EFFECTS OF THE PROCESS OF REAR TIRE DELAMINATION ON VEHICLE STABILITY

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Paper Number 07-0142

ABSTRACT

The effects of the delaminated tire after a tread separation event on the handling of a vehicle have been well documented. However, the period when the tire is delaminating, which can last from about one and one half to many seconds, can pose a serious threat to vehicle stability depending on the duration of the delamination process, the design of the rear suspension of the vehicle, and the speed at which the delamination commences. This paper will present the results of testing where a delaminating tire results in a bump on the tire and a subsequent loss of control even with expert drivers. Similar vehicles were tested under a controlled environment to determine that the cause of the loss of control is axle tramp induced by the bump frequency of the delamination occurring at the natural frequency of the axle/spring (the tire is the dominant spring) system. During this tramping the handling characteristics become severely oversteer. The resulting oversteer has been measured using standard SAE J266 test procedures for various models of vehicles characterized by a Hotchkiss type rear suspension system. Proposed solutions were increasing the tramp damping characteristics of the axle system and/or the addition of dual wheels on certain vehicles. These solutions are examined for their effectiveness. Testing will illustrate how proper shock absorber sizing and placement will have a positive effect on the oversteer situation.

INTRODUCTION

Though public awareness of tire failures and tire delamination events has greatly increased over the last several years, these events are not unanticipated or new to the vehicle dynamics community, tire designers, and others. However, the detrimental effect of a tire delamination event on the vehicle handling is an area that is currently being researched. A further understanding of the dynamics of the interaction of the delamination process and the suspension sub-system will allow vehicle designers to anticipate the adverse effects of this process on vehicle handling and stability and design a system that is more robust and less likely to lose its directional controllability during such a foreseen event.

OVERVIEW

It is rather intuitive to a vehicle dynamicist that the reduced friction associated with a tire that has lost its outer tread belt and is rolling on the steel wires composing the steel belt will have less lateral traction at this location. It is also well understood that with regards to a certain steering wheel angle, this lower lateral traction will lead to an increased slip angle at this corner of the vehicle than would be developed by a non-compromised tire. The terms understeer and oversteer are defined by relative slip angles. If the slip angle generated by the front tires of the vehicle is greater than that generated by the rear, the vehicle is said to be understeer. Alternatively, if the rear slip angle exceeds that of the front, the vehicle is said to be oversteer. A special case can exist where the front and rear slip angles are equal. This situation is known as neutral steer. Using these definitions to analyze a vehicle with a delaminated tire, it can be concluded that if the failure is on the front of the vehicle, the vehicle's understeer will likely be increased, and a delaminated tire on the rear will result in reduced understeer which could transition to oversteer. Dynamic testing has proven that vehicles with delaminated tires are in fact limit oversteer vehicles.

A much less intuitive analysis is required to understand the effects on the vehicle directional control characteristics of a tire in the process of a delamination event. During this process of the tire shedding its outer tread cap, a rotating imbalance is developed and transmitted to the rear suspension system. As the cap separates, the unbonded cap can fold over on itself until it completely separates, or the cap can separate in pieces leaving some attached to the tire. Either of these situations will cause a lump and a rotating imbalance and result in a cyclic forcing frequency at that tire. It is this approximately one and one half to several seconds duration event with which the research presented in this paper is concerned. During this time, at highway speeds, the previously mentioned vertical oscillations can induce the tramp natural frequency of the rear axle (usually around 10 to 15 Hz). When this occurs, the rear traction is severely compromised. On Hotchkiss type suspensions, as shown below, this tramp mode is transmitted across the rear axle causing both rear tires to intermittently lose traction. Recent vehicles with this type of suspension include SUVs, cargo and passenger vans, and light trucks, among others.

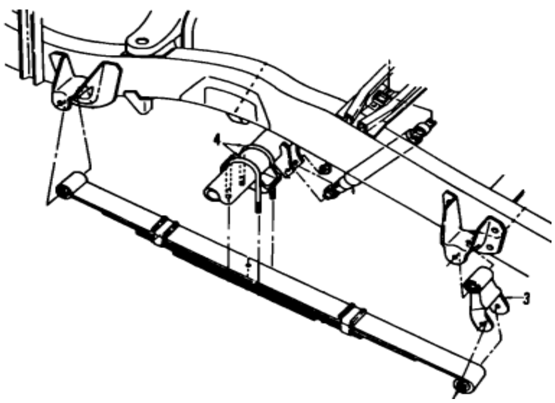


Figure 1. Illustration of Hotchkiss rear suspension.

This paper will discuss testing which has demonstrated that a severe oversteer condition can occur during the delamination event resulting in sudden loss of directional stability.

Nearly all vehicles sold to the public are designed to be steady-state understeer vehicles. Therefore, an understeer vehicle is what the motoring public is accustomed to driving. An understeer vehicle is considered safer for an average driver. An oversteer situation, especially a snap oversteer, creates a dangerous situation for untrained and unsuspecting drivers. An oversteer vehicle actually over responds to driver inputs, by steering more than the steering wheel angle and vehicle geometry would predict. Thus, it is vital for vehicles to be designed to remain controllable during a tire delamination event and not suddenly become a highly oversteer condition. The research presented here not only demonstrates the oversteer associated with tire delamination events, but also outlines design principles that significantly reduce or even eliminate the oversteer during the delamination event.

TESTING BY THE ENGINEERING INSTITUTE

Testing Protocol

All testing conducted referenced "SAE J266, Steady State Directional Control Test Procedures for Passenger Cars and Light Trucks." The test method followed was the constant radius test. In this test, the vehicle is driven on a constant radius circle at a slowly increasing speed. As the lateral acceleration on the vehicle increases, the driver is to apply appropriate steering to keep the vehicle following the path.

The test is analyzed by plotting the wheel angle (steering wheel angle divided by the steering ratio) against the lateral acceleration. The slope of the curve gives the understeer/oversteer gradient. The curve is not linear, and the gradient is often reported at low lateral accelerations, referred to as the linear range, and at the limits of tire adhesion, referred to as the limit range. The standard units for the understeer/oversteer gradient are degrees per g. A positive number is usually reserved for understeer; whereas, a negative slope indicates that the vehicle is oversteer. Figure 2 shows a typical understeer/oversteer plot for a vehicle with linear range and limit understeer.

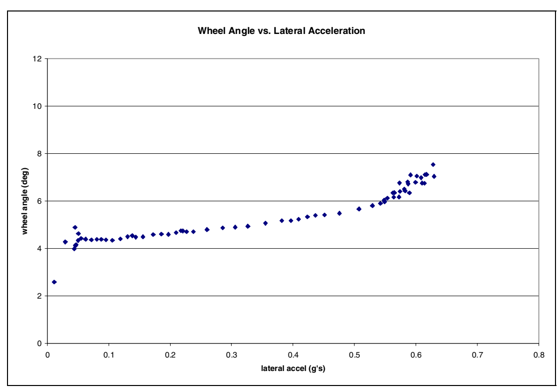


Figure 2. Exemplary understeer/oversteer plot for an understeer vehicle.

To simulate the cyclic input, tread pieces were either vulcanized or bolted to the outer surface of the tire. For the circle testing, 3 tread pieces were bolted around the circumference of the tire at 120 degree intervals. This was done in order to induce the tramp mode frequency at speeds attainable in the circle test. A frequency of 10 to 15 Hz would occur at speeds of 60 to 70 mph with a single lump generated by a delaminating tire. The design of the SAE J266 maneuver limits the maximum attainable speeds to much less than this. The maximum attainable speed is a function of the size of the test circle and the vehicle design. For a vehicle with a lateral handling limit of 0.75 g's being driven on a 130 foot radius circle, the maximum attainable velocity as predicted by (Equation 1) is 38 mph.

$$A_y = \frac{v^2}{r} \qquad (1).$$

Therefore, in order to simulate the 10 to 15 Hz input at a relatively safe speed attainable in a constant circle test, the three lumps were applied to reduce the speed by a factor of 3, approximately 20 to 23 mph. Examples of the lumped tires prepared for testing are seen in Figures 3 and 4.

Figure 3. Prepared tire with bolted lumps.

Figure 4. Prepared tire with vulcanized lumps.

General Testing Results

The test vehicles were all linear and limit understeer in their standard configuration with the exception of the fully loaded passenger van discussed later. However, testing demonstrated that the vehicles are all severely oversteer in a range of frequencies at and around the tramp mode natural frequency of the rear suspension system. The data plots during the oversteer condition are characterized by a wide band of data points indicating that the steering necessary to remain on the path was widely varied and unpredictable.

Another commonality between the vehicles tested besides all being Hotchkiss rear suspensions is a relatively far inboard placement of the shock absorbers on the axle as exemplified by Figure 5. This significantly reduces the effective tramp damping at the wheels. Since the input responsible for exciting the tramp mode natural frequency is coming from the tire, it was theorized by Kramer [Kramer, 1996] that greater effective damping at the tire would help control the motions of the tire and axle and decrease the induced oversteer.

Figure 5. Hotchkiss rear suspension system showing shock placement.

Aftermarket externally adjustable shock absorbers with high levels of damping were purchased to test the theory that greater damping on the rear axle would reduce the oversteer condition. Also, where possible, the shock absorbers were moved farther outboard to increase their effective damping rate. In addition, an alternative suspension system consisting of a rocker pivot arm amplifying the damping via a mechanical advantage was designed and tested. Testing demonstrated that tuning the effective damping could have beneficial effects on the vehicle handling. Figure 6 is a damping plot for the aftermarket shock absorbers.

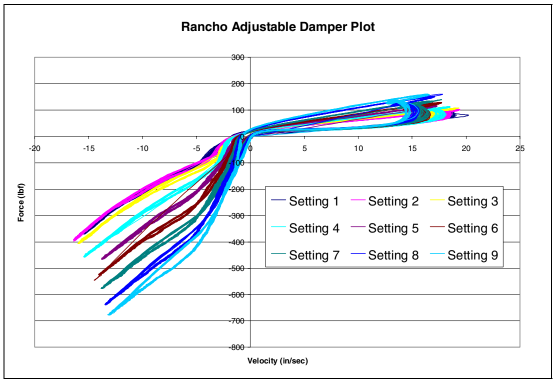


Figure 6. Damping plot for adjustable damping shock absorbers.

Detailed Testing Results

<u>Sport Utility Vehicle Testing</u> – The first testing into the effects of the lumped tire on directional stability involved a sport utility vehicle (SUV). Since the initiation of this test program, various sport utility vehicles and configurations have been tested. All tested vehicles share a similar rear suspension design and share design similarities with regards to the relative placement of the rear shock absorbers. Each vehicle tested demonstrated understeer characteristics in the standard configuration, 'as-designed' state. However, the addition of the lumped tire drastically altered the handling characteristics of the vehicle by inducing oversteer at low lateral accelerations.

Figures 7 and 8 show exemplar data plots resulting from standard configuration testing of two SUVs. The positive slope of each curve is indicative of an understeer characteristic. The understeer gradient for SUV 1 is around 2.8 degrees/g for the range of 0.2 to 0.4 g's and is approximately 2.6 for SUV 2.

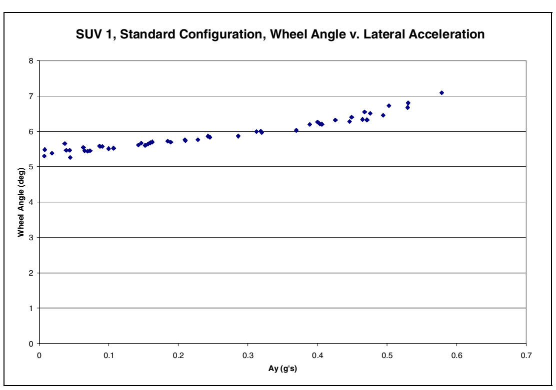


Figure 7. Data plot for SUV 1 standard configuration testing.

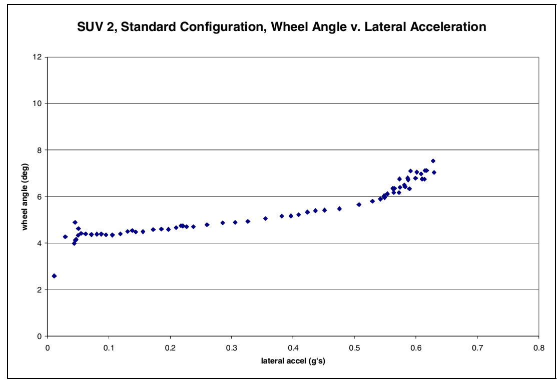


Figure 8. Data plot for SUV 2 standard configuration testing.

The following figures graphically illustrate the striking difference encountered when the vehicles were tested in the presence of the lumped tire. The negative slopes are indicative of an oversteer condition. Since the oversteer occurs at low lateral accelerations, it can be concluded that the oversteer could be induced even with minor steering inputs in a real-world driving situation.

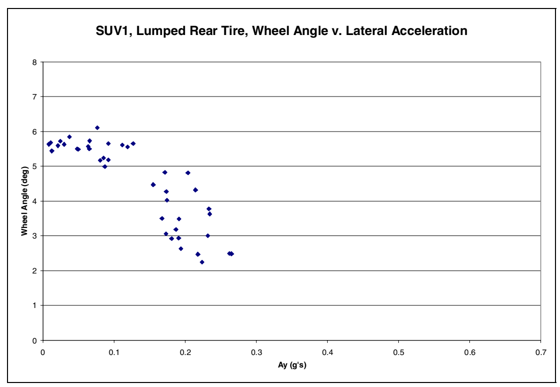


Figure 9. SUV 1 data plot resulting from testing with the lumped tire.

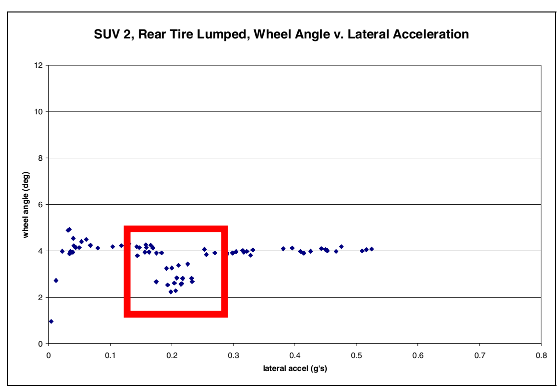


Figure 10. Lumped tire test data plot for SUV 2 with region of oversteer boxed in red.

Figure 10 demonstrates how the oversteer is most pronounced at input frequencies near the rear axle tramp resonant frequency. An accelerometer mounted on the rear axle indicated that the forcing frequency at the rear axle was around 13 to 14 hertz at the time the vehicle is oversteering. It is noteworthy that the vehicle was basically neutral steer (slope = 0) on either side of this frequency band.

Adjustable shock absorbers were installed on both SUVs. This allowed damping to be set to levels greater than possible with the original replacement shock absorbers. Also, new shock mounts were fabricated and installed allowing the shock absorbers to be moved as far outboard as possible. The increased damping improved the directional stability of both vehicles with the lumped tire. SUV 1 remained an understeer vehicle in the lumped tire testing, and SUV 2 exhibited basically neutral behavior. In both cases, the test driver commented that the vehicles were predictable with the damping modifications; a characteristic that was lacking in the lumped tests with the standard vehicle configuration.

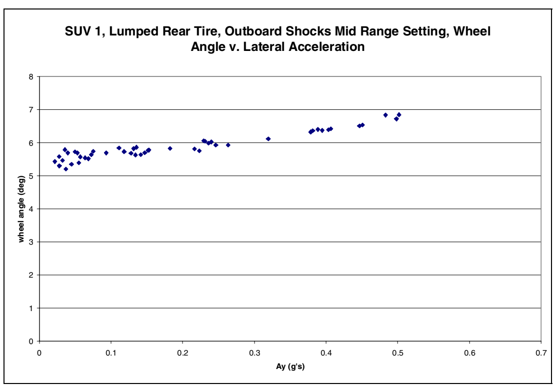


Figure 11. Data plot of lumped tire testing from SUV 1 with outboard mounted higher damping shock absorbers.

Figure 12 shows the effects of the outboard mounted dampers on SUV2. As mentioned, there was a marked improvement in the handling with this set-up.

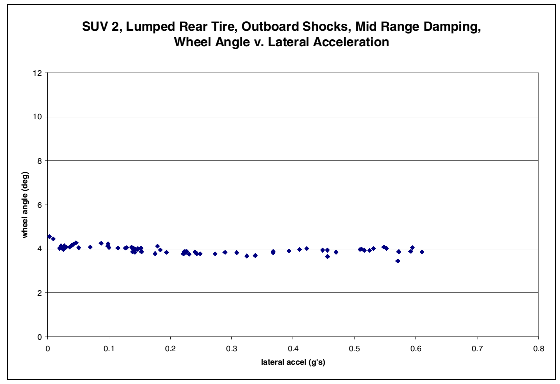


Figure 12. Data plot from SUV 2 outboard shocks lumped tire testing.

<u>15 Passenger Van Testing</u> – Similar testing was conducted on a 15 passenger van. A difference between the van tested and the SUV is that at the heavily loaded (near gross vehicle weight) condition, the van is a limit oversteer vehicle. This condition arises from a center of gravity (CG) shift that accompanies the loading. With the test loading simulating occupants, the CG moved upward and rearward. Static measurements have shown that the upward shift can be between 1 and 2 inches. The longitudinal shift is considerably more. This is due to the design characteristic of the van tested that places a significant amount of the loading behind the rear axle. Static measurements have demonstrated a longitudinal shift rearward of the CG of as much as 17 to 20 inches. Even in the unloaded condition, data scatter is seen at the limits of lateral adhesion, and the driver said the vehicle felt very much on the edge of transitioning to oversteer. However, in the fully loaded testing, the vehicle spun-out at the limit due to its oversteer characteristic.

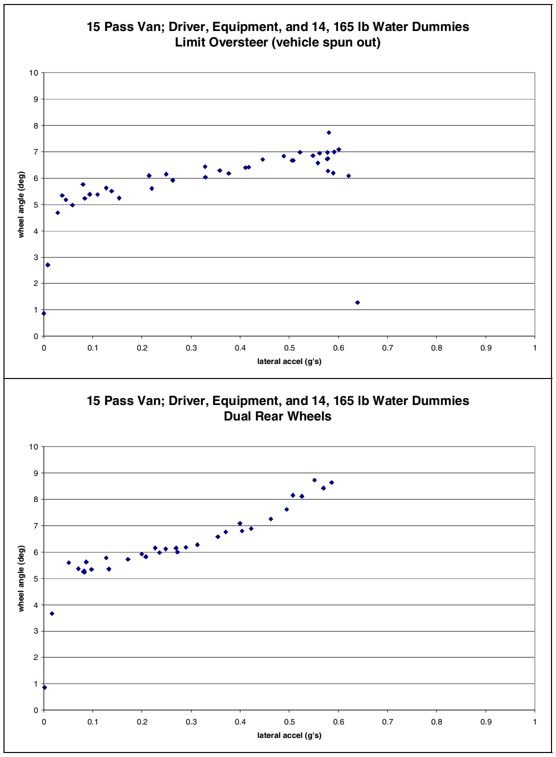


Figure 13. Data plot comparison of standard configuration GVW 15 passenger van testing without (top) and with dual rear wheels.

A method to improve these undesirable handling traits is the addition of dual rear wheels to the van. The dual wheels effectively widen the rear track of the vehicle while simultaneously increasing the lateral grip available at the rear of the vehicle relative to the front. Therefore, in terms of the previous discussion regarding slip angles and oversteer, the slip angle of the rear is reduced relative to the front; thus, promoting an understeer situation. The dual wheels also have a positive effect on transient oversteer.

Not only did the dual rear wheels eliminate the oversteer in a standard test, they also allowed the vehicle to remain understeer when one of the dual wheels was detreaded to the steel belts. This indicates that this vehicle will be understeer before and after a tire delamination.

However, lumped tire testing with this van demonstrated that the van will be oversteer at low lateral accelerations and that the oversteer is much more prominent during the delamination process. The initial round of testing on this van did not test increased damping. An alternative damper mount is currently being designed to mount to this vehicle to allow greater effective damping at the wheels. This future testing will be reported in subsequent publications.

The lumped tire plots for the clockwise and counterclockwise tests are below.

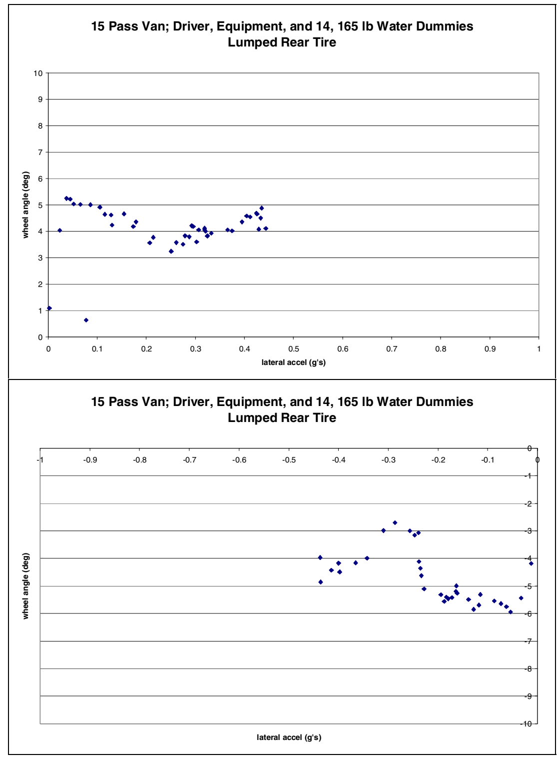


Figure 14. Data plots of lumped tire testing for the 15 passenger van.

Light Truck Testing With Lumped Tires – All vehicles discussed pose a special dilemma when evaluating the effects of a cyclic input into the rear axle and ways of reducing this effect. However, this is especially true with light trucks with heavy duty cargo and towing capacities. Each class of vehicle discussed is designed with the ability to carry relatively large payloads. This means that the load on the rear axle can vary greatly depending on the loading. Light trucks have the greatest variance in that with the unloaded condition, there is relatively little weight on the rear axle; and with loading, it is the rear axle carrying most of the weight. The rear suspension systems on these vehicles has to be designed to be able to accommodate the heavy loading, creating a stiffly sprung system. At unloaded conditions this creates a basically rigid system leading to wheel and axle hop. With the wheel hopping, the rear sprung and unsprung systems are coupled and moving as a single unit. Therefore, the shock absorbers are not being activated and cannot be used as effectively to control the oversteer condition.

A heavy duty ¾ ton truck was tested in various configurations. It was tested unloaded, with a 1400 cargo load behind the axle, and pulling a heavy equipment trailer loaded with a Bobcat skid steer and sweeper attachment. The trailer as loaded had a tongue weight of 1200 lbs. Each load configuration was tested with OEM replacement shock absorbers mounted at the standard mounts and was tested with adjustable shock absorbers mounted on a pivoting lever arm.

The lever arm was designed such that the attachment point to the axle was as far outboard as possible. In addition, a mechanical advantage of 1.5 was incorporated into the design. This system resulted in variances in the damping ranging from fairly soft to basically rigid by adjusting the damper dial settings from 1 to 9. Figure 15 shows the pivoting lever arm and attachments.

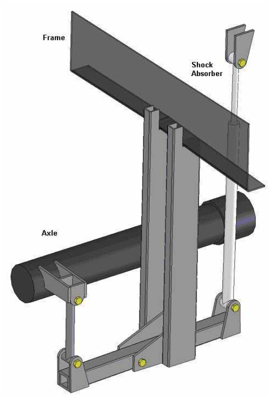


Figure 15. Illustration of pivoting lever arm shock mount.

The figures below show the oversteer associated with the lumped tire testing for the vehicle with no cargo load. For this testing, the lumped tire was placed on the left rear. The first figure shows the clockwise test. With the lumped tire mounted on the left rear, it is on the outside of the turn for the clockwise test and on the inside for the counterclockwise test. Notice the wide scatter in the data. This is indicative of widely varying driver steering inputs. The driver was not able to anticipate the vehicle responses to the steering input and was constantly having to input steering corrections. It is obvious from both the slope of the graphs and the data scatter that this configuration is highly unstable.

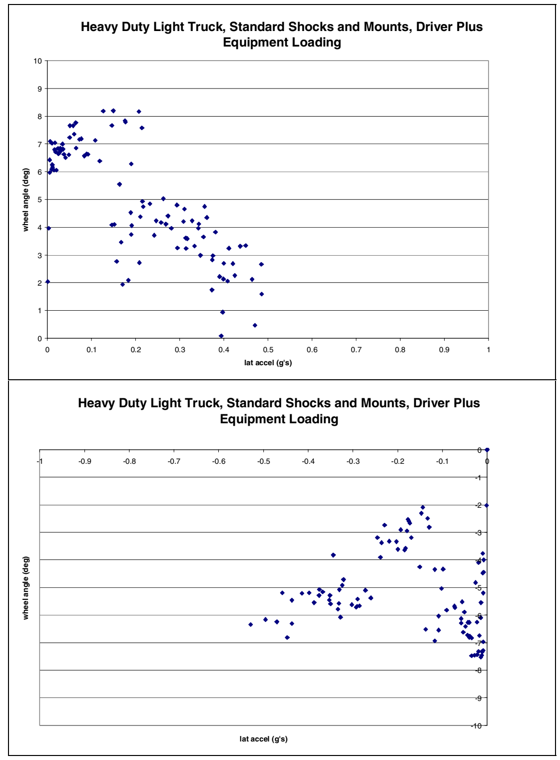


Figure 16. Heavy duty light truck unloaded tests results for the clockwise (top) and counterclockwise test.

The results of the testing with the lever arm and the shock setting 5 are shown for comparison (clockwise test shown first).

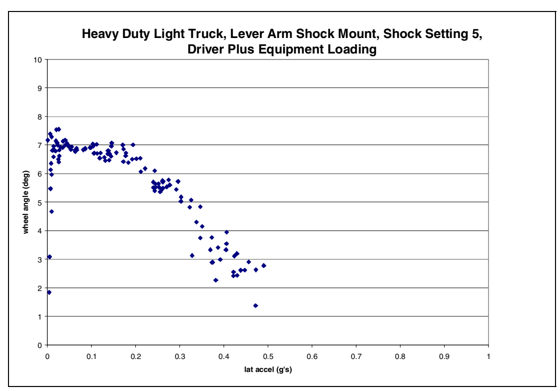


Figure 17. Test Results for the unloaded testing with lever arm shock mount with setting 5 damping (clockwise).

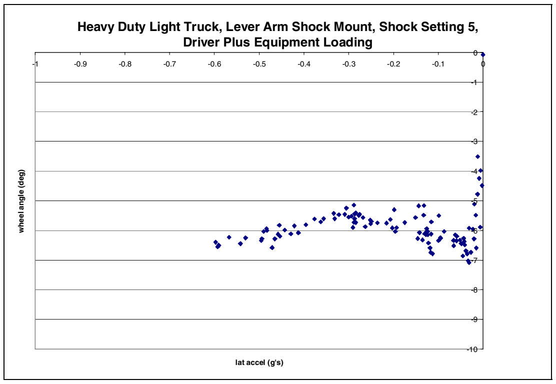


Figure 18. Test results for the unloaded condition with lever arm shock mounts and adjustable shocks setting 5.

Though the general trend of the negative slope is unchanged in this clockwise test, there is much less scatter in the data. This indicates that the driver was able to predict the response of the vehicle and input the appropriate steer to remain on the path with less varied steering wheel angles. The driver stated that the vehicle felt much more controllable in this situation, even though the gradient from each test is similar. A marked improvement is seen in the counterclockwise testing. The driver's feeling during this testing was that the vehicle was near neutral steer and directionally stable.

With the rearward biased cargo load and the standard shocks and mounts, the vehicle was still very unpredictable and unstable as seen below. The top plot shows the clockwise test with the lumped tire on the outside of the turn, and the bottom plots shows the results of the testing with the lumped tire on the inside of the turn (counterclockwise).

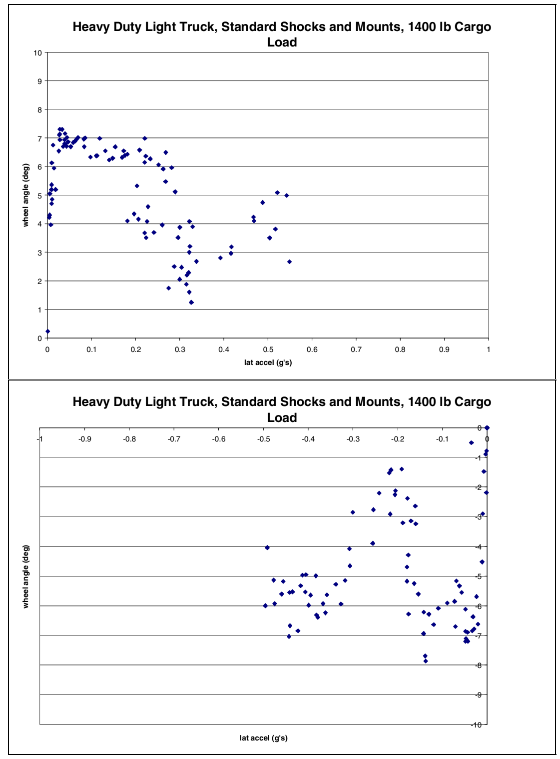


Figure 19. Standard vehicle set-up testing with 1400 pound cargo load.

Again, a dramatic increase in the controllability and predictability of the vehicle was seen in the alternative design shock mount testing, even with the damping on the shock set as low as possible. This is graphically represented below.

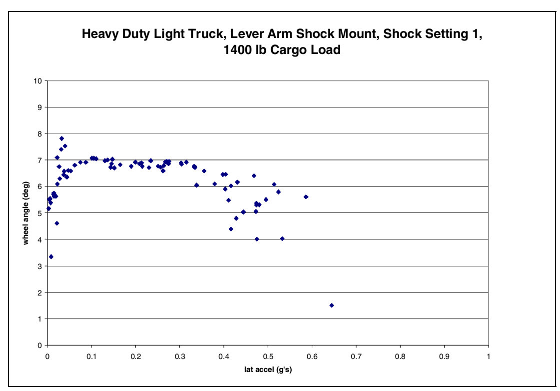


Figure 20. Lever arm shock testing setting 1 with 1400 lb cargo load (clockwise)

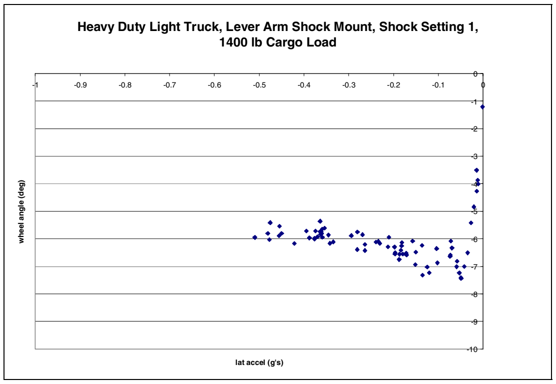
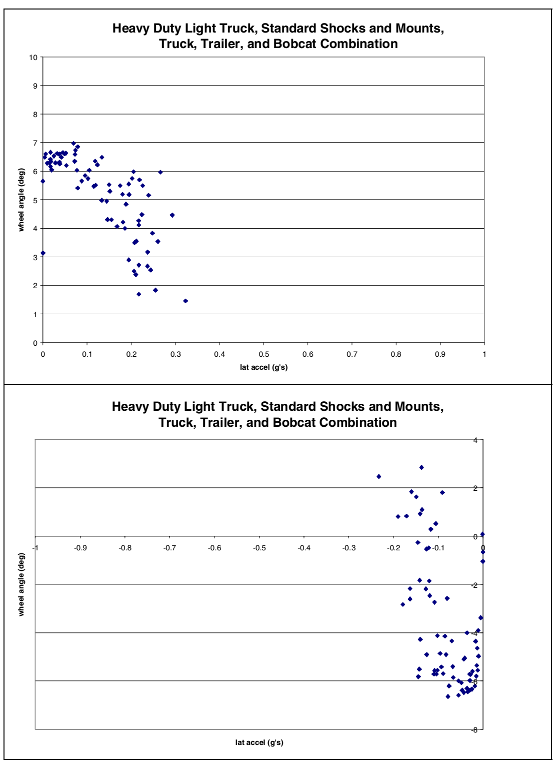


Figure 21. Lever arm shock mounts with shock setting 1 and 1400 lb cargo load.

The final four plots (lumped together as Figure 22) compare the loaded trailer testing with the standard mounts and shock absorbers to the testing with the alternative design. Again, the alternative design greatly improved the handling, especially with the lumped rear tire on the inside of the turn. The top two graphs are the standard configuration clockwise and counterclockwise test, respectively, and the bottom two are the plots for the pivoting lever arm testing.



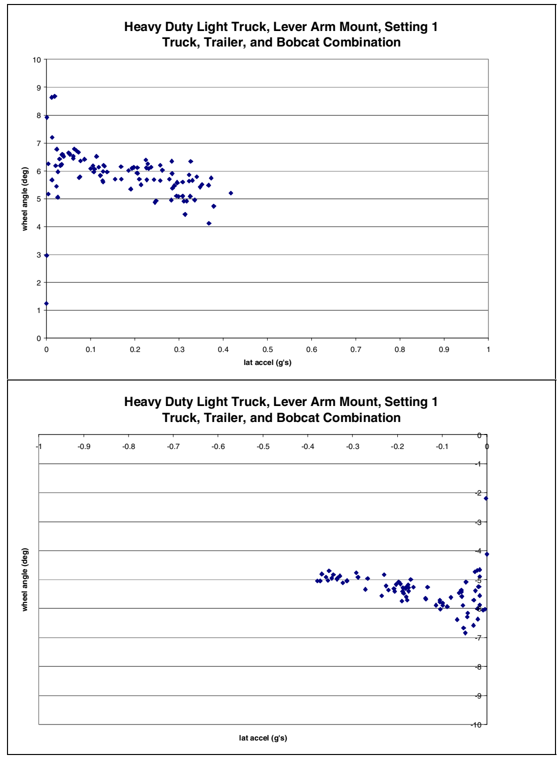


Figure 22. Lumped tire testing results for truck and trailer combination.

CONCLUSIONS

In conclusion, testing has demonstrated the effects of a cyclic input on the suspension systems tested. Cyclic inputs near the tramp mode natural frequency result in a highly uncontrollable vehicle response characterized by severe oversteer even in the quasi-static SAE J266 Steady-State Directional Control Test.

The results of this testing can be extrapolated to real-world highway speed tire delamination events and clearly reveal what a dangerous situation this is for these vehicles traveling at highway speeds.

Testing has also revealed the positive effects of suspension tuning on the controllability of these vehicles during the process of a tire delamination.

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