Heavy Truck Rollover Characterization: New Generation Single Tires vs. Standard Duals

H. E. (Bill) Knee, Gary Capps and Oscar Franzese
Oak Ridge National Laboratory
Center for Transportation Analysis
Knoxville, Tennessee USA
E-mail: kneehe@ornl.gov

Paul Pollock and Daniel Coleman
Dana Corporation

Ibrahim Janajreh, Steven Haas and Norman Frey
Michelin Americas Research and Development Corporation

Harry Law and Eric Johnson
Clemson University

Joe Petrolino and David Rice
National Transportation Research Center, Inc.

Summary/Abstract: Heavy truck rollover crashes are not frequent occurrences. They represent approximately three percent of all crashes and 13 percent of all crashes involving fatalities for combination trucks. Although this percentage is low, fatalities associated with heavy truck rollovers are inordinately high.

The research reported in this paper was conducted under sponsorship of the National Transportation Research Center, Incorporated (NTRCI) for the Federal Highway Administration (FHWA). The objective of this research was to form a baseline analysis of tractor/trailer rollover characteristics for further comparative studies, to look at run-off road contributions to rollover and to do a preliminary analysis of the impact of replacing standard duals with next generation single radials.

The approach was to instrument a class-8 tractor-trailer with various vehicle dynamics sensors and outriggers, and to engage in various rollover catalytic maneuvers (evasive maneuver, constant radius, and run-off-the-road). A Swept Sine test was also conducted to collect data regarding the vehicle's dynamic frequency response. Data (e.g., lateral acceleration, trailer roll angle) were captured for maneuvers conducted with standard duals on the tractor and trailer (base case), new-generation singles on the tractor and trailer, combinations of singles and doubles on tractors and trailers, and included runs which involved the use of wider-slider suspensions on the trailer.

Results from six test series showed that in most cases, the use of new-generation single tires and wider-slider suspensions, provided a benefit for

minimizing rollover propensity when compared to standard dual tires and standard suspensions. For the evasive maneuver, the use of new-generation single tires and a wider-slider suspension on the trailer resulted in a decrease of the maximum trailer roll angle per lateral acceleration ratio by 45%.

BACKGROUND

The Heavy Truck Rollover Characterization Project is a major research effort conducted by the Oak Ridge National Laboratory (ORNL), in partnership with Dana Corporation (Dana), Michelin Americas Research and Development Corporation (Michelin) and Clemson University (Clemson), for the National Transportation Research Center, Inc. (NTRCI) under the Heavy Vehicle Safety Research Center (HVSRC) for the Federal Highway Administration (FHWA) [1}. 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. 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.

Heavy Truck Rollover Characterization: Phase 1

Phase 1 involved a 1999 Peterbilt 379 class-8 tractor and 2004 Wabash dry freight van trailer with dual tires on the tractor drive axles and on the trailer axles (both equipped with rear air suspensions). The tractor and trailer were instrumented with a number of sensors to capture their dynamics as they engaged in various testing maneuvers (an evasive maneuver, swept sine, constant radius, and a run-off-the-road maneuver). Candidate maneuvers considered for this project were derived by examining various vehicle dynamics sources including ISO standards and SAE papers [2]. Phase 1 testing generated controlled baseline data that is usable for comparison with Phase 2 results and all future testing in this program. 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 and software were provided by Michelin.

Heavy Truck Rollover Characterization: Phase 2

Testing in Phase 2 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. Testing with the trailer was done with and without a wider-slider suspension. Table 1 provides a listing of the vehicle tire configurations for Phase 1 and 2 testing.

PROJECT DESCRIPTION

ORNL, with input from project partners developed a test plan for Phases 1 and 2. The plan called out the types of tests to be performed, number of tests, goals of each test, participants, location, individual participant responsibility, and data collection protocols. Additionally, a

Table 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	1	dual	dual	*not used*
2	2	new-generation single	dual	*not used*
3	2	new-generation single	new-generation single	*not used*
4	2	dual	new-generation single	*not used*
5	2	new-generation single	*not used*	new-generation single
6	2	dual	*not used*	new-generation single

scheduling matrix was developed that optimized resource efficiency. Primary instrumentation of the tractor-trailer was accomplished by Dana staff with support by Michigan Scientific of Charlevoix, MI. Testing was conducted at the Transportation Research Center (TRC) Inc., in East Liberty, Ohio. Tilt-table testing was conducted at the University of Michigan Transportation Research Institute (UMTRI).

Test Track Testing

Evasive Lane Change Maneuver. This maneuver was setup with pylons as shown in Figure 1. A level asphalt area of sufficient size (50 sq acres) to accommodate safe entry and exit of the course for the test vehicle was defined. The test consisted of negotiating a left-hand lane change. Gate 1 was entered at a constant speed. While maintaining that 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.

For all of the tests, the vehicle was loaded will 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). Information was also captured via videotaping (one camera inside the cabin; three others outside; 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 realized. However sufficient data was collected to demonstrate the trends and patterns in the heavy truck rollover phenomenon.

Table 2 presents a summary of the evasive maneuver tests. Fifty-five tests at different speeds were conducted for this maneuver, for all of the six series. For each series (column) in Table 2, 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. Wheel liftoff was determined by checking whether the vertical-force transducer mounted on the trailer's rear axle showed a null or negative force.

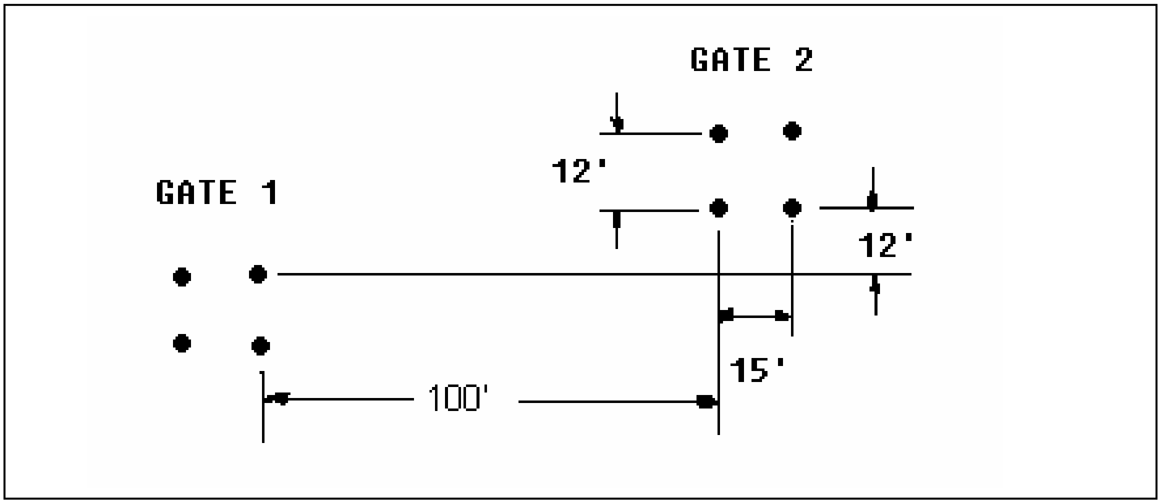

Figure 1. Evasive maneuver pylon layout.

Table 2. 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

Swept Sine Maneuver. This maneuver provides complementary information regarding sensitivity between (for example) the steering wheel input and resulting yaw rate and lateral acceleration as a function of frequency. This test provided information relating to the vehicle frequency response. The vehicle maintained a constant speed of 50 mph throughout the maneuver. Beginning with a sinusoidal steering rate of 0.2 Hz, the driver determined the steering angle required to generate (at 0.2 Hz) approximately +/- 0.2 g peak lateral acceleration as measured at or near the tractor center-of-gravity (CG). The steering amplitude was found to change somewhat when different tires were used.

The driver was asked 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 25.0 sec test interval. The peak steering wheel input was allowed to drop appreciably at the higher frequencies in order to avoid acceleration levels becoming too high. The maneuver was practiced a number of times until the driver felt comfortable with the procedure. The steering amplitude was regulated by the driver so as not to exceed safe acceleration levels at any time during the test. The test procedure was run at 50 mph, for 25 sec with at least 0.5 sec straight line driving at the beginning to establish zeros. Eight passes were completed with a sampling rate of 100 Hz.

Steady State Constant Radius Turn - 150 ft Radius and 400 ft Radius. 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.

The driver was asked 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 (counter-clockwise) direction.

Straight-Line Road Edge Rollover - Step Function. This test was to have been 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. The test was not completed because of safety concerns. The test track was not appropriately configured to conduct this test safely and was therefore aborted after an initial trial.

The driver was asked 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.

Summary of tilt-table testing. Tilt-table testing was conducted by UMTRI at UMTRI facilities 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, and permitted roll freedom of the vehicle slightly beyond its roll stability limit. Tilt testing performed in this project involved tilting the tractor-trailer combination to one side only. Tire configurations for the tilt table testing were the same as for series 1, 3 and 5, and were repeated three times for each configuration.

Instrumentation Highlights

The test 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 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 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.

DATA COLLECTION AND ANALYSIS

Data Collection Overview

Data Collection System. The central data acquisition system 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. Instrumentation of the vehicle was a 2-to-3 week process.

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. 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.

Data Collected. A significant amount of data was collected (1.2 Gigabytes of data from 45 data channels sampled at 0.01 sec). Due to a number of issues related to the sensors, and idiosyncrasies in the data, a statistically-meaningful data set was not possible. However, sufficient data was collected to show trends and patterns in the truck rollover phenomenon.

Data Analysis Overview

Summary of evasive maneuver analysis. Analyses of the data were performed by each of the partners. ORNL and Dana analyzed the evasive maneuver data. A roll stiffness (RS) parameter was generated by computing the ratio between the maximum roll angle for the trailer and the maximum lateral acceleration (measured at the trailer's CG). RS is a measure of the stability of each Series during the evasive maneuver (degrees per g). The results, shown in Table 3 indicate that all configurations using single tires (i.e., Series 2 to 6) performed better than the configuration with dual tires (Series 1).

Table 3. Trailer roll stiffness 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

Results for the evasive maneuver test indicated that the tractor-trailer tire configurations that included the new-generation single tire performed better 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 (series 5 and 6), improved stability and increased effective stiffness of the trailer were experienced. It should be noted, however, that although Series 3 and Series 5 had new-generation tires on the tractor and trailer the roll stability was almost the same in both cases despite the use of the wider-slider suspension in Series 5. Additionally, Series 6, which utilized standard dual tires on the tractor out performed series 5 with new-generation singles all around. The explanation of these results is not clear, and may involve driver control issues. One suggestion was that the "feel" of driving with new-generation single tires may have been somewhat different from what the driver was used to experiencing, thereby impacting the control of the tractor-trailer. Another suggestion involves the sidewall stiffness of the new-generation singles. That is, when used on the drive axle of the tractor, they may effectively be more compliant than the compliancy when using dual tires. These issues will be looked at in more detail in Phases 3 and 4 of the truck rollover characterization research.

Summary of constant radius analyses. Four different tests were conducted for this maneuver: two (clockwise [CW] and counter-clockwise [CCW]) at a radius of 150 ft, and two at a radius of 400 ft. For the purpose of the ORNL analysis, only those cases were considered in which liftoff conditions were reached. This occurred only for the 150 ft constant radius test (the 400 ft radius was too large to induce lateral accelerations that could result in a liftoff situation). Also, since the rear trailer 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 correspond only to the 150 ft constant radius CW turning maneuver. Analyses for the constant radius maneuvers were done in a similar fashion as that conducted for the evasive maneuver, i.e., a roll stiffness parameter was calculated. The roll stiffness parameters for the 150 ft constant radius maneuver is presented in Table 4.

Table 4. Trailer roll stiffness for the 150 ft constant radius maneuver (CW).

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

Similarly to the results of the Evasive Maneuver analysis, ORNL found that the 150 ft Constant Radius CW maneuver showed that Series 6 and 5 (with the wider-slider suspension) performed the best when compared to the basic case (Series 1), followed by Series 2 and 3. As with the evasive maneuver results, case 6 out performed case 5 (i.e., new-generation singles on the tractor and trailer). The worse performance of series 4 than series 1 (duals on the tractor and trailer) is unexplained and may be an anomaly of not having sufficient data for drawing a more sound statistical conclusion.

Clemson University also conducted the analysis of the constant radius maneuvers conducted at radii of 150 ft and 400 ft. Variables different from those addressed by ORNL were analyzed and included 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). The differences in Clemson's and ORNL's results for series 5 and 6 will be investigated further in Phase 3 and 4 research. 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.

Summary of Swept Sine Analysis. Michelin analyzed the data from the swept sine maneuver. Six frequency response functions (FRFs) were computed for each of the six test series (e.g. yaw rate to steering wheel angle FRF, and lateral acceleration to steering wheel angle FRF). An analysis of the coherent frequency range of each FRF was also performed. For the FRFs examined, it was found that differences between the test series for the swept sine maneuver were typically small with an exception being the trailer roll to trailer lateral acceleration FRF. Here, for the coherent frequency range of approximately 0.2 to 0.7 Hz, the estimated trailer roll gain was lowest with the wider-slider configuration.

TEST CONCLUSIONS

This project has contributed to the understanding of the roll stability and roll characteristics of tractor-trailers engaged in severe driving maneuvers using both standard dual tires and new-generation single tires; and utilizing wider-slider suspensions. Results suggest that real and significant improvements in roll stability for tractor-trailers are possible via tire and suspension improvements. The data collected in this project suggests that the performance of new-generation single tires resulted in improved roll stability over the performance of standard dual tires. Wider-slider suspensions added even better roll performance.

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. The testing in this project [1] in conjunction with modeling, simulation [3,4], and industry experience has led to several methods by which roll stability can be increased:
:

- Increase track width,
- Decrease payload CG height,
- Decrease tire compliance to limit the lateral translation of the CG,
- Eliminate fifth wheel and spring lash, which appear as free play in the rolling motion,
- 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,
- Increase drive axle suspension roll stiffness,
- Reduce lateral compliance (deflection) of the suspension,
- Increase front axle suspension roll stiffness while considering ride quality trade-offs,
- Increase the stiffness of the truck frame allowing the drive to better sense roll motions,
- Raise the suspension roll axis to reduce body roll angle,
- Distribute load among suspensions in proportion to the distribution of roll stiffness,
- Reduce lateral beaming of the vehicle frame,
- 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 study, along with the direction of future rollover phases of this research, provide insights for the development of future rollover prevention systems that could incorporate the above-mentioned methods.

FUTURE RESEARCH

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, suspensions, and frames optimized for the new-generation single tires. While some proprietary testing has occurred using the new-generation single tires, 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. By integrating new-generation single tires, wider axles, associated suspensions, wider frames and torsionally optimized 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 need to be modeled, simulated, 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.

Building on the results of Phase 1 and 2 testing, the research team in this project has proposed a new effort (Phase 3) that will involve 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.

It is proposed that 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.

Also proposed was Phase 4 research involving 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 tailor torsional stiffness. These modifications will mimic, to a large extent, a production tractor with wider frame rails.

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