AN ANALYSIS OF THE MECHANISM CAUSING LOSS OF CONTROL DURING A TIRE DELAMINATION

David Renfroe
Alex Roberts
The Engineering Institute
USA
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ABSTRACT

Electronic controls cannot always compensate for the destabilization of a poorly designed vehicle caused by tire delamination. Axle tramp caused from rubber strips on the track showed axle skate [1]. Further research, reported at ESV 2007 [2] demonstrated that lumps on a single rear tire caused 15+ degrees/g of oversteer.

The Engineering Institute has shown that the process of tire delamination causes some vehicles to become unstable at highway speeds. This was accomplished by actually preparing tires to partially delaminate while at 95 to 115 KPH on a remotely controlled vehicle. This testing demonstrated a severe loss of control as the tire was delaminating. The testing also showed that the predominate mechanism of control loss arises from the imbalance created during the delamination process.

A discussion of the testing illustrating accelerations on the rear axle as well as displacements of the shock absorbers will be used to illustrate the imbalance excitation and the tramping motion of the axle. Previous research indicated that the oversteer gradient during such an event to be between 15 and 20 degrees per g. This would then yield a critical speed of about 45 KPH. The testing illustrates how a vehicle loses control when the vehicle transitions from understeer to oversteer at highway speeds significantly above the critical speed from tire failure induced forces. Alternative suspensions were tested using the same simulated tire failure and illustrated how the vehicle stability is increased.

Using these results, a design criteria based upon a percentage of the critical rotational damping is proposed to control axle tramp from excitations at the harmonic frequency.

INTRODUCTION

Goodyear president John Polhemus has said, "[Tire] tread separation is the most common form of failure for all light commercial tires regardless of who manufactures them." [3] Complete loss of control of vehicles during testing has been demonstrated by Tandy [4] and Arndt [5] during tire delamination tests at highway speeds. In Florida (1993 – 2000) and in Texas (1994 – 1999) 220 and 550, respectively, fatal tire failure related rollovers in SUV's have been identified from databases maintained in the respective states. A report to NHTSA in June of 2001 identified significant differences between some SUV's with respect to others in their propensity to lose control and rollover from a tire failure based on those statistics [6]. This then brings up the question as to whether there is a design parameter that can be identified to increase the ability of drivers to maintain control of a vehicle in a tire failure situation, particularly a tire delamination.

Two mechanisms for loss of control during the tests in References 4 and 5 have been suggested. One suggested cause was that there was hard braking on the rear wheel that pulled the vehicle to the side due to tread interaction with the vehicle [4]. This is very unlikely since testing by Tandy, et al. (see figure 1) shows that the longitudinal forces caused by a braking effect of the delaminating tire is insufficient to cause such a course altering pull to the right [7]. The longitudinal force is varying from positive 1000 lbs to negative 1000 lbs. This would certainly shake the vehicle but not cause sufficient force on the right rear corner to pull the vehicle to the right.

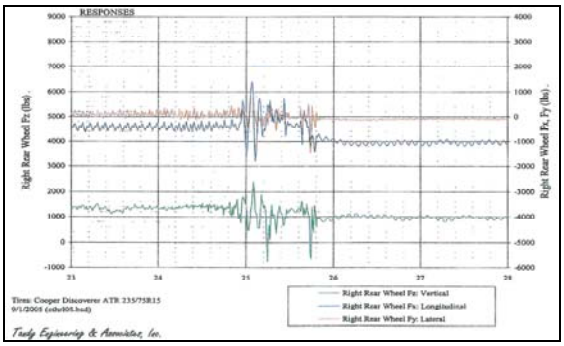

Figure 1. Wheel forces of delaminating tire. Test 41A [7]

A closer examination of the data presented in Figure 1 revealed that the forces being shown were not solely the result of a braking effect of the tire tread separation process. By zooming in on the data, it is seen that during the delamination, the peak of the longitudinal force corresponds to the neutral value of the vertical force, and vice versa. This is demonstrated in Figure 2 and indicates that the force values are more likely due to a rotating imbalance than a braking effect. The slopes of the neutral value lines are due to instrument drift. This is more evident in the vertical force plot. The vertical force begins at a neutral value of 6561 N (1475 lbs), which is consistent with the pre-test weights recorded. However, after the delamination, the neutral value is around 4448 N (1000 lbs).

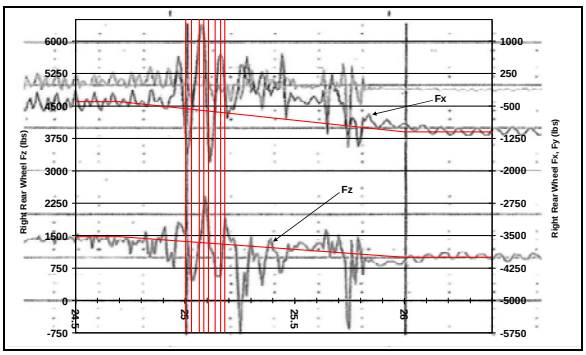

Figure 2: Zoomed view of Figure 1.

Gardner stated, "The results of the testing show that the forces developed during a tread belt detachment are well within the range of a driver's ability to control a vehicle [8]. Fay reported that while driving a Ford Taurus, "Little or no corrective steering action was needed to maintain control of the vehicle during the tread separation events [9]." Klein [10] stated that maintaining control of the vehicle after treadbelt separation required a steering torque similar to that required for a lane change maneuver. Were braking the causative factor of the loss of control, there would be no differentiation between vehicle brands and the propensity to lose control and rollover as was found in the Reference 5. Kramer [1] has determined that insufficient rotational damping can cause loss of control from rear axle tramp initiated by bumps to the wheel.

Based on Kramer's work, Renfroe [11] has proposed that the cause for the loss of control is rear axle tramp caused by the imbalance of the delaminating tire. Kramer, et al [1] found that the rear axles of Ford light trucks were susceptible to rear axle tramp and what he called "skate" between wheel bump impact frequencies of 10 to 15 hertz. "Skate" is a term used by Ford that describes an oversteer condition caused by rear axle tramp and the resulting reduction of lateral force capability of the rear tires. That skate tendency of certain Ford vehicles could account for the statistical difference between vehicle brands as seen in field data from Reference 5. From Figure 1 it can be seen that vertical forces on the order of 3558 to 4448 N (800 to 1000 lb) are occurring at a frequency of about 10 hertz, the rotational frequency of the wheel while traveling about 97 kph (60 mph) during the tire delamination process. Control was not lost in that test since delamination was over in 5 revolutions of the wheel or ½ of a second. In the test 2030 G [5] half of the tread remained attached through out the test and control was never regained even with a trained driver applying significant counter steer to the left. In Run 10 by Tandy [4], the delamination process lasted about 1.5 seconds and the vehicle traversed more than one lane to the right while significant counter-steer to the left was employed by a professional driver. When the tread finally released the vehicle responded to the steering input of the driver. In observing the video of Run 10, the wheels on both sides of the vehicle can be seen to alternately bounce. Alternating skipping tire marks from Arndt Run 2030 G can be seen on the pavement after the event indicating rear axle tramping while yawing. In testing of a Ford Excursion with ½ of the tire tread attached to the rear wheel conducted by the authors, control was lost and the vehicle veered across the track to the right. Alternating skipping marks were also seen on the pavement as a result of the tramping of the rear axle. This is shown in the figure below. Note in the figure, the left rear is the modified tire, yet distinct gaps are seen in the yaw marks of the right rear.

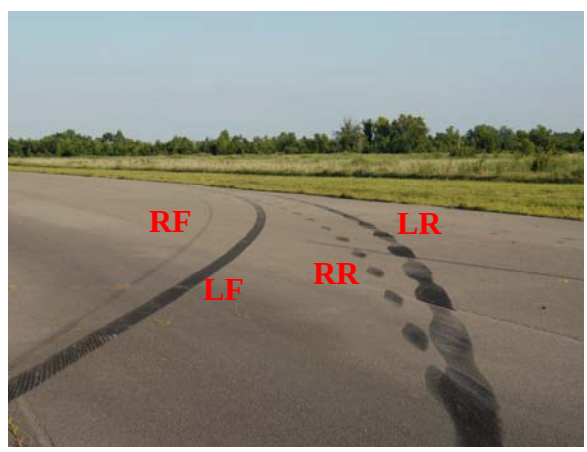

Figure 3. Photographs of tire marks from Excursion testing

Kramer found that control of the tramping motion can be accomplished by increasing the rotational damping of the rear axle. This could be

accomplished by stiffening the shock absorbers and/or moving them further outboard on the axle. Renfroe, et al [2, 11, 12] have validated Kramer's findings and quantified the magnitude of oversteer caused by the rear tramp and the effects of his alternative designs. This paper will suggest a rotational damping design criteria, a percentage of critical damping, for the solid rear axle whereby the designer may be assured that sufficient rotational damping is designed into the vehicle to maximize vehicle handling stability during a tire disablement or while traveling over rough roads.

First, a more complete discussion of the forces from the delaminating tire will be given and why they are being generated. This will be followed by a description of testing from many researchers using devices to generate rear axle tramp under various damping conditions. From that testing we will be able to determine the axle/spring system critical damping, and then calculate the actual rotational damping on the particular vehicle system. Knowing the control characteristics of the particular axle/shock system, correlation can be made between the percentage of critical rotational damping and the level of control.

FORCES GENERATED DURING A TIRE DELAMINATION

Forces on the wheel during a tire delamination are vertical and longitudinal in nature as shown in Figure 1. The longitudinal forces will be generated from the retardation of the rotation caused by impacts of the tire flap with the fender and other body parts while rotating resulting in wheel braking. The effects on the retardation of the vehicle cannot exceed the coefficient of friction of the tire interface with the pavement. That interface will most often be the steel belt on the carcass from the tire and the pavement. Previous studies have shown that the friction at that interface is around 50% of the normal friction between the tire and pavement [13]. This is consistent with what others have found in other studies, except for Reference 4. The premise for conducting that research was based in part on results reported in Reference 13 wherein they stated that longitudinal forces ranged between 361 and 1151 lb. Unfortunately, the authors of that paper later recanted their statement and said that the forces were ½ as large as previously stated [14]. Although the researchers in Reference 4 were able to achieve yaw effects similar to a rear tire delamination as shown in 2030 G, they could only do so by installing a racing tire on the single rear braked wheel. That tire, the G-Force Radial from Goodrich, was advertised as the stickiest road tire in the world developing a friction coefficient of 1.06. Also during their test where the similar yaw velocity occurred there was little or no counter steering. In Arndt's and Tandy's experiences, they steered up to 300 degrees opposite the direction of the yaw with no effect. Thus, consistent with the measured forces from a wheel force transducer and the experience of other researchers, the effect of the drag associated with the process of tire delamination is similar to a gust of wind and not from very large drag effects of the delaminating tire.

The cyclic vertical component of forces is generated due to the imbalance of the tire caused as sections of the tire tread are releasing. The tread flap and remaining tread cause significant imbalance in the tire and are experiencing 250 G's while turning at highway speeds. The magnitude of the vertical force will be affected by the weight of the attached tread and its radius from the axle, the weight of the detaching flap and the radius of the center of gravity of the flap from the center of rotation, and the rotational speed of the wheel. Testing reported by Arndt in Reference 15 illustrates how the response of the axle from a single tread section encompassing ½ of the tire causes a sudden growth in response as the harmonic frequency of the axle/tire-spring system are approached. However, instead of the response decreasing after the area of harmonic frequency is passed as the speed increases to 112 KPH (70 MPH), the response shows a slight decrease then continues to grow. This would be due to the increase in force from the dynamic imbalance increasing as a square of the velocity of the tire. As the high side of the harmonic frequency band is reached, the tire force has grown sufficiently to continue to drive the tramp motion of the axle. Thus for an under damped axle system cyclic tramping motion will continue beyond the band associated with the harmonic frequency, 10 to 15 hertz.

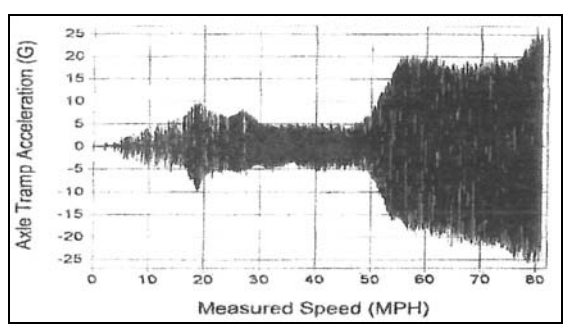

Figure 4. Axle motion from ½ of tread remaining on tire with a small step from tire carcass to the tread strip [15].

For example, a mere 15 cm (6 inch) section of tire tread weighs 1 kg (2.2 lb). At 80 kph (50 mph) this section of tire tread will generate 1.23 kN (277 lb) of cyclic force. At 112 kph (70 mph) that same piece of tread will generate 2.42 kN (544 lb). While the tire is delaminating the section of tread will begin as a 244 cm (8 foot) long section of rubber and steel and begin to decrease in size in an unpredictable manner throughout the process of delamination. Thus, there is significant potential for large cyclic forces on the order of 4478 N (1000 lb) to be generated during delamination. One mechanism suggested in the past for the generation of the large cyclic forces on the wheel was bumps created by the delaminating tire. Creation of bumps on the road and on the tire have been effective in the study of the axle motion and the effects on vehicle handling from a tramping axle [2, 11, 12]. That method has also allowed the quantitative study of the effects of various damping methods to control axle motion and thus vehicle handling through the application of quasi-static tests such as SAE J266. However, this study and others have clearly shown the actual mechanism of force generation during tire delamination is from the imbalance. The first clue was in observing both the 2030 G and Run 10. Both began with a severe loss of control when the tire began to separate at speeds above what would be considered the harmonic frequency of the system, indicating large driving forces to cause the tramping. When the vehicle begins to decelerate from 112+ KPH (70+ MPH) it immediately enters the harmonic range of axle oscillation that only makes control more difficult. Oscillation from imbalance was further illustrated in the study from Arndt [15]. The vehicle was placed on a chassis dynamometer with ½ of the tread attached to the tire, and a very small step at the front edge of the tread piece of only 5/8 of an inch. The data showed the effects of imbalance with increasing force from increasing speed, but there was no real second force occurring from the leading edge of the tire striking the roll. Then in a recent study by Pascarella [16] a single 15 cm (6”) long strip of rubber with a 3 cm (1.25”) step was vulcanized to a detreaded tire carcass similar to what was done by Renfroe, et al [2, 11, 12] and similar to the cross section of the rubber strip on the track utilized by Kramer [1]. He then drove the vehicle to 100 KPH (60+ MPH) and measured the response. What the data shows is that as the harmonic frequency of the axle is approached, the bump produces a significant vertical force pulse, but the imbalance also produces a vertical pulse that is increasing by the square of the speed. By the time the rotating tire system reaches the speed where the bump would cause a harmonic response, the imbalance is causing a vertical response as shown in Figure 5.

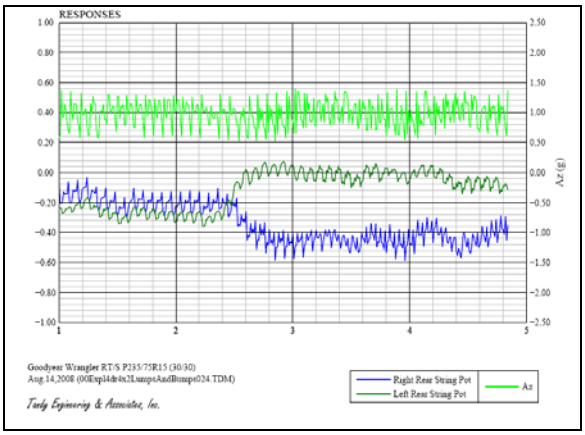

Figure 5. Motion from a single stepped lump vulcanized to the tire.

Thus, as the wheel approaches the harmonic rotational frequency, forces from the step of the rubber block occur, and simultaneously, imbalance forces begin to grow with increasing speed. As the rotational frequency approaches the harmonic frequency of the axle/spring system, the imbalance forces grow as a square of the rotational velocity approaching the same magnitude as that produced by the step. As is seen in Figure 5 at the harmonic rotational frequency of approximately 12 hertz the recorded motions show 24 hertz. The resulting motion of the axle is very small, 0.45 cm (0.18”) as measured at the shock absorber, and this vehicle remains stable as was demonstrated in the testing.

This conclusion was confirmed by testing performed for this study. Ninety degrees of the tread was removed, and ninety degrees was cut in from each side leaving a small amount bonded along the circumferential center. Figure 6 shows an actual delaminated tire at the scene of an accident and Figure 7 shows a tire prepared for the referenced testing. The step of the rubber on the leading edge of the attached tread was only 1.5 cm (5/8 “).

Figure 6: Photograph of an actual delaminated tire taken at the scene of an accident.

Figure 7. Picture of prepared tire.

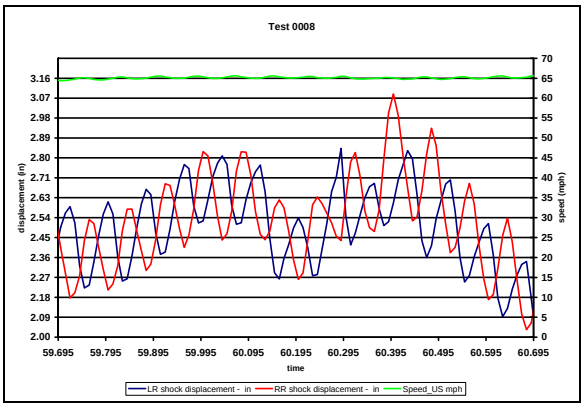

Figure 8. Axle motion for Test 0008 with ½ tread attached and 90 degree flap prepared to separate at speed. (RR Shock: blue; LR Shock: red; speed: green)

Figure 9: Screen capture shots from Test 0008 illustrating shock absorber motion.

When the vehicle was tested by driving it with a remote control up to 100+ KPH (60+ MPH) the axle began to tramp and control was lost as the tread separated. This motion is shown in Figures 8 and 9 and can be compared to the motion seen in testing with the single stepped block as illustrated in Figure 5.

First note how the axle motion is at the expected frequency of the rotation of the tire. Then note how the two sides of the axle are out of phase 180 degrees with similar vertical motions of the shock absorber of 1.0 cm (0.39”). In the video of the testing the tires can be seen having significantly more motion than 1 cm.

That is explained from the geometry of the suspension. With the shocks placed 77.5 cm (30.5”) apart and the track width being 148.5 cm (58.5”), the

motion at the tire is approximately double that of the shock. Also, the compliance in the bushing is about 3 mm (0.125") which will add more to the actual wheel motion. As the motion of the wheels is alternately bouncing on each side, control of the vehicles in these tests was lost in several cases. From Tandy's testing [7], vertical wheel motion of 3.6 cm (1.4 in) was recorded while the tire was delaminating. The motion in the tests where control was lost appears to be more.

Therefore, with a single force input at the frequency of the turning wheel at or above the natural frequency the axle tramps on each side and control can be lost. Whereas when there is a single stepped rubber block attached to the tire carcass the forces from the impact of the step in conjunction with the increasing forces from imbalance occur at twice the rotating frequency as highway speed approaches. Then there is insufficient time for the axle mass to react with an actual vertical motion. Therefore, there will be no tramp; and, therefore, no transition to oversteer and loss of control. So we conclude that the mechanism of force input to cause tramping and loss of control, as seen from 2030G and Run 10, is from tire imbalance occurring during the delamination process.

MANAGEMENT OF AXLE TRAMP THROUGH DESIGN

Kramer [1] noted in his study that "skate" can be controlled by increasing the axle tramp damping. This can be accomplished by increasing the stiffness of the shock absorber and/or by moving the shocks further apart. Renfroe, et al [2, 11, 12] measured the handling characteristics of a vehicle experiencing tramp excited by bumps on one rear tire causing force inputs at the axle harmonic frequency, and noted the effects of various shock absorber damping rates and placement on the understeer of the vehicle. As noted by Kramer [1] increased control occurred when the shocks were either stiffened and/or moved outboard. This is effectively increasing the rotational damping of the rear axle along the longitudinal axis or tramp mode.

Critical Damping of axle/spring system-In this section we derive the equations that define the rotational damping of the rear suspension of a vehicle and the critical damping. Then we will examine damping characteristics of various shock absorbers and look at the effects on handling that has been recorded. From these observations we will be able to look at the percentage of critical damping where control was maintained or lost or an understeer gradient was shown to be negative. From this limited set of data we can indicate the approximate value of the percentage of critical damping where control will be maintained under the conditions that would most likely cause axle tramp.

Critical damping is the damping at which a spring/mass system will return to equilibrium position in the least time. This particular system is for the rotational damping of the rear axle. The moment of inertia for the axle along a longitudinal axis with respect to the vehicle will be defined as I (length-force-time^2), rotational displacement will be θ, rotational damping coefficient will be C (length-force-time), and rotational stiffness K_{rot} (length-force/radians). The general equation of motion for the axle system is

$$I\ddot{\theta} + C\dot{\theta} + K_{rot}\ \theta = 0 \qquad (1)$$

Substituting $\theta = e^{\lambda t}$ and then divide by $e^{\lambda t}$ and I yields

$$\lambda^2 + \frac{C}{I}\lambda + \frac{K_{rot}}{I} = 0 \qquad (2)$$

Solving for the roots gives

$$\lambda = -\frac{C}{2I} \frac{+}{-} \sqrt{\left(\left(\frac{C}{2I}\right)^2 - \frac{K_{rot}}{I}\right)} \qquad (3)$$

Critical damping C_c occurs when the value under the radical is zero. Then

$$\left(\frac{C_c}{2I}\right)^2 - \left(\frac{K_{rot}}{I}\right) = 0 \qquad (4)$$

From equation 4 the critical damping is

$$C_c = 2I\sqrt{\frac{K_{rot}}{I}} \qquad (5)$$

Note that since the tires are the springs of this system, they can never go into tension. Thus there are two conditions of vibration, (1) where the tires never leave the ground and (2) where one tire is in the air and one is on the ground. For the purposes of this discussion, the idea of the critical damping is merely to characterize the system and to use a percentage of the system characterization to quantify the damping needed to manage the tramping rear axle and maintain control of the vehicle. Therefore, when speaking of critical damping we will be considering the first condition where both tires are on the ground.

Shock absorber damping-The damping considered in the equations is a linear function of a force generated by the shock being moved at a certain velocity. Actual shock absorbers usually have a preloaded force from a gas charge in the shock and the design of the valves in the shocks can allow it to have a non-linear response to the velocity of the shock. During the tramping of an axle, testing has measured displacements of 12.5 mm (0.5 in) and velocities in the 25 cm/s (10 in/s) range. Therefore, to characterize the shock absorbers used in these tests and to compare their relative effects the force versus velocity used will be that recorded at 34 cm/s (13.35 in/s). This was a standard recorded velocity and force measurement for the equipment being used and is the approximate velocity of the shock absorber while the axle is tramping in the harmonic range.

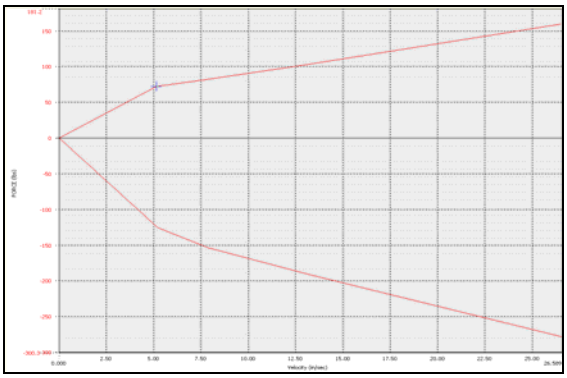

Figure 10. Typical Shock Curve Showing Force vs. Absolute Velocity

Vehicle testing and analysis-Over 50 different vehicle – shock absorber tests were conducted to determine the vehicle longitudinal stability. There were both circle tests with a lumped tire to input vertical forces at the harmonic frequency at low speeds, and straight line high speed tests with simulated delaminating tires to investigate controllability at highway speeds with vertical forces generated at and above the harmonic frequency. There were two general results, instability or stability. In the circle test instability was measured by recording a negative understeer. In the straight line high speeds instability was illustrated by the loss of control.

Appendix A is a tabular summary of those tests showing stable and unstable vehicle configurations and the associated percent of critical damping. In the cases where instability in both test conditions, low speed circle and high speed straight line driving, occurred the rotational damping of the axle was only 6% of critical. Maintenance of control was obtained in all instances for the high speed tests with the simulated delaminating tire when the rotational damping was 20% of critical. In the circle tests with the vertical forces cycling at the harmonic frequency with lateral accelerations at 0.2 – 0.3 g's stability was maintained with rotational damping of 31% of critical. This high percentage of critical damping was generated with a softer shock than the stable high speed example but with a wider spacing. As was discussed by Kramer, the spacing of the shock is the most effective method of increasing the rotational damping, since the rotational damping increases as a square of the spacing between the shocks. Also, by spacing the shock absorbers further outboard, there is increased motion in the shock which will minimize the effects of the undamped rubber bushings of the shock mounting.

CONCLUSIONS

In conclusion, it has been found that the destabilizing forces generated during the delamination of a tire will be from the imbalance of the tire due to the section of tread remaining on the tire. Until the tire is clear of tread there will remain the propensity to tramp if it is rotating at or above the harmonic frequency of between 10 and 15 hertz.

Secondly, increasing the percentage of critical damping of the axle/tire system to at least 20% appears to assure stability during tire delaminations at highway speeds. Added stability and a less harsh ride can be accomplished by moving the shock absorber outboard. Increasing the shock spacing will allow the shock to be softer while actually increasing the rotational damping of the system and thus allowing even greater control of the vehicle.

ACKNOWLEDGEMENTS

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Appendix A: Testing Details and Percent of Critical Damping for Each

Table 1.
Summary of Tests Relied Upon

Test Vehicle	Test Type	Shock Absorbers	Shock Placement	Compression Damping Force @ 13.2-13.3 in/s	Effective Comp Damping Due to Shock Angle	Rebound Damping Force @ 13.2-13.3 in/s	Effective Reb Damping Due to Shock Angle	Test Termination Condition	% Of Critical Damping
1994 Ford Explorer, 2dr, 2WD	Circle w/ lumps (CCW)	88134	Standard	103.6	91.2	191.8	168.8	OS	6
1995 Ford Explorer, 4dr, 4WD	Circle w/ lumps (CW)	Rancho RS9000X, Setting 5"	Outboard	189.0	189.0	468.0	468.0	US	31
1995 Ford Explorer, 4dr, 4WD	Straight line simulated delamination	New Monroe replacement shocks	Standard	81.5	71.7	229.1	201.6	Tramp/loss of control. Flap began to come unbonded around the mid-50s. Tramp then loss of control around 67 mph.	6
1995 Ford Explorer, 4dr, 4WD	Straight line simulated delamination	737971	Standard	199.7	175.7	805.8	709.1	Vehicle controllable throughout. 63 mph top speed. Some vertical motion seen on RR.	20