnitude.

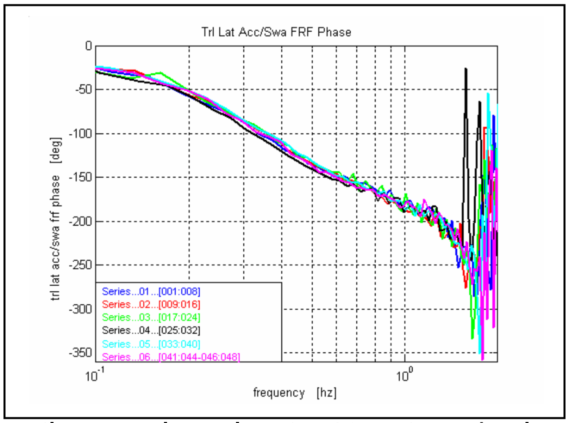


Figure 5.3.18 Trailer Lateral Acceleration/ Steering Wheel Angle FRF Phase.

No appreciable differences between series appear evident in the magnitude and phase FRFs. The trend of the gain appears to decrease monotonically with increasing frequency, having a different shape than that for the tractor. As with the trailer yaw rate FRF, the phase lag is considerably larger for the trailer as compared to the tractor.

5.3.10 Summary

The analysis was conducted on test data gathered on swept sine tests conducted as part of the Phase 1 and 2 test plan for this project. Six test series were run consisting of unique tire or vehicle configurations.

Six FRFs were computed to include an analysis of the coherent frequency range of each. Typically, this procedure is used to calculate yaw rate-to-steering wheel angle and lateral acceleration-to-steering wheel angle FRFs. Inputs are kept relatively low to approximate linear behavior required for the analysis. It was noted that some of the additional FRFs analyzed (particularly between the tractor and the trailer) may not be as linear, and should be interpreted accordingly.

With some exceptions, the higher values of the coherent frequency range were between approximately 0.2 Hz to 1.3 Hz for the tractor and approximately 0.2 Hz to 0.7 Hz with the trailer. For the tractor in particular, this range could probably be increased with some changes to the steering input.

In general, differences between the test series were small with the exception of the wider slider configuration. Here, the estimated trailer roll gain was noticeably lower with the wider slider configuration.

5.4 DATA ANALYSIS OF STEADY CORNERING TESTS

This part of the report was prepared by Professor Harry Law and students (Eric Johnson, Robert Lawson and David Moline) of Clemson University.

5.4.1 Summary of Steady Cornering Testing

This section of the report discusses the data analysis associated with the steady cornering characteristics associated with heavy truck rollover. Vehicle speed was increased linearly as the vehicle circled the skid pad until the critical lateral acceleration was reached and the vehicle exhibited incipient rollover. For each vehicle configuration, both the 150 ft and 400 ft skid pads were utilized, and for each skid pad the test was performed in both a CW and CCW direction. Therefore, for each vehicle configuration four sets of data were created.

5.4.2 Findings for Constant Radius Maneuver

Incipient rollover can be evaluated based on the wheel load transducers that were placed on axles 3 and 5 of the vehicle. By logging the output of these sensors during the tests and with knowledge of the trailer's lateral acceleration behavior, it is possible to determine at what value of lateral acceleration the vehicle experienced no vertical load on the inside tire (i.e., when the vehicle is on the verge of rollover). The load transducers were mounted on the passenger's side of the vehicle for all tests; this meant that for the CCW maneuver, the outside wheel load was logged. To find the point of zero load for the inside wheel during CCW tests, the outside wheel load was subtracted from the static axle load to determine the inside wheel load. Table 5.4.1 shows the results of the data analysis performed on the various sets of supplied data. The shaded cells contain the highest values of the averaged lateral acceleration for each axle for the 150 ft and 400 ft skid pads. Plots of raw and filtered data and a detailed explanation of the analysis are included in the Data Analysis section below

Table 5.4.1 Lateral Acceleration (g) for Zero Normal Load (lbf).

Lateral Acceleration (g)						
400 ft	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
Axle 3 CW	0.53	0.57	0.54	0.53	0.60	0.58
Axle 3 CCW	0.56	0.58	0.52	0.56	0.61	0.61
Average Axle 3 (400 ft)	0.55	0.58	0.53	0.55	0.61	0.59
150 ft	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
Axle 3 CW	0.55	0.58	0.55	0.55	0.57	0.60
Axle 3 CCW	0.67	0.64	0.60	0.66	0.67	0.71
Average Axle 3 (150 ft)	0.61[9]	0.61[1]	0.57[1]	0.60[1]	0.62[1]	0.65[1]
400 ft	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
Axle 5 CW	0.51	0.50	0.54	0.53	0.51	0.52
Axle 5 CCW	0.53	0.52	0.48	0.50	0.50	0.49
Average Axle 5 (400 ft)	0.52	0.51	0.51	0.51	0.51	0.51

Table 5.4.1 Lateral Acceleration (g) for Zero Normal Load (lbf) (Continued)

Lateral Acceleration (g)						
150 ft	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
Axle 5 CW	0.48	0.47	0.50	0.50	0.48	0.51
Axle 5 CCW	0.53	0.54	0.49	0.46	0.46	0.47
Average Axle 5 (150 ft)	0.51	0.50	0.50	0.48	0.47	0.49

The data was also averaged across both the 150 ft and 400 ft tests, and then averaged again across both axles 3 and 5. Table 5.4.2 shows this information. It can be seen in Table 5.4.1 that axle 3 does

[9] The CCW data seems unusual for this test and may have caused the averages to be erroneous.

not exhibit zero normal load until a higher lateral acceleration than axle 5, as would be expected. For axle 5, all of the series appear to perform relatively equally.

Table 5.4.2: Averaged Acceleration (g) for Zero Normal Load (lbf).

Averaged Acceleration (g)						
	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
Axle 3 Average	0.58	0.59	0.55	0.57	0.62	0.62
Axle 5 Average	0.51	0.51	0.50	0.49	0.49	0.50
Average Total	0.54	0.55	0.53	0.53	0.55	0.56

Values of trailer roll gradient (deg/g) were calculated for the various sets of data. These values provide another quantitative method for determining the differences between the various vehicle configurations. The roll gradients represent the value of the slope for a first order curve fit applied to roll angle vs. trailer lateral acceleration. Table 5.4.3 contains the roll gradients for the various vehicle configurations.

Table 5.4.3: Averaged Acceleration (g) for Zero Normal Load (lbf).

Averaged Acceleration (g)				
	150 ft		400 ft	
	CW	CCW	CW	CCW
Series 1	7.86	8.97	9.07	9.03
Series 2	8.94	9.06	7.98	8.57
Series 3	9.52	9.00	8.58	9.69
Series 4	8.68	9.30	8.83	8.48
Series 5	7.52	7.22	7.57	6.78
Series 6	7.21	8.25	7.67	7.68

The shaded cells indicate the configuration with the lowest trailer roll gradient for a given maneuver direction and skid pad size. It can be seen that Series 5 rolls less per unit of lateral acceleration than the other series. Series 6 was the next lowest in all cases for which it was not the best. Series 5 and 6 trailers were both equipped with the wider-slider mechanism.

The DAS utilized during the testing allowed for the roll moment at the fifth wheel connection to be analyzed. The fifth wheel used on the tractor during the testing had the capability to function as a load transducer and provided data on the forces and moments present at the connection throughout the test. The roll moment data was formatted in terms of a sensitivity value that resulted from applying a first order curve fit to filtered data vs. trailer lateral acceleration. Table 5.4.4 contains the sensitivity values for the roll moment at the fifth wheel.

Table 5.4.4: Fifth Wheel Roll Moment Sensitivity (ft lbf/g).

Fifth Wheel Roll Moment Sensitivity (ft lb/g)					
	150 ft		400 ft		
	CW	CCW	CW	CCW	Avg.
Series 1	53640	36590	58230	43570	48010
Series 2	56030	41370	43470	42460	45830
Series 3	57840	40170	58910	41830	49690
Series 4	52410	43640	53600	46550	49050
Series 5	52480	28510	46770	31090	39710

Series 6	49870	29940	51160	33340	41080

The shaded cells indicate which Series has the lowest roll moment sensitivity for a given direction and skid pad size. The lower the roll moment sensitivity, the less likely the vehicle will be to rollover because a smaller moment is generated per unit of lateral acceleration. It can be seen from the data above that Series 5 gives the best overall performance in terms of roll moment generation, followed somewhat closely by Series 6. Further details on the processing of the roll moment data are included in the Data Analysis section below.

5.4.2.1 Axle Roll Angles

The axles of the test vehicle were fitted with string pots on either side of the centerline of the truck frame. The data recorded from these string pots allowed the individual axle roll angles to be determined using known data of absolute vehicle roll angle. Axles 1, 3, and 5 were outfitted with string pots, but only axle 5 could be evaluated due to sensor errors causing the tractor roll angle to be unreliable. The roll angle data for the trailer demonstrated a “ripple” effect due to a once-per-revolution change in track banking. A plot of the raw data for the trailer roll angle is provided along with an explanation of this occurrence in the Data Analysis section below.

The relative roll angle of the axle was calculated using the distances between the string pots and the data recorded from the pots. This relative roll angle was then subtracted from the absolute roll angle of the trailer to determine the absolute axle roll angle.

$$\Phi_{Trailer} - \Phi_{\mathrm{Re}lative} = \Phi_{Absolute}$$

Table 5.4.5 shows sensitivities recorded for the axle absolute roll angles that were calculated. The sensitivities were obtained in the same manner as the ones recorded earlier. The data in the table represents the values of the slope for a first order curve fit of the data against trailer lateral acceleration, after filtering of the data. The curve fits for the axle absolute roll angle data were plotted against lateral acceleration and can be found in the Data Analysis section below.

Table 5.4.5: Axle 5 Roll Angle Sensitivities (deg/g).

Axle 5 Roll Angle Sensitivity (deg/g)					
	150 ft		400 ft		
	CW	CCW	CW	CCW	Average
Series 1	7.30	8.95	8.19	8.46	8.22
Series 2	8.44	9.08	7.13	7.82	8.12
Series 3	9.20	9.00	7.83	9.56	8.90
Series 4	8.12	9.25	8.04	8.13	8.38
Series 5	5.62	6.80	3.77	4.74	5.23
Series 6	4.62	7.99	4.30	6.32	5.81

It can be seen from the data in Table 5.4.5, that Series 3 exhibits more axle roll than the other Series. This might be expected since Series 3 has new-generation single tires mounted on the tractor drive axles and the trailer axles. The new-generation single tires have less-stiff sidewalls than the dual tire configuration. Series 4 shows the next highest axle roll angles; Series 4 is also the only other Series with new-generation single tires mounted on the trailer axle without the wider-slider.

5.4.2.2 Wheel Lateral Forces

The wheel transducers fitted on the test vehicle provided information regarding lateral forces on the wheels. It is necessary to remember that the wheel transducers were mounted on the passenger side of the vehicle during the tests. Sensitivities were not recorded for this analysis, only plots for this data were generated and are included in the Data Analysis section below.

5.4.2.3 Understeer Gradient

It is possible to examine the vehicle's handling characteristics in addition to rollover performance from the data recorded during these tests. Wheel lateral loads have already been discussed and plots of the data are provided in the Data Analysis section (5.4.3.3) below. Understeer gradient is a value that characterizes a vehicle's tendency to oversteer or understeer during steady state cornering. The understeer gradient relates the vehicle steering wheel angle to lateral acceleration. If the driver must input more steering wheel angle as lateral acceleration is increased, the vehicle is said to exhibit understeer. Should the driver have to reduce the steering wheel angle to maintain control of the vehicle as lateral acceleration is increased, the vehicle is exhibiting oversteer. Plots of steering wheel angle versus trailer lateral acceleration were created to investigate understeer gradient. Understeer gradient is the slope of the line on a steering wheel angle vs. lateral acceleration plot. If the slope is positive, the vehicle is exhibiting understeer, if the slope is negative the vehicle is in an oversteer state. For the trucking industry, understeer is a more desirable characteristic than oversteer because an understeering truck is easier to control. The figures below contain plots of the steering wheel angle curve fit against trailer lateral acceleration for the various tests. The data processing is explained in depth in the Data Analysis section below.

Figures 5.4.1 through 5.4.6 show the understeer characteristics for each series of data for the 400 ft skid pad. To create the figures, the CW and CCW data was plotted and then an average of those two maneuvers was calculated and plotted as well. The values of steering wheel angle at zero lateral acceleration were subtracted from the data to ensure that the curves pass through the origin.

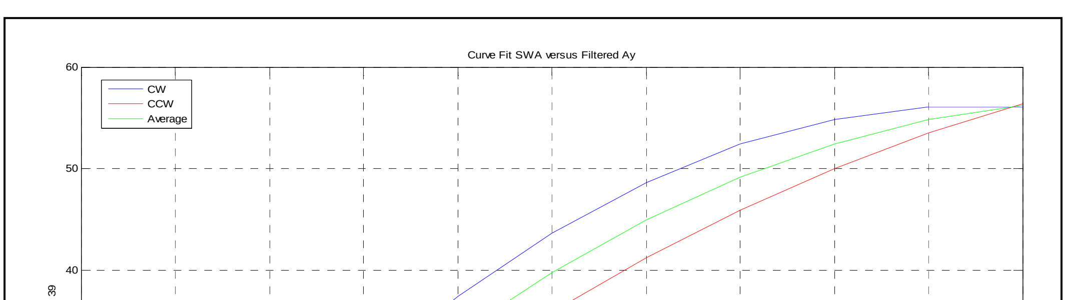


Figure 5.4.1 400 ft Series 1 Steering Wheel Angle (deg) vs. Lateral Acceleration (g).

Series 1 is understeer but as lateral acceleration increases above 0.3 g the vehicle seems to exhibit a tendency for less understeer.

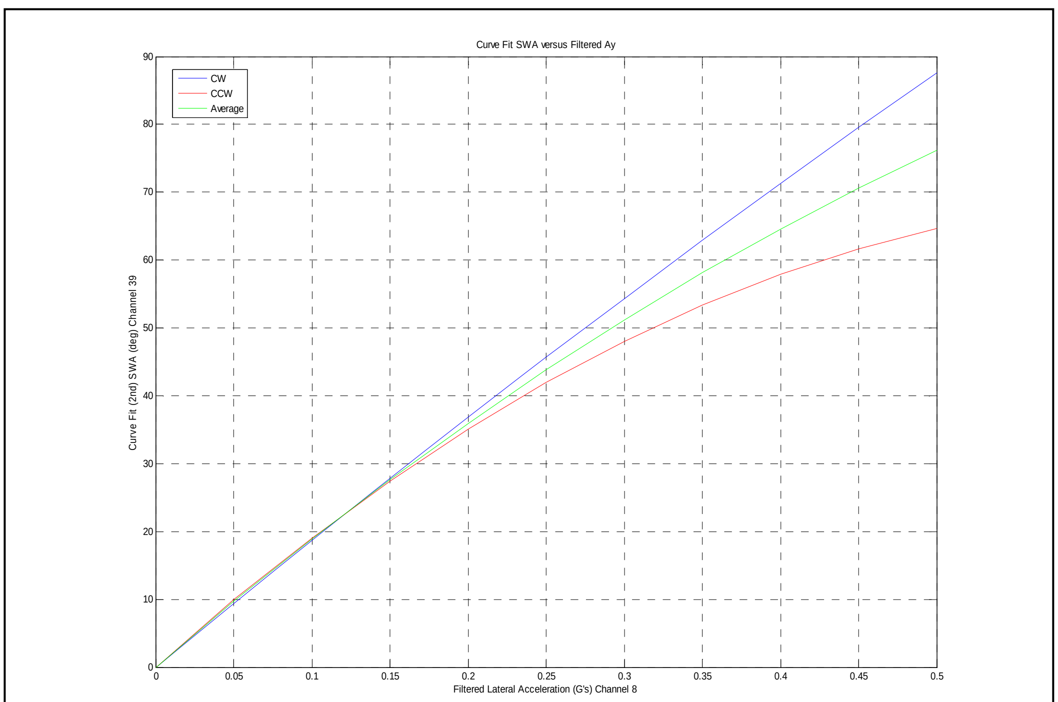


Figure 5.4.2 400 ft Series 2 Steering Wheel Angle (deg) vs. Lateral Acceleration (g).

Series 2 data shows a similar trend to Series 1, i.e., dominant understeer that decreases at higher accelerations.

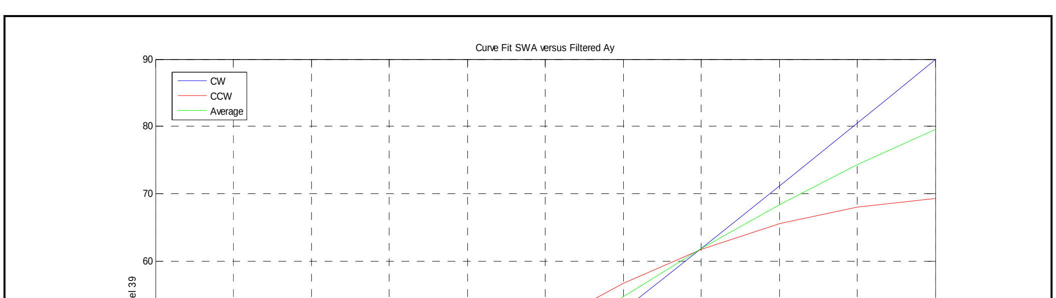
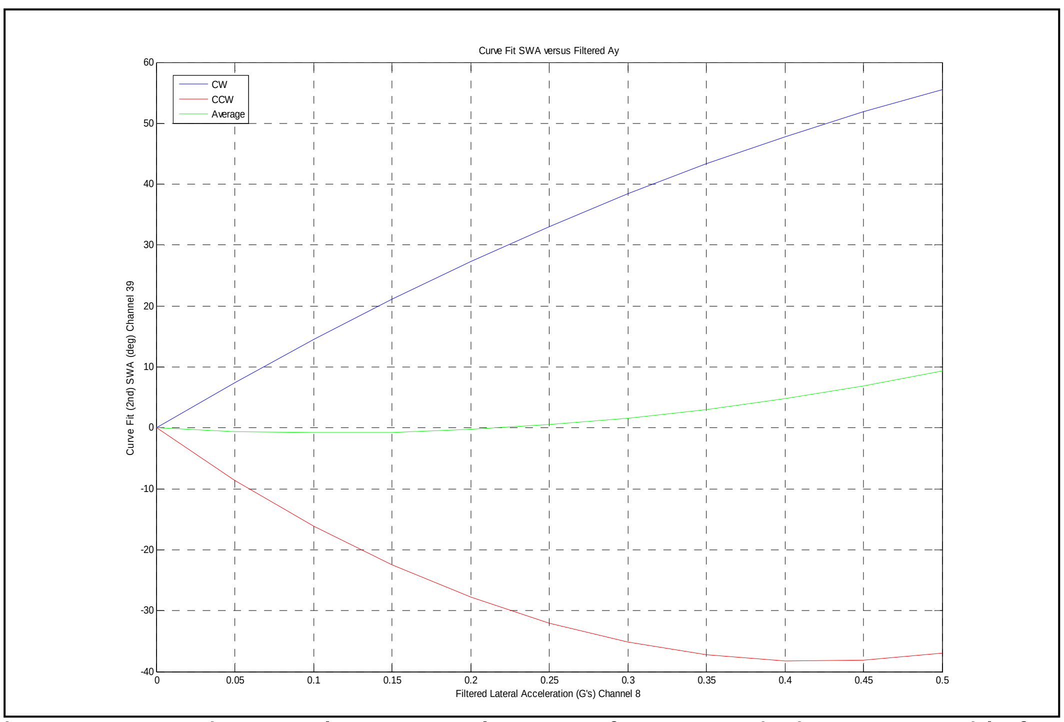


Figure 5.4.3 400 ft Series 3 Steering Wheel Angle (deg) vs. Lateral Acceleration (g).

Series 3 has a very gradual trend toward less understeer; however the CW maneuver of this series trends towards increasing understeer at higher lateral accelerations.



Series 4 data appears to show an almost neutral steer performance, which is questionable for such a vehicle; perhaps there are some anomalies in the data that have adversely affected the results especially for the CCW test. The CCW data for Series 4 is suspect and therefore when considering this series, the CW data should be used.

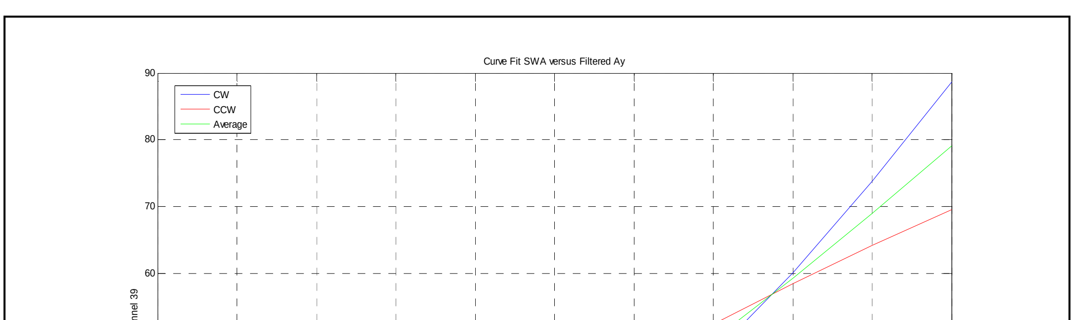
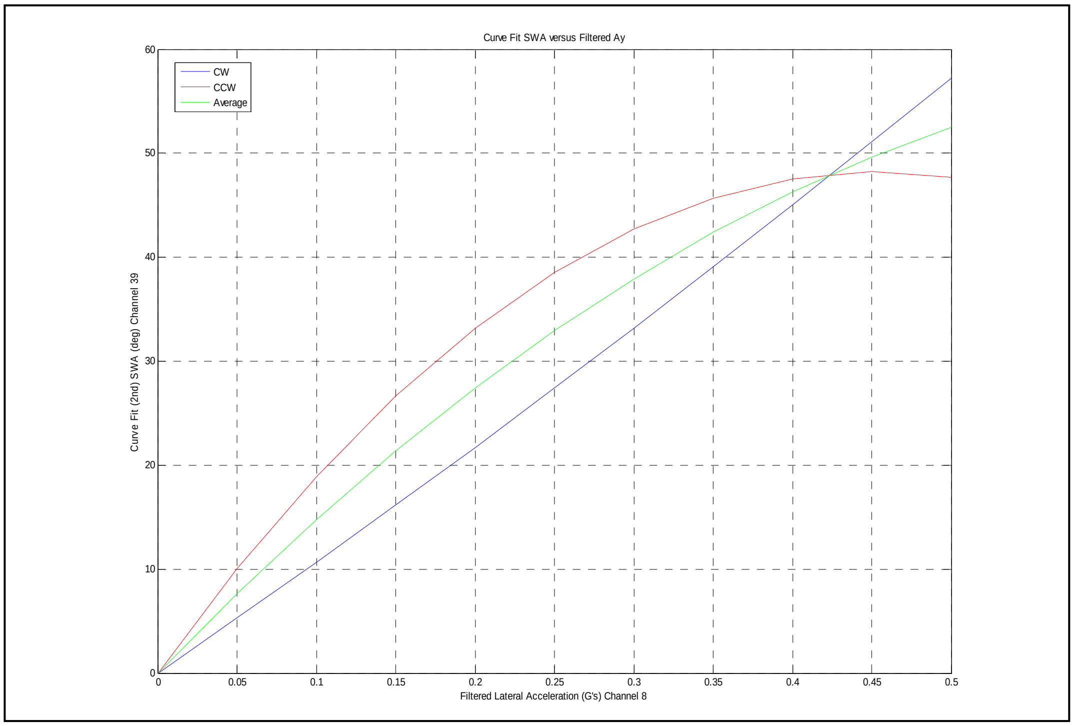


Figure 5.4.5 400 ft Series 5 Steering Wheel Angle (deg) vs. Lateral Acceleration (g).



Series 5 exhibits a documented characteristic of new-generation single tires. That is, the vehicle exhibits understeer which increases with lateral acceleration. This phenomenon is documented in Figure 2 of SAE paper 2000-01-3432 [1]. Series 5 shows this characteristic because for that configuration, new-generation single tires were mounted on the tractor drive axles and the trailer axles.

Series 6 shows a result similar to other Series in that the dominant understeer characteristic trends towards oversteer at higher values of lateral acceleration.

Figures 5.4.7 through 5.4.12 show similar results on the 150 ft skid pad to those on the 400 ft skid pad.

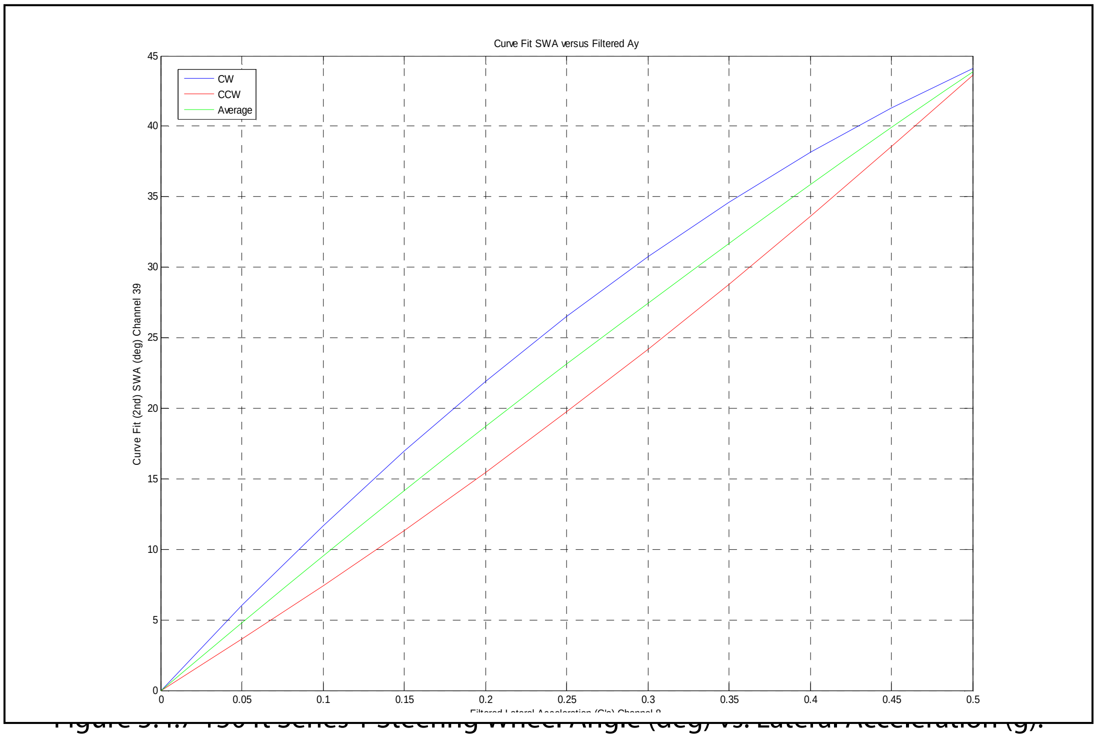


Figure 3.1.7 150 ft Series 1 Steering Wheel Angle (deg) vs. Lateral Acceleration (g).

Series 1 appears to have less variation in understeer gradient with lateral acceleration as compared to its behavior on the 400 ft skid pad.

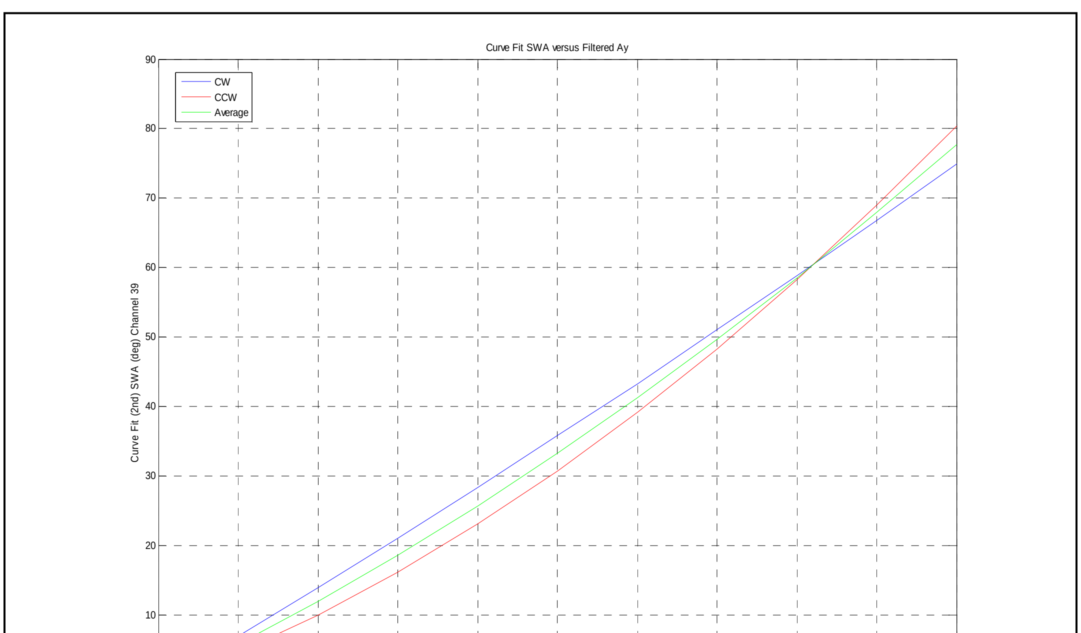


Figure 5.4.8 150 ft Series 2 Steering Wheel Angle (deg) vs. Lateral Acceleration (g).

Series 2 appears to exhibit some of the documented phenomenon of increasing understeer at higher lateral accelerations.

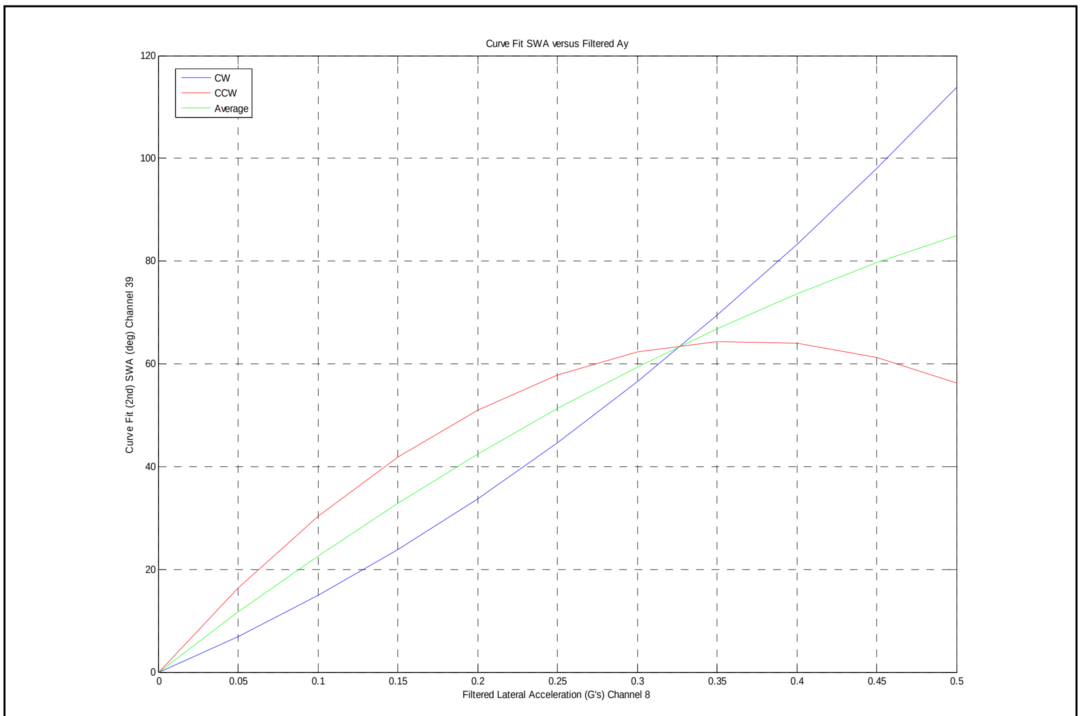


Figure 5.4.9 150 ft Series 3 Steering Wheel Angle (deg) vs. Lateral Acceleration (g).

Series 3 still trends towards less understeer at higher accelerations, but the CW maneuver is exhibiting an increasing understeer phenomenon.

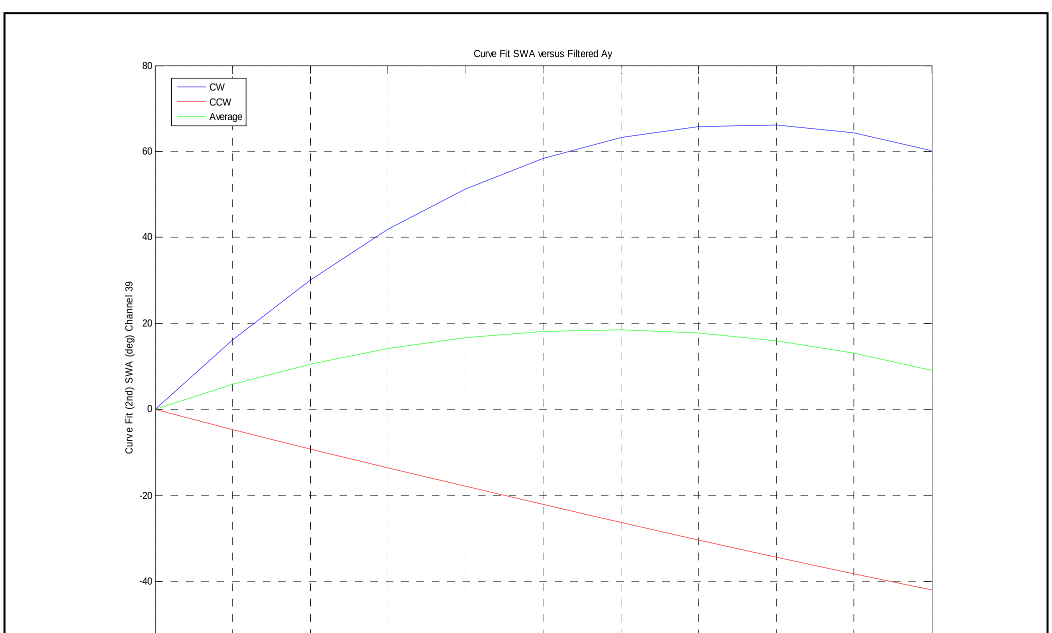
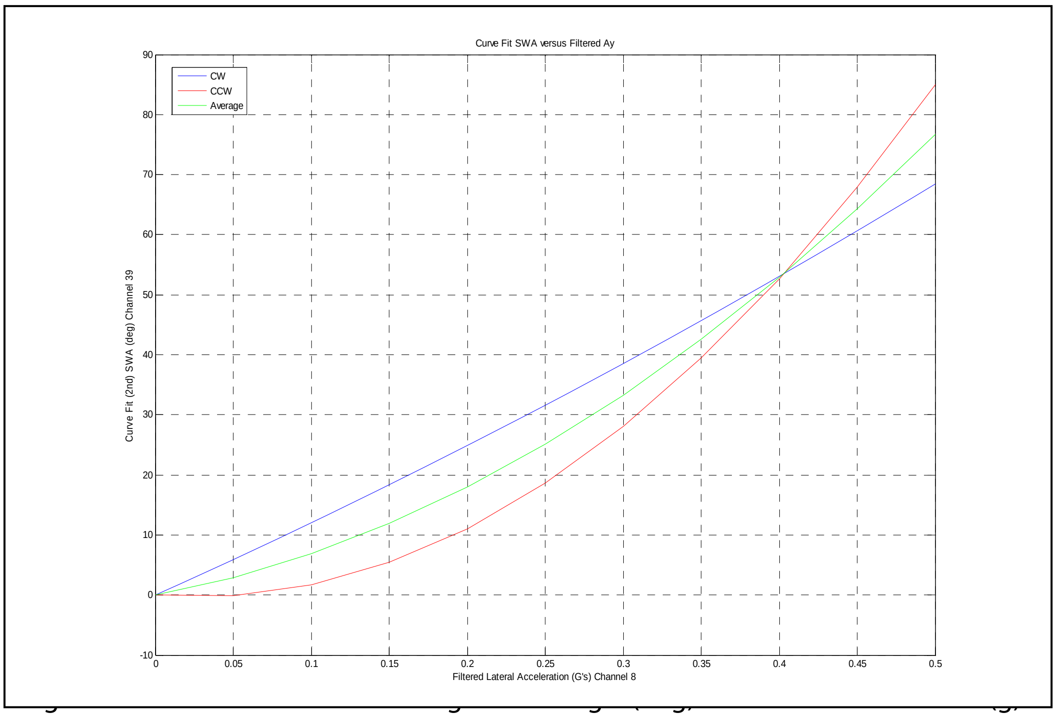


Figure 5.4.10 150 ft Series 4 Steering Wheel Angle (deg) vs. Lateral Acceleration (g).

Series 4 (CW) exhibits initial understeer that decreases with increasing lateral acceleration.



Series 5 performs almost exactly the same way for both skid pads.

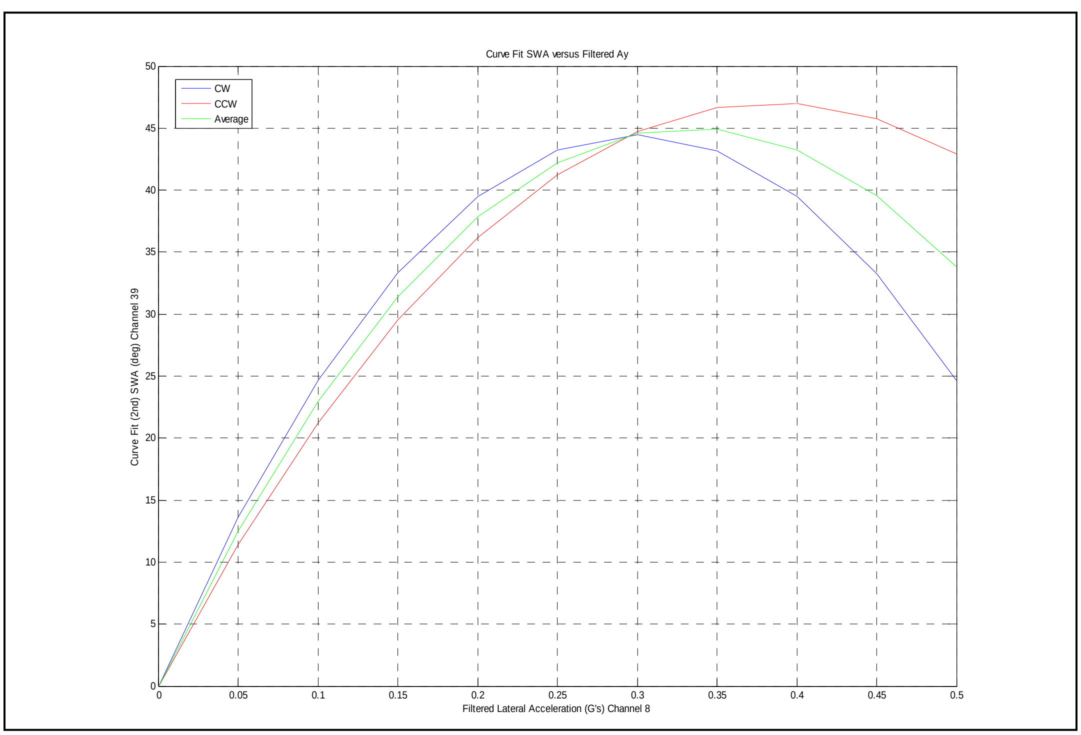


Figure 5.4.12 150 ft Series 6 Steering Wheel Angle (deg) vs. Lateral Acceleration (g).

Series 6 appears to trend to oversteer much more severely on the 150 ft skid pad than the 400 ft. Series 6 maintained the dominant understeer characteristic for the 400 ft skid pad; however on the 150 ft skid pad the vehicle is exhibiting dominant oversteer above 0.3 g.

5.4.3 Steady Cornering Data Analysis

5.4.3.1 Lateral Acceleration Data Processing

The lateral acceleration information used in this analysis was from the Oxford sensor mounted close to the trailer CG. The processing of this data (a combination of low pass filtering and curve fitting - depending on the ultimate use of the data) is described below. The effect of the filtering applied to the lateral acceleration data can be seen in Figure 5.4.13. The filtering reduced the noise in the data while preserving the overall trend. The filtering process utilized a five pole Butterworth filter as implemented in Matlab with a low pass cutoff frequency of 0.01Hz. It can be seen from the figure that the vehicle speed increased (approximately linearly with time); and when considering the portions of the test of increasing speed and decreasing speed separately, the lateral acceleration closely resembles a quadratic function of time. Therefore, the accelerating and decelerating points of the lateral acceleration vs. time data were each fitted with second-order polynomials.

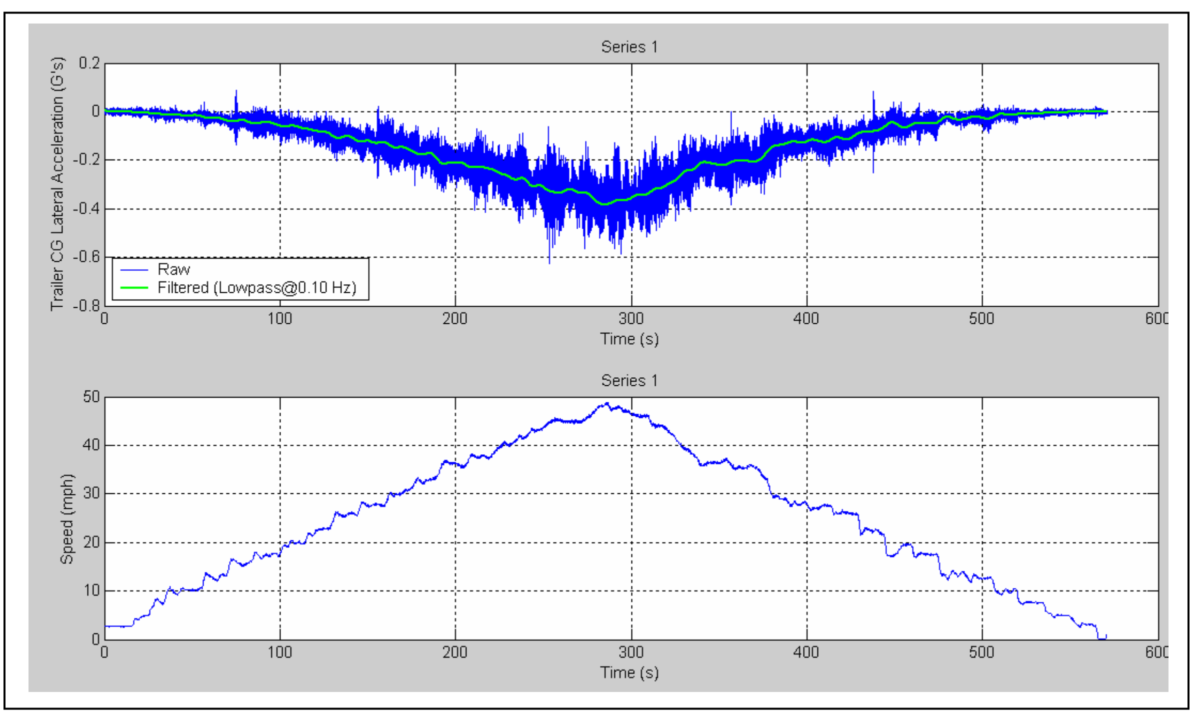


Figure 5.4.13 Typical Lateral Acceleration (g) and Vehicle Speed (mph) vs. Time (sec) Plots.

5.4.3.2 Axles 3 and 5 Normal Load Data Processing

Figures 5.4.14 and 5.4.15 show the data for the normal loads for axles 3 and 5 plotted against time. The top plot in each figure is the raw data plotted against time, while the bottom plot in the figure is the data plotted against time after being filtered; the filtering process was identical to that performed on the lateral acceleration.

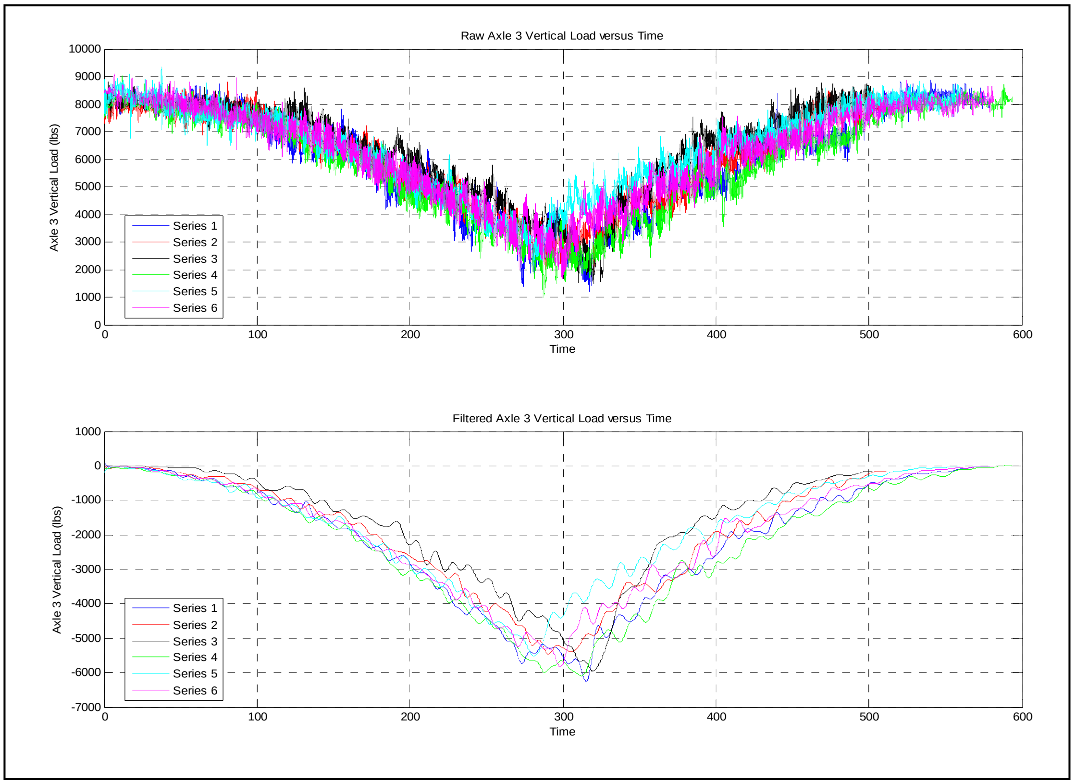


Figure 5.4.14 Raw and Filtered Axle 3 Normal Loads (lbf) vs. Time (sec).

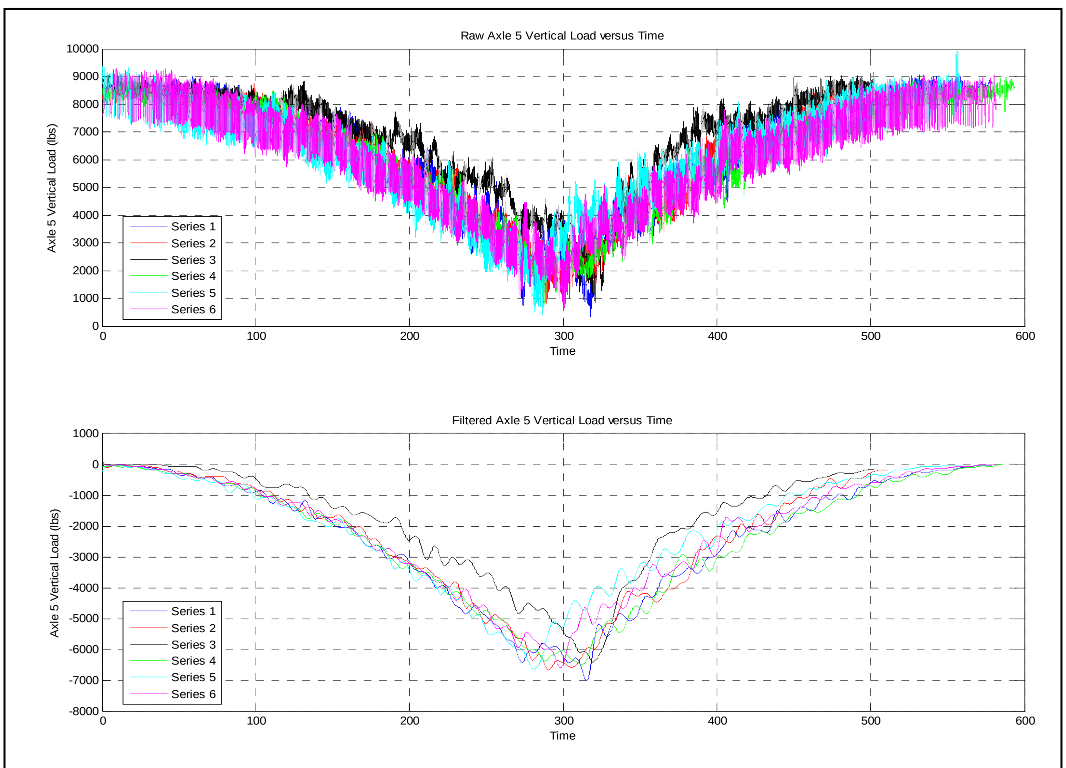


Figure 5.4.15 Raw and Filtered Axle 5 Normal Loads (lbf) vs. Time (sec).

5.4.3.3 Wheel Lateral Forces

The transducers were mounted on the passenger side of axles 3 and 5. Consequently, they were on the inside wheels for the CW maneuvers and on the outside wheels for the CCW. Figure 5.4.16 shows data from the 150 ft tests in the CW direction. It can be seen that the lateral force increases initially, but then plateaus as the wheel load is decreased. Likewise Figure 5.4.17 shows the data for the 150 ft CCW maneuver where the lateral force increases with lateral acceleration. The wheel lateral force increases because the transducers are mounted on the outside wheels during the test. The data was similar for the 400 ft tests depicted in Figures 5.4.18 and 5.4.19. In Figure 5.4.18 it can be seen that the lateral force does not level off to a constant value exactly like the 150 ft data, but it begins to increase at a slightly slower rate.

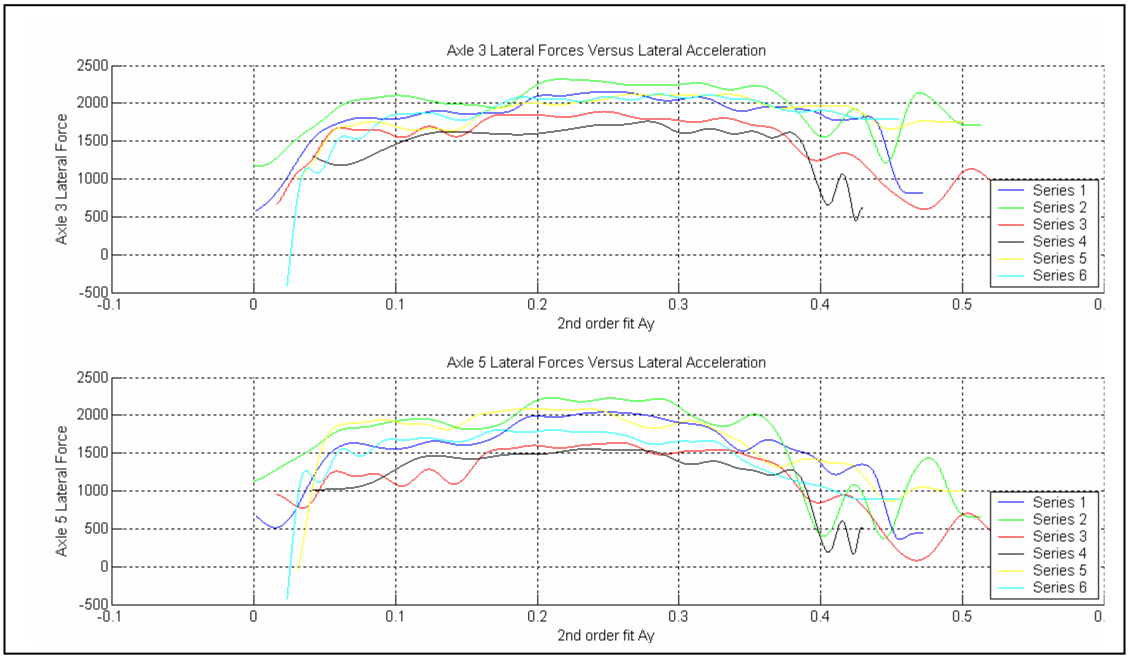


Figure 5.4.16 150 ft CW (inside wheel) Wheel Lateral Force (lbf) vs. Lateral Acceleration (g).

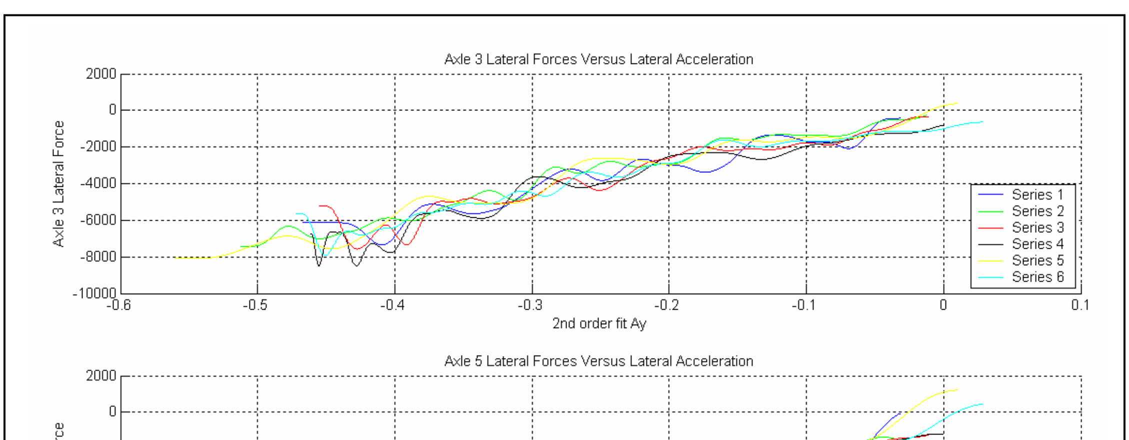


Figure 5.4.17 150 ft CCW (outside wheel) Wheel Lateral Force (lbf) vs. Lateral Acceleration (g).

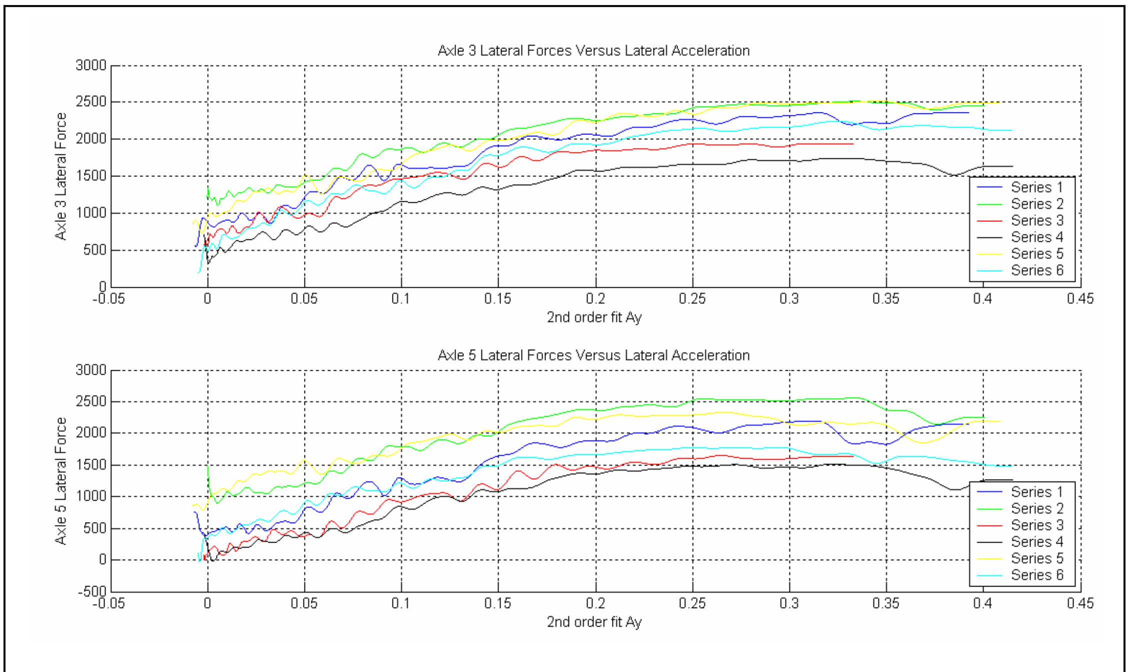


Figure 5.4.18 400 ft CW (inside wheel) Wheel Lateral Force (lbf) vs. Lateral Acceleration (g).

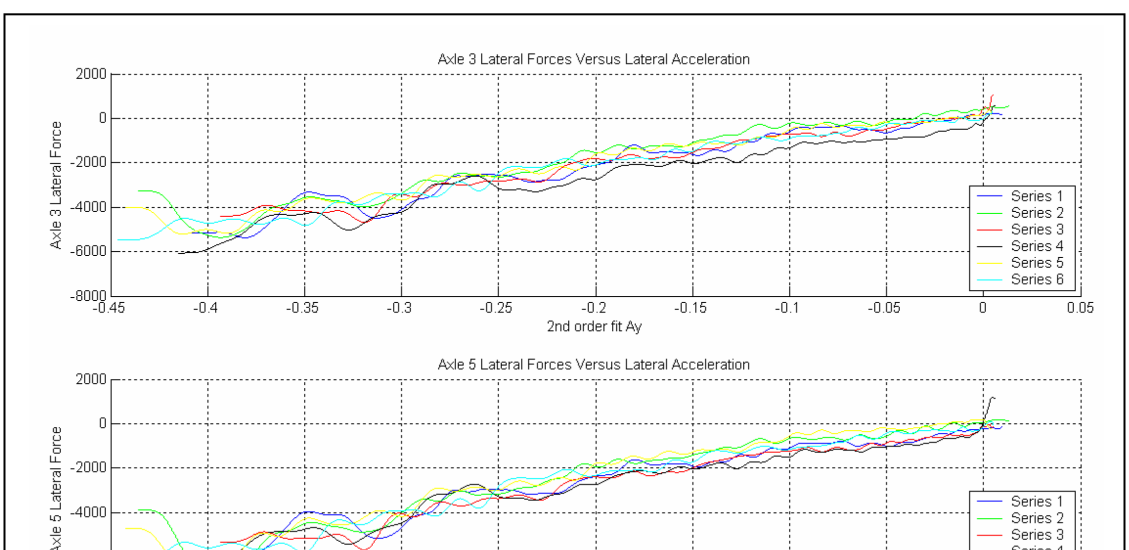


Figure 5.4.19 400 ft CCW (outside wheel) Wheel Lateral Force (lbf) vs. Lateral Acceleration (g).

5.4.3.4 Fifth Wheel Roll Moments

The roll moments were low pass filtered in the same manner as described above for the lateral acceleration data. When the filtered roll moment data were plotted against the filtered lateral acceleration data "loops" existed that caused the plots to be difficult to read (Figure 5.4.20).

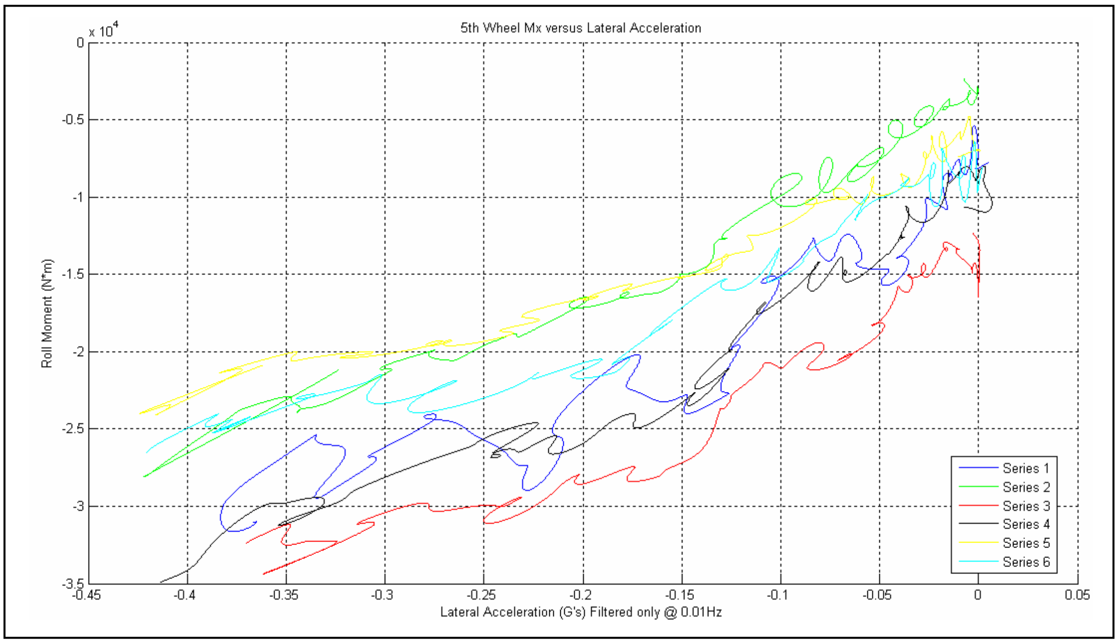


Figure 5.4.20 Filtered Fifth Wheel Roll Moment vs. Filtered Lateral Acceleration (g).

To make the plots easier to decipher, the lateral acceleration versus time data was fitted with a 2nd order polynomial after being filtered; this removed the "loops" from the data and provided a graph that was easier to read. Figure 5.4.21 is a plot of the data after the lateral acceleration had been curve fit as well as filtered. The method for curve fitting the acceleration was the same as discussed earlier in the Data Analysis section.

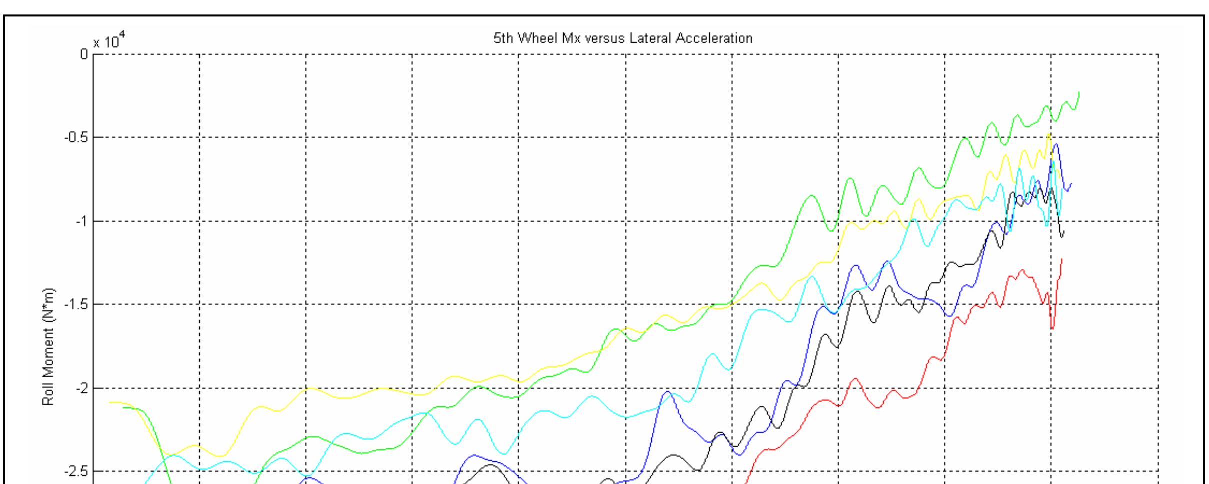


Figure 5.4.21 Filtered Fifth Wheel Roll Moment versus Filtered and Fit Lateral Acceleration (g).

The trends in Figure 5.4.21 appear to be fairly linear, so in order to determine the sensitivity values for the fifth wheel roll moment, a curve fit was applied to the data. The roll moment data (filtered) was fit against the lateral acceleration data (filtered and second-order fit) to create Figure 5.4.22. In Figure 5.4.22, the intercept of the curve fit was selected to be zero, to facilitate easy comparison between the various series of data. The sensitivities tabulated in the body of the report were taken from the values of the slope of the curve fits.

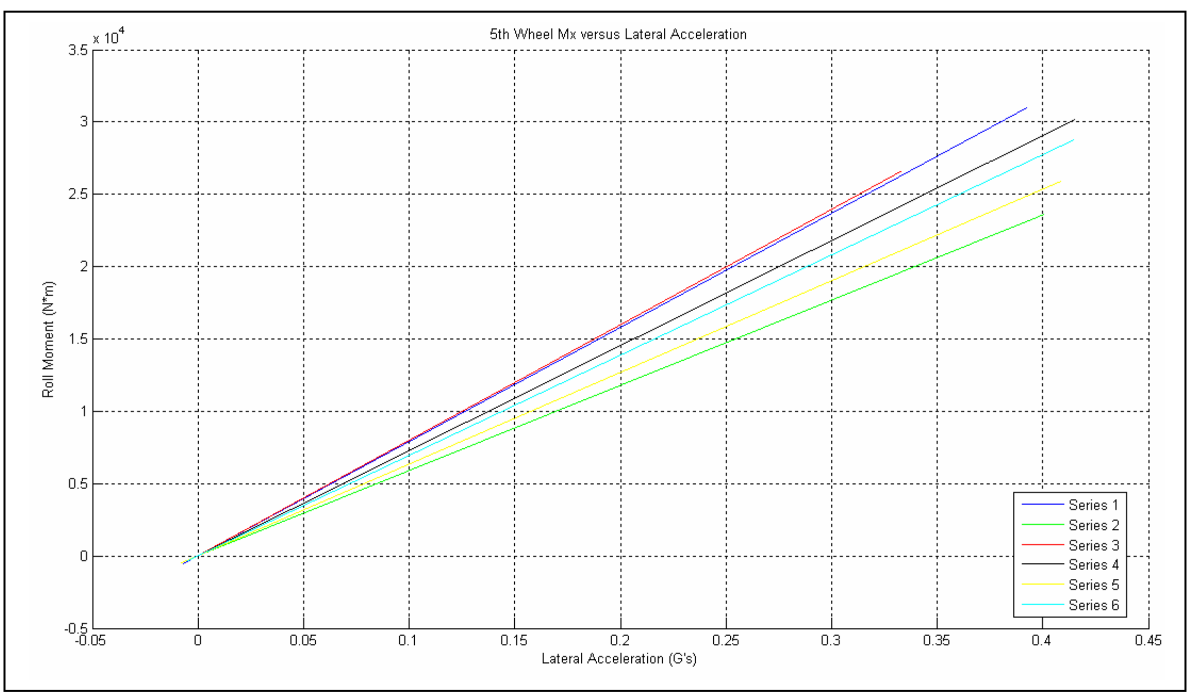
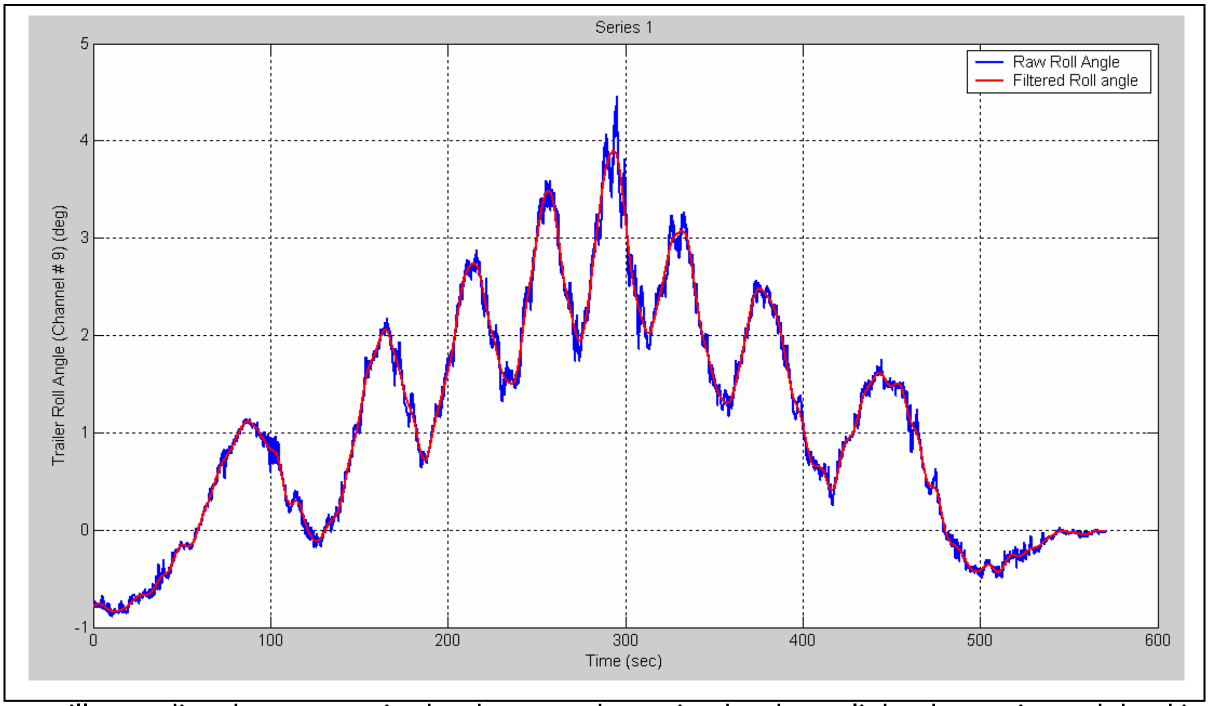


Figure 5.4.22 Fifth Wheel Roll Moment Fit vs. Filtered and Fit Lateral Acceleration (g).

5.4.3.5: Trailer Roll Angle Data vs. Time

The trailer roll angle data contains an irregularity that was determined to be due to a track banking issue. The roll angle data was plotted versus time and is presented in Figure 5.4.23.



The oscillatory disturbance seen in the data was determined to be a slight change in track banking that occurred once per revolution of the surface. Each cycle on the above plot was examined and the time interval for each cycle was found. Trapezoidal integration was applied to the speed vs. time curve over that same interval to determine the distance traveled around the circumference of the skid pad. The distance traveled during the time period of one cycle observed in the roll angle data is equivalent to the circumference of the skid pad that was being used for the test in question.

5.4.3.6 Axle 5 Absolute Roll Angle Data Processing

The plots of axle 5 absolute roll angle versus lateral acceleration are found in Figures 5.4.24 through 5.4.27. The various curve fits for each Series were plotted against lateral acceleration with the intercept of each fit selected to be zero to facilitate easier comparison.

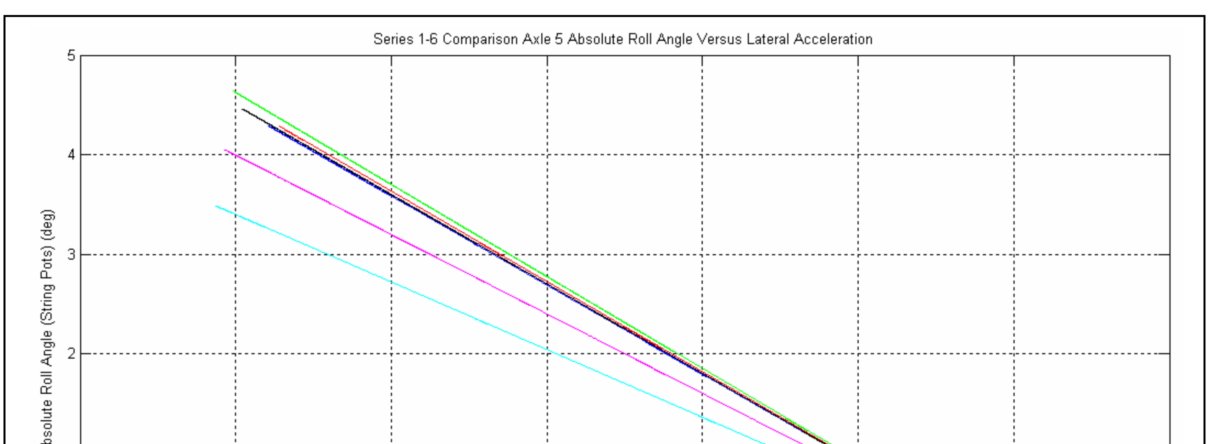
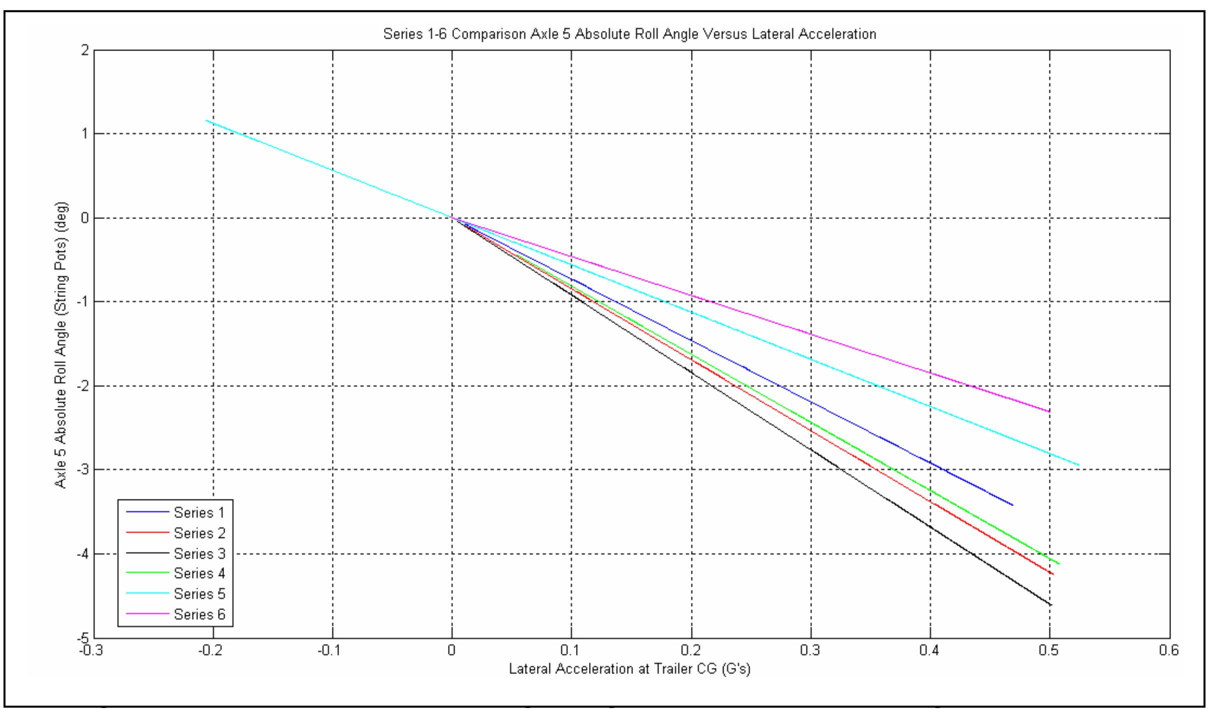


Figure 5.4.24 Axle 5 Absolute Roll Angle (deg) vs. Lateral Acceleration (g) 150 ft CCW.



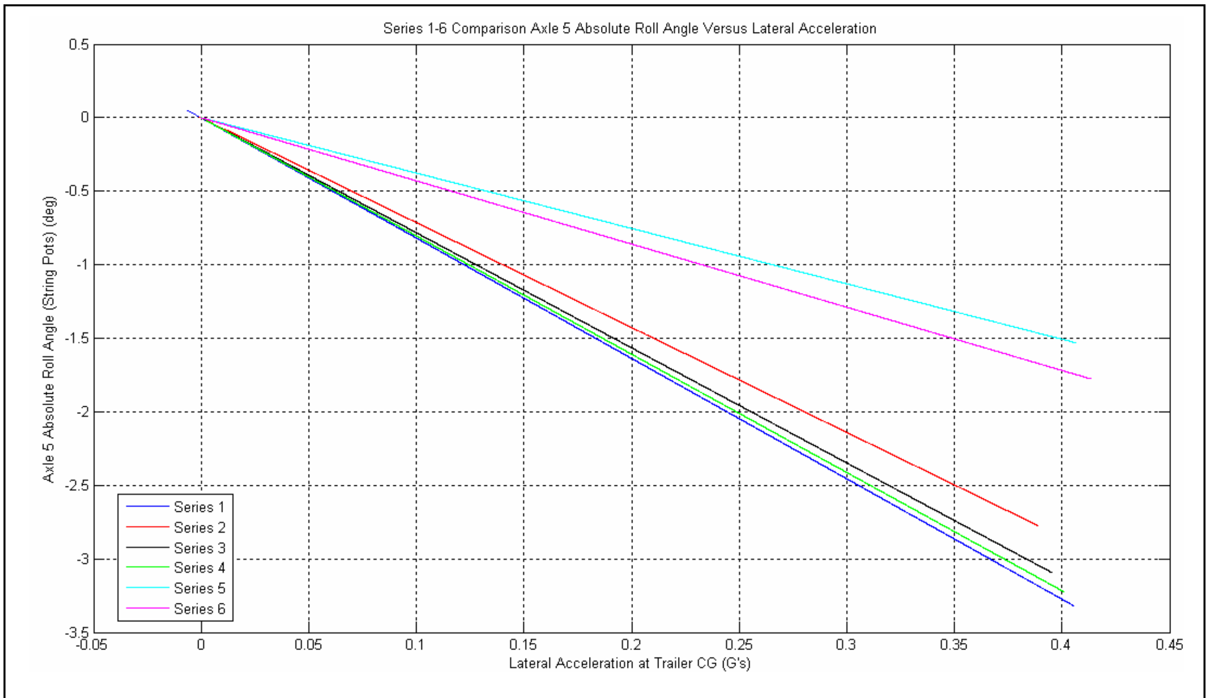


Figure 5.4.26 Axle 5 Absolute Roll Angle (deg) vs. Lateral Acceleration (g) 400 ft CCW.

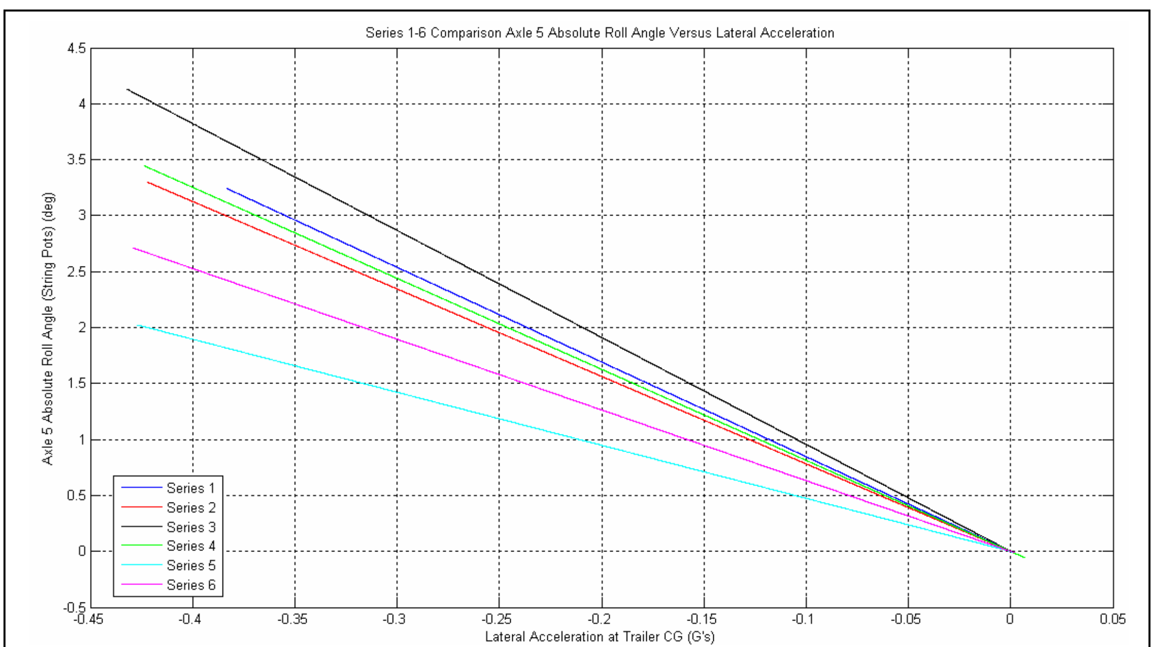


Figure 5.4.27 Axle 5 Absolute Roll Angle (deg) vs. lateral Acceleration (g) 400 ft CW.

5.4.3.7 Understeer Gradient Data Processing

To be able to investigate the understeer gradient for each vehicle configuration, it was necessary to filter and curve-fit the steering wheel angle data. Figure 5.4.28 shows the time history of the raw and filtered steering angle data.

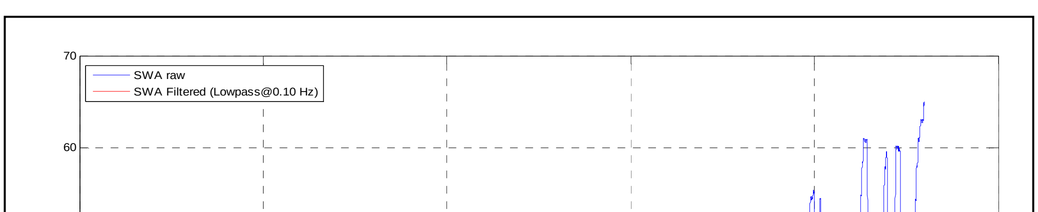


Figure 5.4.28 400 ft CW Series 5 Steering Wheel Angle (deg) versus Time (sec).

Figure 5.4.29 shows the various stages of data processing of the steering angle versus lateral acceleration. No observations can be made from the top plot of the figure containing the raw SWA and raw lateral acceleration. The filtered SWA plotted against the filtered lateral acceleration is a much cleaner plot, but contains "loops." The data was then curve fit in the final stage of processing.

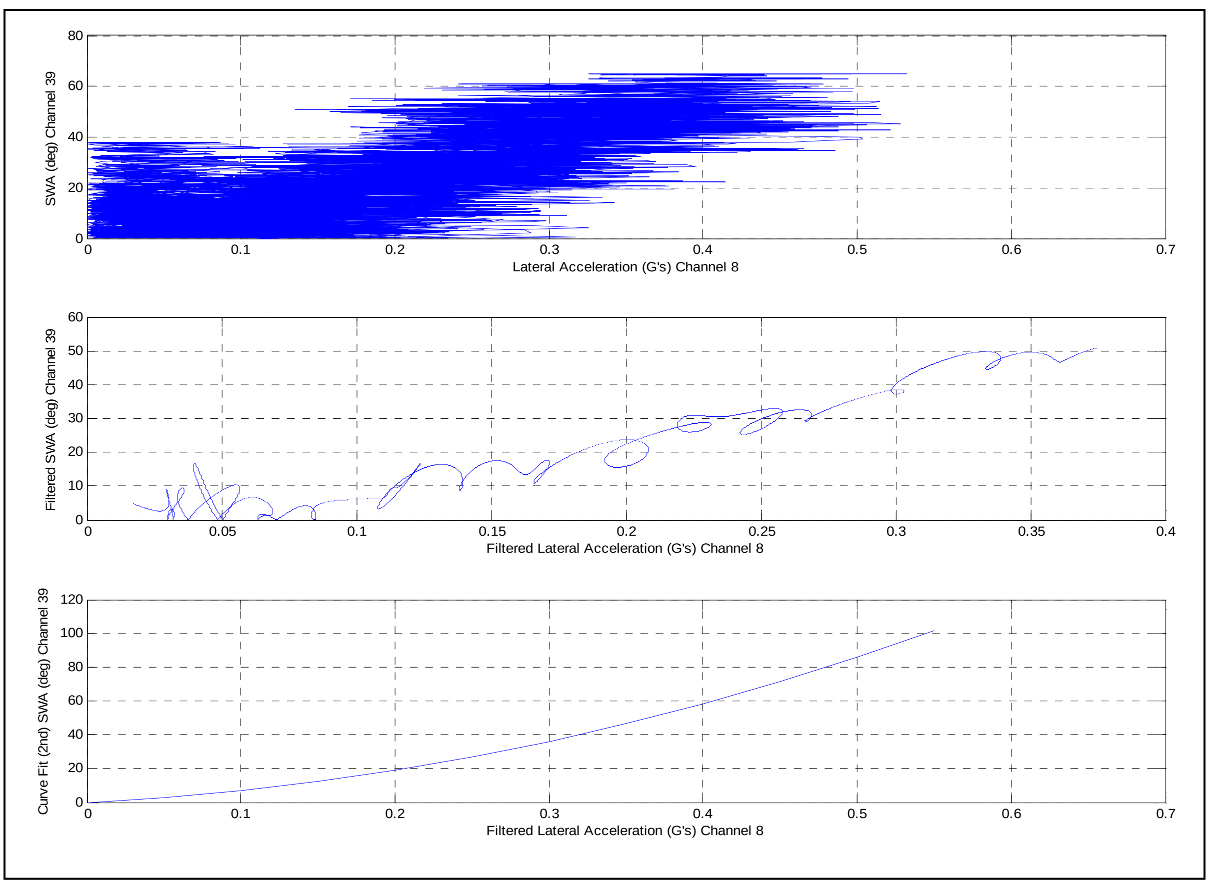
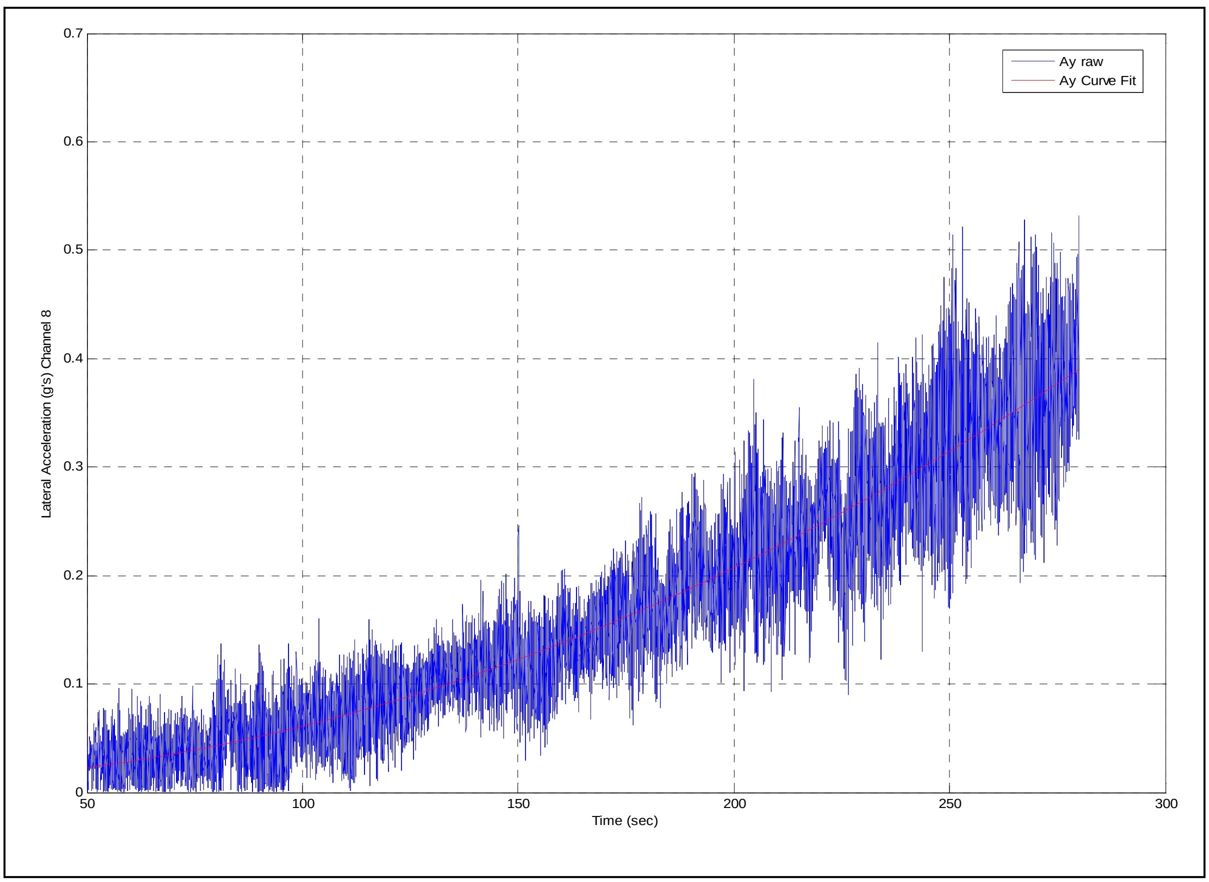


Figure 5.4.29 Steering Wheel Angle (deg) vs. Lateral Acceleration (g) (Raw, Filtered, and Curve Fit).

Figure 5.4.30 shows the lateral acceleration data corresponding to the steering wheel angle data for the Series 5 400 ft CW maneuver. This data was processed in the same manner as was described for the other lateral acceleration data used.



REFERENCES

1. M. Markstaller, A. Pearson, and I. Janajreh, “On Vehicle Testing of Michelin New Wide Base Tire,” SAE Paper 2000-01-3432

5.5 SUMMARY OF TILT-TABLE TESTING

This part of the report was prepared by Mr. Steven M. Karamihas of UMTRI under contract to Dana Corporation, as an effort within this project.

5.5.1 Overview of the Tilt-Table Testing Effort

In September and October of 2004, UMTRI conducted tilt-table tests of three configurations of a tractor-trailer combination for the purpose of determining their static rollover threshold. The tests were conducted using the UMTRI Heavy Vehicle Tilt-Table.

The test vehicle was a 1999 Peterbilt 379 tractor with a 2004 Wabash Dry Freight Van. The vehicle was loaded with steel weights within load racks placed on the floor near the front and rear of the trailer. This scheme provided loading that was concentrated over the drive axle and trailer axle suspensions, and a relatively low composite CG for the vehicle.

The front suspension of the tractor was a standard 12K Peterbilt leaf spring and beam, and the rear suspension was a Peterbilt Low Air Leaf. The vehicle was tested in three different configurations:

1. Baseline: The trailer suspension was a standard Hendrickson Vantraax (box width 48 in). Standard dual tires were mounted to the trailer and drive axles. Testing of this configuration was performed on September 20, 2004.
2. Wide-Based Tires: The trailer suspension was a standard Hendrickson Vantraax (box width 48 in), but the drive and trailer axles were fitted with new-generation single tires (Michelin 445/50R22.5). This increased the track width at both axles. Testing of this configuration was performed on September 21, 2004.
3. Modified Trailer Suspension: The trailer suspension was replaced on the trailer with a Hendrickson Vantraax with a wider-slider (box width 54 in). The drive and trailer axles were fitted with the same new-generation single tires (Michelin 445/50R22.5). The wider trailer suspension increased the trailer track width even further. In addition, the design included inward tapering of the trailing arms on the axle tube to help maintain their torsional stiffness. Testing of this configuration was performed on October 20, 2004.

Prior to testing, all tires of the test vehicle were inflated to recommended cold inflation pressures. In all tests, the fuel tank was approximately 5/8 full. Safety restraints were installed between the tilt-table and the test vehicle such that the vehicle was free to roll, up to and through the point of roll instability, but was restrained from actual rollover. All tilt tests were conducted toward the left side of the vehicle. Three repeat tilt tests were conducted for each configuration through the point of roll instability.

The rollover threshold of all three configurations exceeded the range that could be tested from a level position. As such, the "high side" tests that included the point of roll instability covered a range from about 7 deg of roll upward. Supplemental "low side" tests were performed in each configuration that started from a level position, and proceeded to a roll angle of at least 15 deg. The low and high side tests together form a complete view of the effective roll compliance of the vehicle.

The inclination of each axle platform was monitored carefully during the tests, and all of the platform angles were held to an equal value within a tolerance of 0.2 deg. Lift off of each axle was monitored using foil tape that was mounted to the tires on the four rear-most axles and to each platform. Additional sensors were placed in five locations: (1) the back of the cab, (2) the front of the tractor, at the low side wheel cover mount, (3) the rear of the tractor, in the center of a frame cross member just behind the fifth wheel, (4) the front of the trailer, on a frame cross member in roughly the same longitudinal location as the tractor rear sensor, and (5) at the rear of the trailer, on a frame cross member just ahead of the bogie. This sensor arrangement was used in all three configurations.

5.5.2 Results of the Tilt-Table Testing Effort

The primary results of the tilt tests are presented in Table 5.5.1 and Figure 5.5.1. The lateral acceleration at the point of instability is the tangent of the tilt-table angle when the last of the drive and trailer axle light side tires loses contact with the table. The loss of contact must be sustained for the entire test. In other words, if the tires lose contact, but come back to rest on the table, the instability point is assumed not to have been reached. The trailing drive axle was the last to lift off in all of the tests listed in table 1.

Table 5.5.1. Tilt-Table Test Results

	Lateral Acceleration at Instability (g)			
Configuration	Run #1	Run #2	Run #3	Ave.
1	0.525	0.529	0.528	0.527
2	0.545	0.542	0.544	0.544
3	0.568	0.563	0.560	0.564

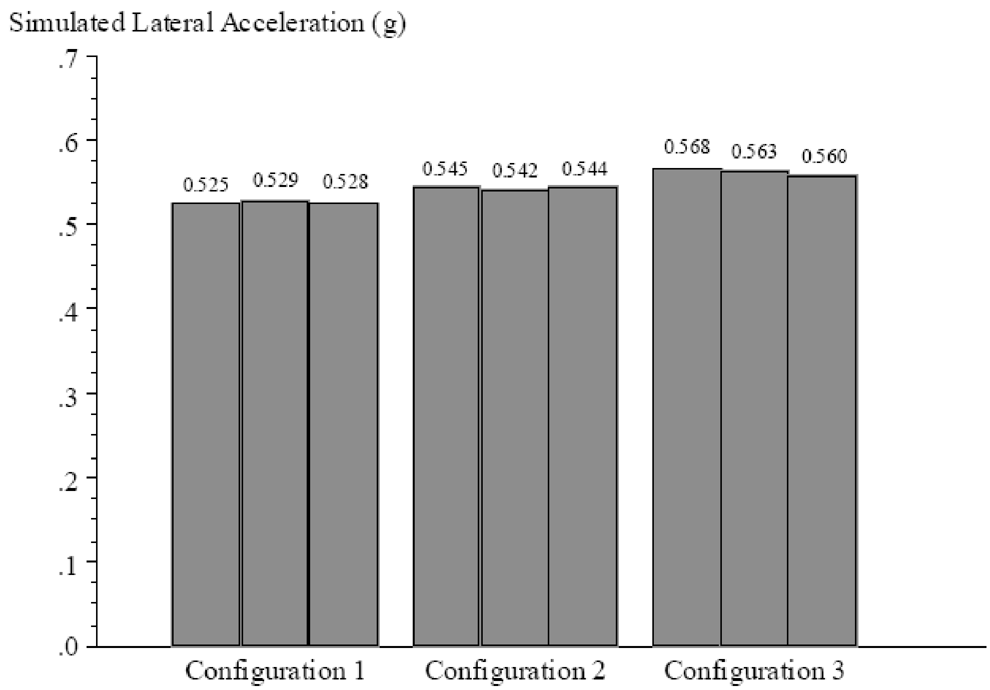


Figure 5.5.1 Tilt-Table Test Results

In configurations 1 and 2, the fifth wheel did not pass though its lash until the point of instability. In configuration 3, the fifth wheel never passed through its lash, even after the instability limit. The "late" occurrence of fifth wheel liftoff in configurations 1 and 2 was the result of the low composite CG of the vehicle. The absence of fifth wheel liftoff may have been caused by the increase in track width at the trailer suspension.

It should be noted that the first test of configuration 3 caused 40 percent of the load resting above the trailer axle to shift about 0.5 in to the left. The impact of this shift was that the simulated lateral acceleration values for configuration 3 are slightly conservative.

5.6 OPTIMIZATION TO REDUCE ROLLOVER PROPENSITY OF TRACTOR-TRAILERS DURING STEADY-STATE CORNERING

In addition to the experimental testing that was conducted, a vehicle simulation study was performed at Clemson University using and expanding upon a previously developed vehicle model. The objective of this study was to determine the vehicle parameters that most influence a vehicle's propensity to exhibit rollover behavior and to specify a vehicle configuration through optimization routines with the goal of reducing that propensity.

5.6.1 Summary of Efforts

Reducing the propensity for rollover during steady-state cornering of tractor semi-trailers is a key advantage to the trucking industry. This may be accomplished through changes in design and loading variables that directly influence the rollover behavior of a vehicle. To better understand the effects of such changes, a computer program was written by Clemson University to optimize certain design variables in an effort to minimize rollover propensity.

The vehicle model used in the optimization program extends that developed by Law [8] and presented in Law and Janajreh [9]. The original model included the effects of tire flexibility, nonlinear roll-compliant suspensions, and fifth wheel lash. This model was modified to include additional effects of:

(a) tractor and trailer torsional frame compliance,
(b) suspension displacements due to tire compliance,
(c) "off -tracking," and
(d) centroidal displacements of liquid loads.

This improved model was used within the optimization program to maximize the Rollover Indicator (RI), a practical measure of rollover propensity. The RI was calculated as an average of two components including (a) the minimum lateral acceleration for which there is no valid solution to the equations of equilibrium (or Critical Lateral Acceleration [CLA]) were rollover is imminent and (b) the lateral acceleration for which inside wheel lift-off first occurs.

Single and double variable optimizations were performed using two nominal vehicle configurations which consisted of a tractor in combination with either a dry van trailer or a liquid tanker. In both of these configurations, the tractor drive and trailer axles were outfitted with new-generation single tiles. The design variables considered within the optimizations were selected to encompass many aspects of tractor-trailer design and included suspension properties such as roll stiffness and vertical stiffness for each axle, and tire properties such as track width, cornering stiffness and vertical stiffness. In addition, operational variables such as payload placement, and adjustments to the fifth wheel and sliding tandem were considered. A summary of the single variable optimizations is given in Table 5.6.1 for ten of the variables which were found to be most influential on the RI.

Table 5.6.1 Single Variable Optimization Summary

Rank*	Optimization Variable	Maximum Changes in Nominal RI (%)			
		Dry Van Trailer		Liquid Tanker	
Nominal RI		0.438 g		0.416 g	
1	Shift in Vertical Payload CG Location (m)	+21.7	-15.9	+19.7	-15.0

2	Adjustment in Axle Roll Bump Stop Clearance, deg (All Tractor Axles)	+14.2	-2.4	+14.2	-2.6
3	Trailer Payload Distribution Case Number	+13.5	-12.3	+10.1	-11.2
4	Track Width Multiplicative Factor (All Axles)	+11.7	-11.5	+11.8	-11.7
5	Track Width Multiplicative Factor (All Trailer Axles)	+7.5	-7.5	+7.7	-7.5
6	Overall Tractor Sprung Mass Torsional Stiffness Multiplicative Factor	+5.3	-17.1	+7.6	-17.5
7	Shift in Longitudinal Payload CG Location (m)	+4.3	-4.6	+5.3	-5.0
8	Track Width Multiplicative Factor (All Tractor Axles)	+4.1	-3.0	+4.2	-3.2
9	Tractor Sprung Mass Torsional Stiffness Distribution Case Number	+3.9	-7.0	+4.6	-7.1
10	Adjustment in Axle Roll Bump Stop Clearance, deg (All Tractor Axles)	+3.7	-2.4	+4.9	-2.6

*Ranking based on maximum increase over nominal RI values.

5.6.2 Observations Made Based on the Single Variable Optimization Results

Numerous observations were made based on the single variable optimization results. A summary of these observations is given below.

1. Vertical payload location was ranked as the single most influential variable on the RI. By-minimizing the height of the payload CG, the nominal RI values were increased by 21.7% and 19.7% for the dry van trailer and liquid tanker configurations, respectively. Changes in the longitudinal payload CG location were less influential yet still important, yielding a maximum increase of 4.3% and 5.3% for the two optimization configurations. To maximize the RI, the payload should be positioned longitudinally as far aft as possible. The actual amount by which the payload CG can be moved, however, is limited by the geometry of the trailer as well as the legally prescribed static axle normal loads.

2. The angular or roll clearance of the roll bump stops for the tractor axles was ranked as the second most influential variable on the RI. By minimizing the clearance on these axles, the nominal RI values were increased 14.2% for each optimization configuration. Reductions in the roll bump stop clearance for the trailer axles, however, was found only to reduce the RI. Thus, the clearance associated with the trailer axles should be maximized to avoid bump stop contact for these axles altogether.

3. Distribution of the payload along the length of the trailer was the third most influential variable on the RI. In order to maximize the RI, the majority of the payload should be distributed over the trailer axles. For the dry van trailer and liquid tanker configurations, optimization of the payload distribution resulted in maximum increases in the nominal RI values of 13.5% and 10.1%, respectively. Distribution of the tractor and unloaded trailer sprung weight had a much less significant effect on the RI, as compared to the payload distribution.
4. The track widths of the tractor and trailer axles were found to significantly influence rollover behavior. The trailer axles, however, were shown to be more influential on the RI than the tractor axles. Nonetheless, the track width of all axles should be maximized to yield the largest RI values. By increasing the track width of all axles 10%, increases over the nominal RI values of 11.7% and 11.8% were obtained for the dry van trailer and liquid tanker configurations.

5. The torsional stiffness of the entire tractor sprung mass was found to have a significant effect on the RI. By maximizing this stiffness, the CLA is also maximized. However, to maximize the RI, which takes into account the CLA and inside wheel lift off, the torsional stiffness should not be

maximized. For the two configurations considered, optimal values for the tractor sprung mass torsional stiffness were between 1.7 and 2.6 times the nominal stiffness value. The torsional stiffness of the trailer sprung mass was found to have a negligible effect on the RI.

6. While maintaining the same overall torsional stiffness, significant increases in the RI were obtained by increasing the local torsional stiffness of the tractor frame around the location of the fifth wheel. The maximum increases over the nominal RI values were 3.9% and 4.6% for the dry van trailer and liquid tanker configurations. The effect of the trailer sprung mass torsional stiffness distribution on the RI was negligible.

7. The presence of fifth wheel lash serves to reduce rollover stability and the RI. Thus, to maximize the RI, the amount of fifth wheel lash should be minimized. By reducing the amount of lash from the nominal value of 2.0 deg to 0.05 deg, the RI was increased by 2.5% and 2.6% for the dry van trailer and liquid tanker configurations.

8. Disparate suspension and tire characteristics among axles contained within an axle group were found to significantly reduce the RI. Thus, to avoid these reductions, properties such as roll stiffness, vertical stiffness, and tire cornering stiffness should be made approximately equal for axles which are in close proximity to each other. Of course, the amount by which the properties of two axles should be allowed to differ depends on how closely those axles are located.

9. Per-axle suspension roll stiffness was found to have a small effect on the RI. To maximize the RI, the roll stiffness of the tractor axles should be made as large as possible whereas the stiffness for trailer axles should be minimized. With 80% of the nominal stiffness values for the trailer axles, the nominal RI values were increased by 1.8% and 1.7% for the dry van trailer and the liquid tanker configurations, respectively. By increasing the roll stiffness of the tractor axles to 120% of the nominal values, the increases were 1.5% and 1.6%.

10. The static axle normal loads also have a significant influence on rollover behavior. These normal loads can be altered by making adjustments to the longitudinal placement of the fifth wheel and each axle. To maximize the RI, these adjustments should be made to place additional load on the trailer axles. For the configurations considered, this required forward movement of each axle and aft movement of the fifth wheel, each with respect to the location of the sprung mass CG. Out of these adjustments, placement of the sliding tandem had the greatest influence on the RI yielding maximum increases over the nominal RI values of 1.1% and 1.6% for the dry van trailer and liquid tanker configurations.

5.6.3 Double Variable Optimizations

Double variable optimizations were also performed using combinations of variables identified as most influential in the single variable optimization study. These optimizations were found to result in significant increases in the nominal RI values. The maximum increases were 35.4% and 33.3% for the dry van trailer and liquid tanker optimization configurations, respectively. These increases were obtained through optimization of the vertical payload location and the roll bump stop clearance of the tractor axles.

In all of the optimization configurations the tractor drive and trailer axles were outfitted with new-generation single tires. These tires differ from conventional dual tires in that they provide increased track width yet have decreased vertical stiffness. To evaluate the effects of these differences, a comparison between new-generation single tires and conventional tires was performed for each of the optimization configurations. The use of new-generation single tires as opposed to conventional dual tires on the tractor drive and trailer axles was found to result in higher values for RI. For the dry van trailer configuration, the RI was increased by 3.6% whereas for the liquid tanker configuration, it was increased by 3.2%.

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6. SUMMARY OF RESULTS

6.1 REVIEW OF PROJECT EFFORTS

Virtually all compliances have the potential for degrading stability. Major influences that affect roll stability include:

- Rigid vehicle stability factor (T/2h),
- Compliant tires,
- Compliant springs,
- Fifth wheel and spring lash,
- Multiple suspensions,
- Lateral suspension and body compliances, and
- Off-center cargo[10].

As a result, understanding truck rollover is complex, and the facilitation of a thorough understanding of the area requires carefully controlled experiments and a significant amount of data collected through such experiments. The research conducted in this project was the initiation of a long-term focus of truck rollover efforts under the HVSRC. The ultimate goal is to provide insight into improving the roll stability of heavy trucks to support the reduction of fatalities and injuries on our nation's highways. Additionally, avoidance of truck rollover crashes will contribute to stabilizing the profit margins of the trucking industry.

The efforts within this research were conducted through a small amount of funding that originally came from the FHWA. These funds were generously supported by the in-kind contributions provided by the industry partners on this project, namely Dana Corporation, and Michelin Americas Research and Development Corporation. Their efforts permitted significant leveraging of the funds from FHWA, and allowed for the conduct of multiple controlled test track efforts, not only from a financial point-of-view, but also because of the significant intellectual capital brought to the team by these partners.

A significant amount of data was collected and analyzed by the team, and although there were significant findings, the amount of data collected was still insufficient to support rigorous statistical tests. Data to support such rigor would have significantly increased the cost of these efforts. This should in no way minimize the value of the research conducted in this effort. The specific findings are summarized below.

6.2 EVASIVE MANEUVER

For the data analysis of this maneuver, ORNL looked at the ratio between maximum Trailer Rollover Angle and the maximum Lateral Acceleration. This ratio is also known as the roll stiffness index. Although the lack of data did not allow for the performance of statistical tests over the data collected, the results indicate that the studied wheel/tire layouts (Series 2 to 6) consistently performed better than the standard layout (Series 1, i.e., both tractor and trailer with dual tires). The results also indicate that Series 5 and 6 were the best performers of all of the six Series analyzed. Both Series 5 and 6, which used a wider-slider for the trailer, improved stability and increased the stiffness of the trailer.

[10] Winkler, C.B., D. Blower, R. D. Ervin, and r. M. Chalasani. (2000). *Rollover of Heavy Commercial Vehicles,* SAE Research Report, Warrendale, PA.

DANA followed four different approaches in analyzing the evasive maneuver data. In the first one, Vehicle Speed at Wheel Lift, although an interesting variable, was inconclusive because it did not account for steering input and vehicle path. The second approach concentrated on analyzing the Trailer Lateral Acceleration at Wheel Lift. Although an overall trend in the data was difficult to decipher, the results showed that Series 3 (i.e., new generation tires on both the tractor and the trailer) required the greatest lateral acceleration to lift the rear trailer axle wheel, while Series 2 (i.e., new-generation tires on the tractor) was the least stable. The third methodology concentrated on the tractor and trailer lateral acceleration at wheel lift. In this case, the results suggested that Series 1 and 2 exhibited the least stability; while Series 4 (i.e., new-generation tires on the trailer), Series 5 (i.e., same as Series 3 but with a wider-slider), and Series 6 (i.e., same as Series 4 but with a wider-slider), appeared more stable. The fourth analysis centered on the roll moment at the fifth wheel. Here, Series 5 and 6 exhibited the least roll moment sensitivity by a wide margin. Series 3 and 4, with the new-generation single trailer tires and standard width suspension, had the highest sensitivity and were thus the least stable configurations.

6.3 CONSTANT RADIUS MANEUVER

ORNL used the same approach as in the case of the Evasive Maneuver to analyze the results of the Constant Radius Maneuver. Similarly to the Evasive Maneuver Test, the 150 ft Radius CW Turn Test showed that Series 6 and 5 performed the best when compared to the basic case (Series 1), followed by Series 2 and 3. Series 4, on the other hand, appears to be worse than Series 1. Again, since there was only one observation per series for this test, it was not possible to statistically analyze the results.

Clemson University also analyzed the data collected for this maneuver, not only for the 150 ft radius, but also for 400 ft radius. Different variables were analyzed in this case, including Trailer Roll Gradient (deg/G), Fifth Wheel Roll Moment Sensitivity, and Axle 5 Absolute Roll Angle Sensitivities. For the Trailer Roll Gradient analysis, the data indicated that Series 5 rolled less per unit g than the other series; with Series 6 following in all cases for which it was not the best (similar to the results found by ORNL for this maneuver).

In general, the lower the roll moment sensitivity, the lower is the rollover propensity of the vehicle. This is the result of a smaller roll moment being generated per unit of lateral acceleration. To study this, Clemson looked at the Fifth Wheel Roll Moment Sensitivity. The results of the analysis indicated that Series 5 gave the best overall performance in terms of roll moment generation, followed somewhat closely by Series 6. When the Axle 5 Absolute Roll Angle Sensitivities were analyzed, the data indicated that Series 3 exhibited more axle roll than the other series. This might be expected since Series 3 had new-generation single tires mounted on the tractor drive axles and the trailer axles. The new-generation single tires have less-stiff sidewalls than the dual tire configuration. Series 4 showed the next highest axle roll angles; Series 4 is also the only other Series with new-generation single tires mounted on the trailer axle without the wider-slider.

Clemson University also analyzed the understeer gradient for the six Series under both 150 ft and 400 ft constant radius maneuver. The understeer gradient is the slope of the line on a plot of steering wheel angle vs. lateral acceleration. For the trucking industry, understeer (a positive slope) is a more desirable characteristic than oversteer (a positive slope) because it results in more ease of control of the truck.

In the case of the 400 ft constant radius test, Series 1 and 2 showed understeering characteristics, which decreased as lateral acceleration was above 0.3 g. Series 3 showed a gradual tendency toward decreasing understeer for the CCW maneuver, and the reverse trend for the CW maneuver. For Series 4 the data indicated an almost neutral steer performance (a questionable result that could be an artifact of malfunctioning sensors). Series 5 exhibited understeer which increased with lateral acceleration, while Series 6 showed that the dominant understeer characteristic trends towards oversteer at higher values of lateral acceleration.

For the 150 ft constant radius tests, the results indicated that Series 1 had less variation in understeer gradient with lateral acceleration as compared to its behavior on the 400 ft skid pad. Series 2 (both CW and CCW) and Series 3 (CW) appeared to exhibit increasing understeer at higher lateral accelerations. Series 4 (CW) and Series 5 (CW and CCW) showed decreasing understeering with increasing lateral acceleration. Series 6 showed a tendency to oversteer much more severely on the 150 ft skid pad than the 400 ft. Series 6 maintained the dominant understeer characteristic for the 400 ft skid pad; however on the 150 ft skid pad the vehicle exhibited dominant oversteer above 0.3 g. In summary, it appears that Series 5 performed the best in this test for both the 150 ft and 400 ft constant radius maneuver.

The Tilt-Table Tests analysis conducted by the UMTRI showed that the values for liftoff of axle 3 that were determined from the steady cornering tests are quite close to those predicted using the tilt-table – an interesting result given that one test was static and the other dynamic. Therefore, both methods for determining steady-state cornering ability and rollover characteristics of heavy vehicles can be regarded with a higher level of confidence.

6.4 SWEPT SINE MANEUVER

The Michelin Americas Research and Development Center analyzed the Swept Sine maneuver for this study. Six frequency response functions (FRFs) were computed to include an analysis of the coherent frequency range of each. The FRFs, which were computed for both tractor and trailer, included yaw rate-to-steering wheel angle, lateral acceleration-to-steering wheel angle, and trailer roll-to-trailer lateral acceleration. In general, the results showed that differences between the test series were small with the exception of the wider-slider configuration. In that case, the trailer roll gain was noticeably lower with the wider-slider configuration.

For the tractor yaw rate-to-steering wheel angle, the results of the analysis showed that no apparently significant differences were present between series within the highest coherent range (i.e., 0.2 Hz to nearly 2.0 Hz), with the possible exception of Series 3 having somewhat lower yaw rate gain. In the case of trailer roll-to-trailer lateral acceleration and within the highest coherence range (i.e., 0.2 to 0.7 Hz), the analysis indicated some distinct behavior between series in the magnitude FRF, particularly for Series 5 and Series 6 which use the wider-slider configuration on the trailer. The estimated roll gain is clearly less for the two wider-slider series. No significant difference in phase lag was noted within the frequency range of interest.

6.5 SIMULATION MODELING

For this study, Clemson University investigated, analytically, which design and loading variables had the largest impact in minimizing rollover propensity. They accomplished this via a computer program which was written to study the effect of these variables on the rollover propensity. The vehicle model used in the optimization program was an extension of original simulation models developed to study the effects of tire flexibility, nonlinear roll-compliant suspensions, and fifth wheel lash. The modifications included additional effects of (a) tractor and trailer torsional frame compliance, (b) suspension displacements due to tire compliance, (c) "off -tracking," and (d) centroidal displacements of liquid loads. This improved model was used within the optimization program to maximize the Rollover Indicator (RI), a practical measure of rollover propensity.

Single and double variable optimizations were performed to determine optimal design variable values that would maximize the RI. The design variables that were found to be most influential on the R1 were identified and include: payload placement, roll bump stop clearance, payload distribution, track width, and torsional stiffness of the tractor sprung mass.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

The Truck Rollover Characterization Project was conducted by a team of professionals involving a national laboratory, private industry, and academia. The expertise mix from these types of organizations coupled with complementary research needs and interests, and a positive "can-do" attitude provided an extremely positive experimental research opportunity for all involved. Furthermore, this team supplied resources that provided a strong positive benchmark regarding the ability to conduct research within a public-private partnership.

One of the primary insights from this research experience was that flexibility in project definition was key in balancing the research interests and needs of the partners. That is, when there are opportunities to seek creative ways of addressing the diversity of partner goals, large complex projects can be formulated and executed in ways that are beneficial to all.

The project contributed significantly to the understanding of the roll stability and roll characteristics of heavy trucks. In particular, the data and analyses related to the performance of the tractor-trailer in harsh maneuvers using both standard dual tires and new-generation single tires, and utilizing wider-slider suspensions is unique and suggests that real and significant improvements in roll stability for tractor-trailers are indeed possible via tire and suspension improvements. Although the data collected in this project did not lend itself to statistical testing, the preponderance of the evidence and the associated data trends suggest that the performance of new-generation single tires consistently resulted in improved roll stability over the performance of standard dual tires. When the wider-slider suspension was added, performance improved even more.

It is concluded that the use of next-generation single tires and wider-slider suspensions seem to provide improved roll stability for class-8 tractor-trailers. Quantification of this effect should be conducted through additional research, and similar studies should be conducted on flat-bed trailers and tankers. Lastly, other technologies exist and are emerging that could also contribute to improved roll stability. Future research involving public-private partnerships that reflect a vested interest on the part of all partners may be the key toward the accomplishment of this important and costly research.

7.2 RECOMMENDATIONS

Even the smallest advances in vehicle stability can reduce truck rollover propensity and consequently contribute to the reduction of the heavy truck rollover accident rate. Roll stability can be increased by a variety of methods:

- Increase track width,
- Decrease CG height,
- Increase the stiffness of the truck frame to allow the driver to sense roll motions of the trailer as a rollover propensity cue,
- Decrease tire compliance to limit the lateral translation of the CG,
- Raise the suspension roll center to reduce body roll angle,
- Increase drive axle suspension roll stiffness,
- Increase front axle suspension roll stiffness while simultaneously considering ride quality trade-offs,
- Eliminate fifth wheel and spring lash, which appear as free play in the rolling motion,
- Distribute load among suspensions in proportion to the distribution of roll stiffness,

- Reduce lateral compliance (deflection) of the suspension,
- Reduce lateral beaming of the vehicle frame,
- Minimize the angular or roll clearance of the roll bump stops for the tractor axles,
- Maximize the roll bump stop clearance for the trailer axles,
- Ensure cargo is placed on-center to control lateral displacement of CG, and
- Reduce torsional compliance of the vehicle frame, particularly flat-bed trailers.

The data and information provided in this report, along with the direction of future rollover phases (see Section 8) provide insight for the development of rollover prevention systems. Examples of these systems are an active roll stabilizer, active yaw control using differential braking, audible warnings based on lateral acceleration compared to the predetermined static rollover threshold, and visual warnings displaying lateral acceleration and rollover threshold.

The data for the evasive maneuver suggested that the truck driver plays a significant role in the quality of the evasive maneuver. From the experiences of the evasive maneuver testing, it is clear that it is not possible for a human being to reproduce the same path every time that this maneuver is conducted (ideal situation), particularly if the wheel and tire layout are changed from test to test, and there is only a short time for the driver to gain practice and to acquire a better "feeling" of the truck drivability. By carefully analyzing the data, those runs in which the evasive maneuver was not performed as planned (i.e., only two turns as opposed to two turns plus a corrective maneuver) were identified, and those that were not performed correctly were eliminated from the analysis dataset. Unfortunately, this reduced the usable data to a few points that were usable in the conduct of the analysis.

It is proposed that this test, which proved to be very valuable in determining the performance of the different wheel and tire layouts studied, be conducted with the aid of a driving robot to keep the variability introduced by the driver to a minimum. The evasive maneuver is simple enough so that a robot can perform it with very few problems. However, it is expected that for each Series, the robot steering would have to be adjusted to maintain the same trajectory for all the tests. This would mimic a real-world situation in which the driver, with enough experience with each tire/wheel combination, can follow exactly the same trajectory, thus eliminating the driver factor from the analysis.

If this maneuver were to be performed in this way, it would be possible to have a higher number of replications of the test so that the results could be statistically analyzed. A larger sample size would also help clarify some effects that were difficult to explain with a very small number of observations. For example, what effect do dual tires on the tractor have when combined with new-generation single tires on the trailer? Series 4 indicated less stability than Series 3, but Series 6 had higher roll stiffness than Series 5. The most rigid configurations have the least compliance. However, because the use of single tires is expected to yield more tire compliance than the dual tires, future research in this area is suggested.

8. FUTURE EFFORTS

8.1 VISION

Almost all testing and data collection done in the area of truck rollover has been accomplished with dual tires on tractors and trailers and standard width tractor and trailer frames designed for dual tires. With the introduction of new-generation single tires and with their growing acceptance by trailer manufacturers, truck manufacturers, and end users, testing is needed to better understand the effects on rollover of this type of tire fitted onto vehicles with axles, suspension, and frames optimized for the new-generation single tires. While some testing has occurred using the new-generation single tire, such tests have been conducted almost exclusively on vehicles using axles, frames, and suspensions optimized to the dual tire configuration. These axles, frames and suspensions are not optimized for the new-generation single tires, which allow for wider frame rails, increased torsional stiffness, and lower vehicle CG. Each of these factors increases vehicle safety by decreasing the vehicle's propensity for roll.

By integrating new-generation single tires, wider axles, associated suspensions, wider frames and torsionally stiffer frame-rails, a vehicle component combination can be created to take better advantage of the new-generation single tire's stability and space saving footprint.

To fully understand and isolate the effects of tire, axle, suspension, and frame changes to overall vehicle dynamics and rollover characteristics, each tire, axle, suspension, and frame change will have to be tested and compared to the vehicle configurations used in the Phases 1 and 2 of this project. Further, the same types of tests will have to be conducted to validate expected improvements in vehicle stability. Much of this testing can be accomplished via computer simulation and modeling, but key baseline data as well as post vehicle modification verification testing will need to be conducted to provide the needed input data for the computer modeling process and to validate the computer modeling results.

With the completion of Phase 1 and 2 testing, the research team in this project has drafted a statement-of-work to build on the initial efforts of the rollover testing with the goal of generating additional data and information on truck rollover not currently available in the industry. This proposed new effort combined with Phase 1 and 2 Rollover Testing will provide a deeper understanding of rollover characteristics and will contribute towards development of a heavy vehicle dynamics model that is reflective pf project results. The focus of this work will be in six areas:

1. Improving truck/trailer suspensions relative to rollover,
2. Vehicle torsional stiffness improvements.
3. Lowering of vehicle CG for tankers and tractors,
4. Better understanding of the dynamics at the fifth wheel,
5. Enhanced understanding of tire performance and vehicle stability, and
6. Enhanced understanding of tire-road interface and roll stability.

Other elements of a longer-term research program (e.g., the effects of active suspensions, electronically controlled braking, active tire pressure changes, road-edge effects, and run-off-the-road (including military vehicle applications) on roll stability) will be considered as funding is made available for such work.

The goals of this research will be to:

- Generate data and information on heavy vehicle suspensions specifically designed for new-generation single tires that will contribute to better understanding of suspension roll stability and roll characteristics.
- Compare recently obtained (Phases 1 and 2) data from rollover tests with the predictions of rollover models.
- Utilization of rollover models in conjunction with the ride models to examine design trade-offs for good performance as measured by the driver's ride environment and the resistance of the vehicle to rollover.
- Facilitate understanding of the effects that suspension roll characteristics have on overall vehicle roll stability.
- Generate vehicle dynamics data for truck rollover events with emphasis on dynamics associated with a tractor-trailer's fifth wheel.
- Utilize rollover data to generate and validate truck rollover models/modules.
- Determine predictive indicators of roll stability capable of providing a pro-active alert/warning to drivers.
- Assist in gaining insights from the effects of improving torsional stiffness in an integrated suspension.
- Assist in gaining insights from the effects of lowering the CG of tanker trailers by lowering the placement of the tank.
- Assist in gaining insights from lowering the CG of the tractor by and moving tractor components (e.g., fuel tanks) in-board of the frame rails.
- Contribute to the compilation of truck rollover data and information within a national data repository for use by researchers in government and industry.

Because of the large scope of this research, vehicle testing will be done in "Phases." Each phase will build on the knowledge gained and success of the previous test, and each will address different vehicle combinations and tire/axle/frame types. Such a phased approach will allow various private industry partners to participate in particular phases that are of interest to them.

8.2 PHASE 3 RESEARCH EFFORTS

Phase 3 research will involve a dry box van trailer, a flatbed trailer, a tanker trailer, and a standard frame class-8 tractor. Baseline rollover data will be gathered on the flatbed trailer and the tanker trailer to compliment the data gathered in Phases 1 and 2. Additionally, torsional stiffness data will be measured for all platforms.

Testing of the flatbed and tanker trailers will be performed with new-generation single tires and dual tires. Kinematics & Compliance (K&C) characterization will be done on these trailers along with a new procedure to evaluate torsional stiffness. A Finite Element Analysis (FEA) of the trailers will be done and compared to K&C results.

The data gathered during this testing will be used along with the data gathered in Phases 1 and 2 to model and simulate potential changes to currently existing axles, frames and suspensions. Simulation of the tests will be performed with a TruckSim or ADAMS model. From this modeling and simulation effort, recommendations of actual hardware changes will be identified in order to optimize these vehicle systems and components to take better advantage of the new-generation single tires. These hardware changes will be implemented in Phase 4. FEA analysis of the modifications will be done to quantify the gain in stiffness. Likewise, simulations in TruckSim/ADAMS will quantify the gain in rollover threshold. The project partners will work "from a clean sheet of paper" to define the critical vehicle (tractor and trailer) parameters to maximize the rollover threshold, handling, and ride comfort without significantly compromising the vehicle durability or other important factors such as fuel economy.

8.3 PHASE 4 RESEARCH EFFORTS

Phase 4 research will involve a modified class-8 tractor with widened frame rails and axles along with a redesigned suspension and new-generation single tires. It is expected that these modifications may involve adding new rails along side of the existing rails and adding needed cross-member support to increase torsional stiffness. These modifications will mimic, to a large extent, a production tractor with wider frame rails. FEA analysis and vehicle dynamics simulations will be done on the tractor to verify gains in stiffness and rollover threshold.

The trailers will undergo similar modifications to improve roll performance and in the case of the tanker, lower the overall effective CG of the vehicle. This will be done by lowering the tanker into the space made available by the new-generation single tires and the wider frame rails. Flatbed trailer torsional stiffness may be increased by widening the frame rails or modifying the suspension to take advantage of the extra space provided by the new-generation single tires.

These “optimized” platforms will be tested again and comparisons will be made with the baseline data to assess the effectiveness of the modifications including roll propensity and torsional stiffness. Upon completion of the testing and analysis, additional modeling and simulation will be conducted to allow recommendation of "advanced" changes for future testing not defined in this report.