Force Characteristics of Tire Tread Delamination

John W. Daws, Ph.D., P.E.*
jdaws@exponent.com
Exponent Failure Analysis Associates
23445 North 19th Avenue
Phoenix, AZ 85027
USA

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*Presenter / Corresponding Author

J.W. Daws

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ABSTRACT: Belt-leaving-belt tread separations in radial tires have been pointed out as a cause of vehicle accidents. This paper presents the results of measurements on the level of forces generated during a tread delamination. This study showed that tires that had been cut to generate a belt-leaving-belt separation always generated a leading edge flap and that the interaction of this flap with the vehicle body is responsible for the tractive force generation. The research also showed that the total impulse generated by a belt-leaving-belt separation represents a small fraction of the total vehicle momentum at highway speed.

KEY WORDS: Tire Tread Delamination, Belt-leaving-belt, Force characteristic, Impulse characteristic

INTRODUCTION

In a tire delamination event, the separation begins when fatigue cracks develop circumferentially at the interface between the two steel belts of a radial tire. Normally, there will be a single location on the tire where the cracks develop into a large pocket under the tread. When this pocket is sufficiently large, the tread and outer steel belt will separate from the inner steel belt and form a flap. This flap may be characterized as a leading edge flap (open facing the direction of rotation at the top of the tire) or as a trailing edge flap (closed facing the direction of rotation at the top of the tire). It is believed that the type of flap that is generated is dependant upon a number of factors such as pocket size, vehicle speed, tire temperature, tire load history, tire pressure history, amount of remaining tread, and so on. However, it is generally acknowledged that there will be either one or both types of flaps generated in a given delamination event, and that these flaps will result in either a full or a partial delamination of the tire. The influence of these various outcomes on the forces transmitted to the vehicle is the object of this study.

Several studies have been performed [1, 2, and 3] that indicate that a tire delamination event produces moderate vehicle force inputs, which are normally easily controlled by a driver. These studies have produced the occasional run in which the forces are more significant. One characteristic of these experimental studies is that delaminations were caused to occur rapidly by cutting a new tire circumferentially to a depth of about 50 mm

(2 inches) between the two steel belts, and then cutting parallel to the outer steel belt wires for some length on both edges of the tread and outer steel belt to force a break in the outer belt to occur in a specific location. The circumferential cuts can be over the entire tire periphery (simulating a full delamination), or over some smaller angle as, for example, 180 degrees (simulating a partial delamination). Obviously, a major difference between these created delaminations and those that occur in the field is that these created delaminations are on unused tires with full tread depth. Another difference is that the unused tires are typically newer than typical used tires, so there is some difference in the age of the rubber and the corresponding temperature history seen by the individual tires. Those delaminations that occur in the field occur on older tires with lower tread depth, and with rubber that has been exposed to higher operating temperatures for a longer period of time. It is important, therefore, to understand what differences in vehicle input forces are generated by unused versus older, used tires.

Arndt, et al. [4] claimed to have measured delamination forces during the course of studying cornering forces on detreaded tires. All but one of the tires in that study had had the tread rubber removed and both steel belts in place during the flat track force measurements. One of the tires shed the outer steel belt during the course of the slip angle sweep measurement, and the resulting forces were claimed to be representative of field tire delamination forces. The force patterns measured in [4] were subsequently used in the National Advanced Driving Simulator (NADS) [5] to represent tire delamination events for the purpose of studying driver reactions. In actual field tire tread delamination, the most common event is that of a belt-leaving-belt separation wherein the tread and outer steel belt of the tire peels away from the casing and inner steel belt. In the field tire tread delamination, the mass of material that is being torn from the tire is significantly higher than simply that of the outer steel belt. It is therefore expected that the delamination forces in actual separation events would be significantly higher than those measured in [4] and used in the NADS [5].

The purpose of this study was to explore the forces created at the wheel hub when a tire delamination occurs. These forces act on the vehicle and therefore are important in explaining the resultant vehicle dynamics. Since a number of on-vehicle studies have been done using tire delaminations created by cutting tires, another purpose of the study was to determine if there were differences in the forces generated that were dependent upon the cutting method or the age of the tire. Since the publication of the forces in [4] were inaccurately claimed to represent delamination, it was also desirable to produce force levels that more reasonably described true on-vehicle tire delamination. A sample application of the forces measured was used in a simple vehicle simulation to evaluate the effect on vehicle trajectory.

Experiment and Data

The present study addresses these points by creating artificial full and partial tire delaminations in the same manner as previous studies [1, 2, and 3] in the controlled environment of a flat-track test machine. Full and partial delaminations were created on unused and used tires of the same type. In the case of partial delaminations, cuts between the two steel belts on both shoulders of the tire of 180 degrees on both shoulders of the tire were used. Also in the case of the partial delaminations, both leading and trailing edge flaps were initiated by cutting parallel to the outer steel belt wires at an appropriate location relative to the cuts between the two steel belts. Daws [6] described the details of the tire cuts made as well as the visual aspect of the torn surfaces of the belt-leaving-belt separations resulting from these tests.

Test Description

All test tires in this study were size P235/75R15. For each test, the subject tire was loaded and accelerated to 112 kph (70 mph) in 11 sec. The vertical load was 6680 N (1500 lbf), camber and steer angle inputs were held at zero, and the tires were free-rolling (no tractive forces were applied). Inflation pressure was set at 180 kPa (26 psi) at the start of the run. Forces and moments on the flat-track hub were recorded at a 50-Hz sampling frequency. In addition, digital video was captured at 1000 frames/sec, giving a visual resolution for the tire rotation of around 3-4 degrees/frame. A manual pre-trigger was used with a recirculating video buffer to ensure the capture of the delamination event.

The test matrix is shown in Table 1. The test matrix was designed to study the effect of a partial delamination (one in which only a portion of the tread and outer steel belt actually separates from the tire) versus a full delamination, as well as the influence of unused versus worn tires. A leading edge flap was defined to be one that had the separating tread opening in the direction of rotation of the tire, i.e., where the direction of propagation of the crack front was opposite to the direction of rotation. A trailing edge flap was opposite in sense to a leading edge flap.

The tires used in the study are listed in Table 2. From the data shown, the average age of the unused tires was about 109 weeks. The average age of the used tires was about 209 weeks. There was therefore about 100 weeks, or about 2 years, difference in age between the unused and used tires in the test. The used tires had also been exposed to variable heat history during the use period. The unused tires were typically spare tires, so they had been exposed to environmental heating but not to operational heat cycling.

Data from the Tests

Physical Examination of Tires

Examination of the tires after the testing revealed some interesting points. In some tests, all the tread and outer steel belt did not separate from the tire. In all tires cut for a full delamination, no tread remained on either the used or unused tires. However, for the partial delamination 180-degree cuts, unused tires were more likely to retain some of the tread. The unused tires having the 180-degree cuts retained 34 and 60 percent of their tread (only two of these tires were tested). Of the four used tires tested with the 180-degree cuts, only one retained any tread, and the amount of tread retained was only 10 percent. That worn tires typically have some level of fatigue crack development in place along the belt edge on both shoulders, which would make peeling of the complete delamination more likely, corroborates this finding.

Video Data

High-speed video data produced clear images of the initiation and progression of the delamination event. Figure 1 shows a sample frame from Tire Number 916-7, an unused tire with an age of 53 weeks that was cut to produce a full delamination. The direction of rotation is clockwise facing the tire. The flat track belt is at the bottom of the frame, and the framework for the machine's measurement head is located above the tire.

In the video frame of Figure 1, the delamination has already initiated and is proceeding toward completion. The tread and outer steel belt are partially attached along the center of the tread zone. At about the 3:00 clock position in the image, the tread is detached and is folded back on itself due to the impact forces associated with the flap's contact with the machine frame and with the flat track belt. The tire's outer steel belt is peeling away from the inner steel belt as the rotation progresses. This delamination is clearly a leading-edge type, in that the flap is open facing the direction of rotation. The delamination, once initiated, grows very quickly, taking about five revolutions in most tests to complete the delamination process.

In comparing the video data to the force data from the measurement spindle on the flat track machine, there were strong correlations associated with the vertical and tractive forces. When the flap attachment point reaches the contact patch, it is pinched between the tire and the road surface, giving a strong input in the vertical, or z-direction. When the flap comes in contact with the machine frame, it generates a strong pull on the tread and gives a strong input in the rearward, or negative x-direction.

The interaction of the flap with the machine frame was uncontrolled in this study. The clearance between the frame and the top of the tire was about 330 mm (13 in), but after several runs, pieces of the tread and outer steel belt were found impaled on bolt heads on the side of the machine. This interaction was clearly a source of variable tractive force in the testing. Obviously, in actual delamination events, the resulting flap interacts with the vehicle body. The clearance between the outer periphery of the tire and a vehicle fender is typically smaller and occurs over a longer circumferential distance than what was present in these tests, which suggests that vehicle fender shape (including underside sheet metal pieces) and clearance between the tire and the fender may be significant parameters in the evaluation of field delamination forces.

The video data showed very clearly that every test run resulted in a leading-edge type delamination event. Even in the cases where the partial cuts were cut at the trailing edge point to try to solicit a trailing edge flap, the resulting delamination event was of the leading edge type. In no case did any tire lose air as a result of the delamination.

The tread pieces resulting from the delamination were ejected behind the wheel in seven out of the ten runs made. In two runs, the tread piece was ejected in the forward direction. The first of the runs was made using a pressure monitoring port mounted on the axis of rotation. On this run, the tread was not ejected, but instead became wrapped around the pressure port. The use of the pressure port was abandoned in favor of using capped pressure. However, the tread was observed in the video of the remaining runs to preferentially eject along the line of travel of the tire rather than to one side or the other, which suggests that a delamination event that included the tread interacting with the axle of the vehicle would be rather rare, but certainly not out of the realm of possibility.

Force Measurement Data

For each test, the forces in the x, y, and z directions and the moments in the x and z directions were recorded digitally. A sample of this data is shown in Figure 2, where the delamination event begins at about 12.9 seconds (sec). There is some activity on the F_y, M_x, and M_z channels, but the main effect of the delamination appears to be the effect on the tractive force, F_x, and the vertical force, F_z. The F_z force variation would be felt by the vehicle occupants in the same way as a tire non-uniformity, i.e., it would excite some vibration mode in the vehicle and there would be some vibration or noise in the vehicle cabin. Since the duration of these delamination events are on the order of seconds including the phase of generation of the flap, the F_z response probably does no more than startle the driver. The actual ranges of the forces and moments measured by tire are shown in Table 3.

The F_x, or tractive, force variation was the largest effect measured. As previously noted, this force was largely a negative impulse and appeared to be linked to the interaction of the flap and the machine structure. These forces were analyzed in detail by looking at the range (maximum to minimum value) of the force, and by integrating the force with time to get the impulse. Integration was taken over 0.5 sec starting with a data point close to the onset of the delamination event.

The F_x range values were examined for any correlation with tire age. Interestingly, there was no such correlation in this data.

Figure 3 shows the F_x data summarized by tire type (unused or used) and circumferential cut type (full or partial). In every case tested, the tread and outer steel belt actually peeled as a leading edge flap regardless of the orientation of the cut made at the outer steel belt edges. Acknowledging this phenomenon, Figure 4 shows the data consolidated for the tires that were cut under the belt edges for a distance of 180 degrees. An elementary statistical analysis of the data shows that, due to variation in the F_x force levels, the groups in Figure 4 cannot be determined to be different at a reasonable level of confidence.

The magnitude of the F_x (tractive) force peaks were significantly larger than those reported by Arndt, et al. [4]. In that paper, the F_x force showed a force range of 1335 N (300 lb). This force was the result of the outer steel belt separating from the inner steel belt, but the tread rubber had been removed from the tire prior to the start of the test. In the present study, which was done on the same test machine but with both the tread and outer steel belt separating from the tire, the F_x ranges were found to average about 7000 N (1570 lb), over five times larger than those reported in [4]. Both the present study and that of Arndt, et al. [4] were performed on a flat track test machine where the interaction effects were limited to the machine's spindle support system. On a vehicle, however, the fender bodywork interacts with the tire flap, so the possible interactions become much more complex. The resulting force levels would, presumably, be subject to much larger variability as a result of this additional complexity.

These ranges are computed from force peaks that that have durations on the order of 0.1 sec. In order to analyze the effect of such short-duration force pulses, the impulse of the x-direction force was computed for all test cases. Figure 5 shows the same groupings in terms of the calculated impulse as Figure 4 does for the force range. The integration procedure was carried out over 0.5 sec for each of the test data, starting at a point where the 0.5 sec window would encompass the delamination event. In terms of the impulse, it can be seen that the unused tires produced about the same level of impulse regardless of the type of cut. However, the used tires that had the partial circumferential cuts produced higher impulse levels than did those that were cut for the full 360 degrees of the circumference. The standard deviations of the impulse averages for the two used-tire groupings were about 50 N-sec (11 lbf-sec), so the used tire difference was statistically significant. Since the force ranges did not show a significant difference for any of the cases, the difference in impulse must be related to the shape of the envelope surrounding the series of distinct pulses that characterize the tractive force. While there was insufficient data in the present study to fully explore this phenomenon, it was possible to examine the question of the effect of impulses of this magnitude on a vehicle's trajectory.

Application of Force Measurements

In order to explore the impact of the F_x forces measured in this experiment, a simple simulation was created. In this simulation, a mid-sized SUV was given a constant velocity of 112 kph (70 mph). A tire delamination was created at the right rear wheel position, and the ensuing trajectory of the vehicle was studied.

The extreme F_x impulse was –1617 N-sec (–363 lbf-sec) for a used tire with a partial circumferential cut, so the peak-to-peak level of force corresponding to this data was used in the simulation. For a vehicle having a mass of 2045 kg (4500 lbm) traveling at 112 kph (70 mph), the momentum would be about 63,600 N-sec (14,300 lbf-sec). Therefore, the total impulse represented by a delamination event is of the order of 2.5 percent of the vehicle momentum, given the test's tire tread and machine frame interaction. This suggests that the differences noted between partial and full delaminations in used tires, while statistically significant, have little physical significance. The simple vehicle simulation showed that the F_x impulse was sufficient to change the direction of the vehicle slightly toward the side of the vehicle having the delamination. Figure 6 shows the results of a simulation where the tractive force of the tire delamination was put on the right rear tire position beginning at 1.0 sec and having duration equal to 0.5 sec. The tractive force was simulated by introducing a pulsed braking force of a magnitude of 6680 N (1500 lbf) at the appropriate frequency. The maximum lateral acceleration produced by this force was 0.2 g, and the maximum yaw angle change was less than 3 degrees. This production of a small yaw by the delamination event agrees with earlier on-vehicle studies [1, 2, and 3] indicating that small driver steering inputs were required to correct for delamination forces.

Conclusions

1. Delaminations of worn tires are very likely to lose all, or nearly all, of their tread and outer steel belt.
2. The tread from a delamination event almost always ejects in the line of travel of the tire. It is possible, however, at least for the treads cut in the manner used in this study, for them to interact with the vehicle axle.
3. The delamination event itself does not damage the tire casing or cause deflation of the tire.
4. The primary forces generated by a delamination event are in the tractive and vertical directions.
5. The vertical force primarily results from the folded tread passing through the contact patch. There also may be additional vertical forces due to interaction of the separating tread section with the vehicle body.
6. The tractive force results from the interaction of the tread flap with the vehicle bodywork.
7. Variations of tractive force levels between unused tires and used tires are of the same magnitude as the variation in the measurement.
8. Tractive impulses from a delamination event with this tread-machine frame interaction are small with respect to the momentum of a vehicle at high speed, but they are sufficient to induce slight vehicle yaw and lateral acceleration.

References

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List of Tables

TABLE 1 – *Test runs generated in the study.*

	Artificial Delamination Created		
Tire Type	Full Delamination	Partial Delamination	
		Leading edge flap	Trailing edge flap
Unused	2	1	1
Used	2	2	2

Notes:

1. Used tires were selected from tires removed from vehicle service with between $^{6}/_{32}$ and $^{7}/_{32}$ inches of tread remaining.

TABLE 2 – *Tires used in this study.*

Tire #	Delamination Cut	Type	Age (wks)
916-23	Full	Unused	128
916-7	Full	Unused	53
916-11	Full	Used	235
916-12	Full	Used	223
916-28	Partial – Leading edge	Unused	128
916-21	Partial – Leading edge	Used	164
916-19	Partial – Leading edge	Used	183
916-30	Partial – Trailing edge	Unused	128
916-20	Partial – Trailing edge	Used	220
916-16	Partial – Trailing edge	Used	229

TABLE 3 – *Range of Forces and Moments in the present study. Forces are in N, Moments are in N-m. Flap indicates the orientation of the transverse cut between the wires of the outer belt and the circumferential cuts between the belt edges.*

Cut	**Flap**	**Tire**	**Age (wks)**	**Fx**	**Fy**	**Fz**	**Mx**	**Mz**
Full	N/A	Unused	128	7648	1911	5145	600	1070
Full	N/A	Unused	53	6900	2089	3956	394	1257
Full	N/A	Used	235	5582	1858	3118	300	274
Full	N/A	Used	223	5893	2129	3773	452	413
Partial	Leading	Unused	128	9288	1577	4272	410	696
Partial	Leading	Used	164	6490	1479	4259	354	688
Partial	Leading	Used	183	7270	1283	3840	379	707
Partial	Trailing	Unused	128	5969	1452	3853	376	429
Partial	Trailing	Used	220	7760	1443	4263	620	725
Partial	Trailing	Unused	229	7194	1399	3813	440	401

List of Figure Captions

FIG. 1 - *Sample video image from high-speed video capture system showing peeling tread and outer steel belt.*

FIG. 2 - *Force and moment data for Tire 916-7 showing the variation and phasing of the hub forces during the tread delamination.*

FIG. 3 - *Comparison of the range of tractive force data comparing the results of used and unused tires for the three types of cuts used. Note that all cuts produced leading edge flaps.*

FIG. 4 - *Results of tractive force analysis combining all partial circumferential delamination cuts. All cut types produced leading edge flap delaminations.*

FIG. 5 - *Comparison of impulse values for the tractive force for used and unused tires by tire cut. Note that all cuts produced leading edge flaps.*

FIG. 6 - *Response of vehicle to tire tread delamination on right rear position. Initial vehicle speed was 70 mph, separation begins at 1.0 sec and lasts 0.5 sec.*

FIG. 1 – *Sample video image from high-speed video capture system showing peeling tread and outer steel belt.*

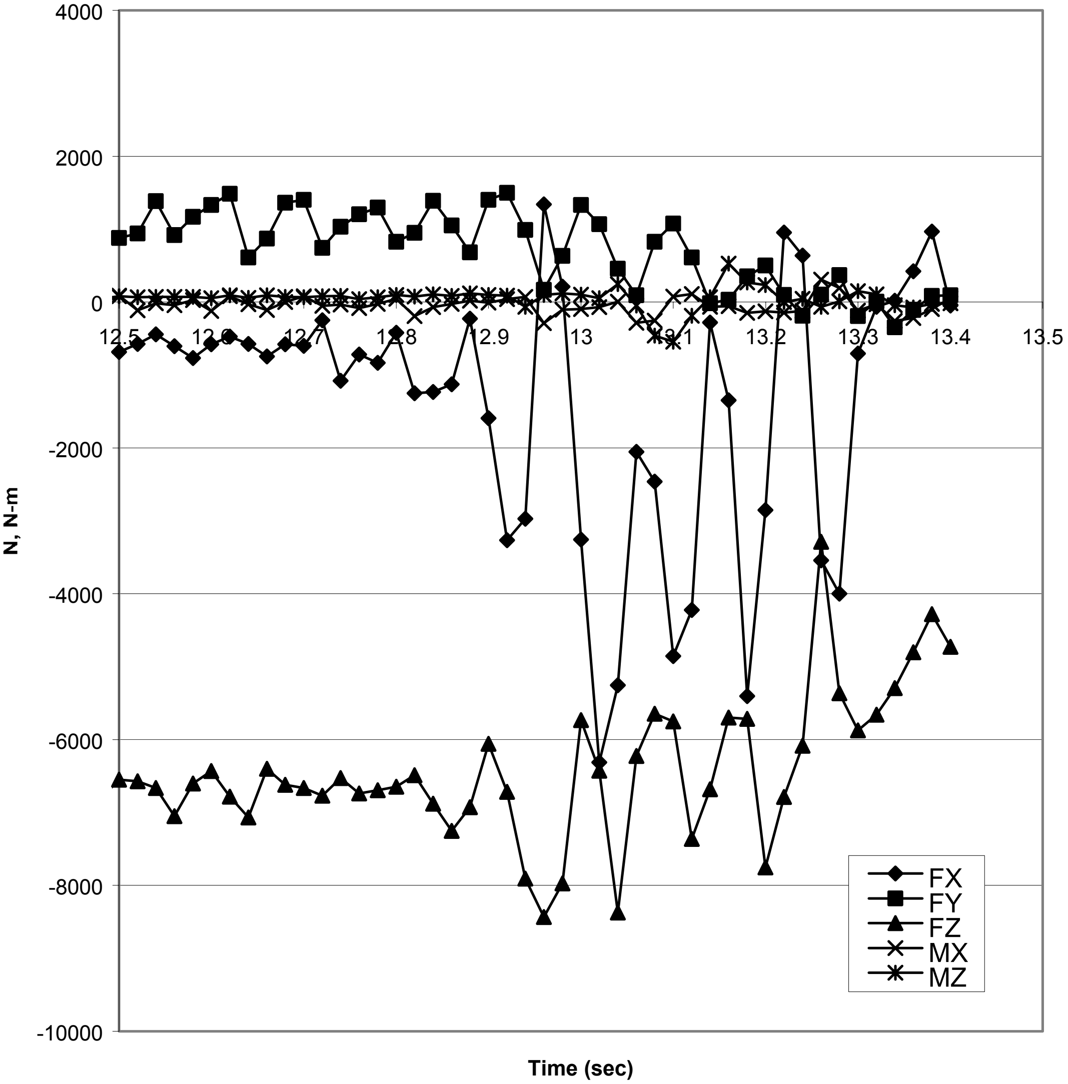
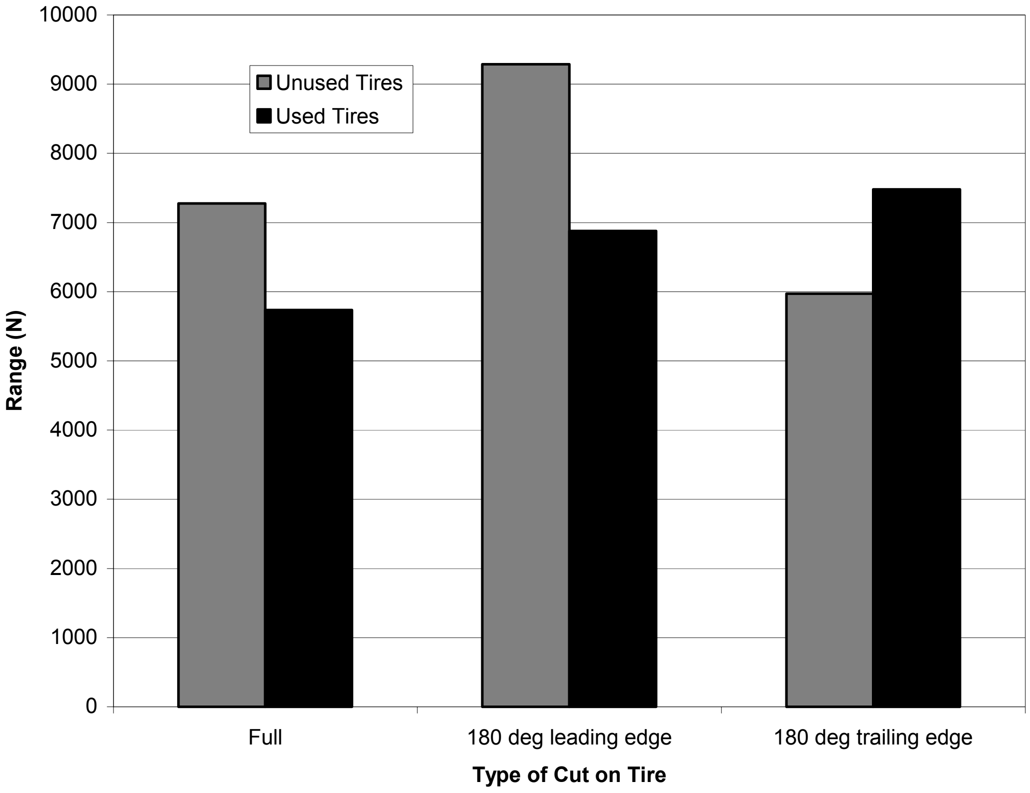


FIG. 2. - *Force and moment data for Tire 916-7 showing the variation and phasing of the hub forces during the tread delamination.*



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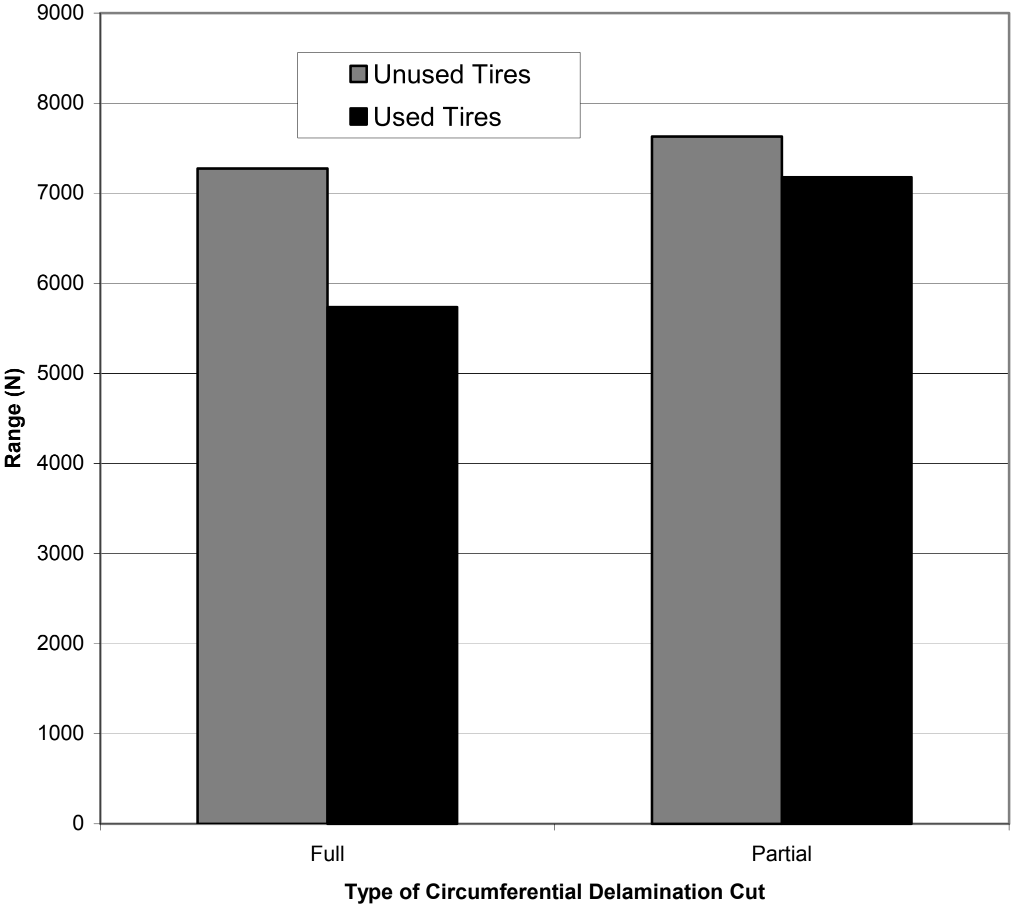

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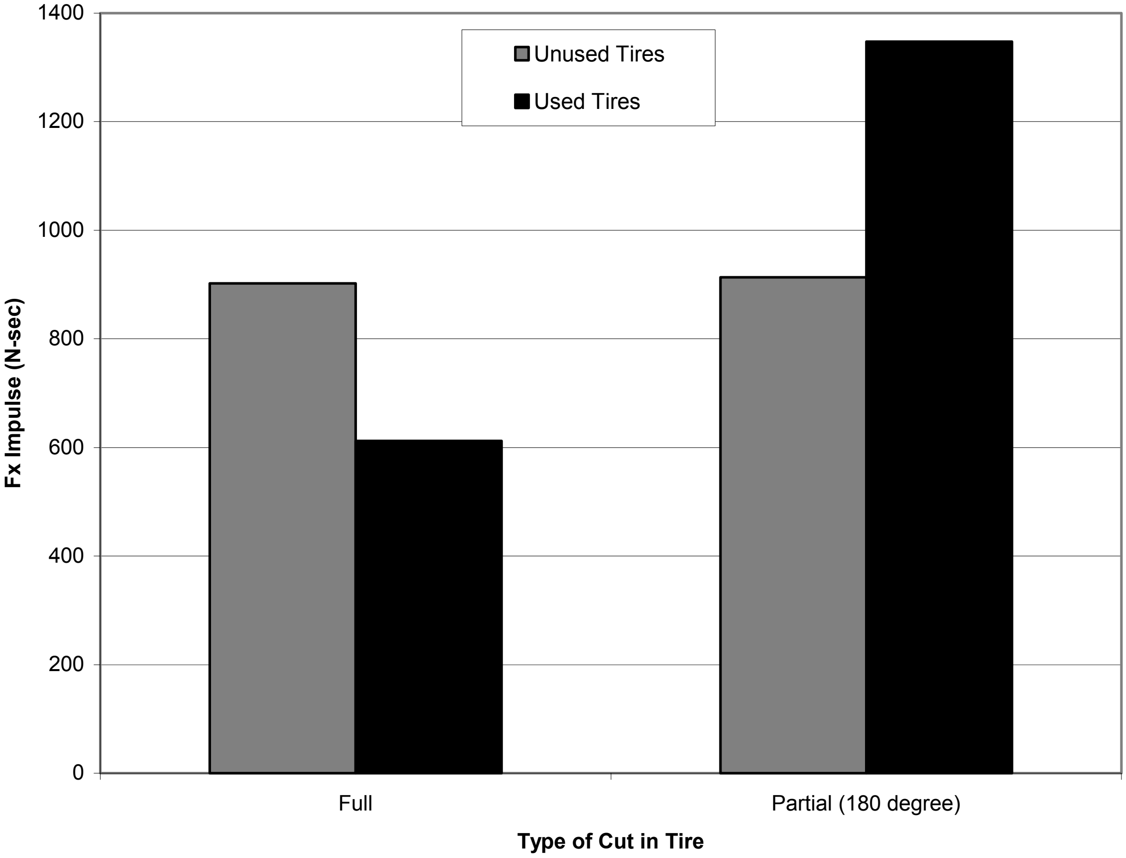

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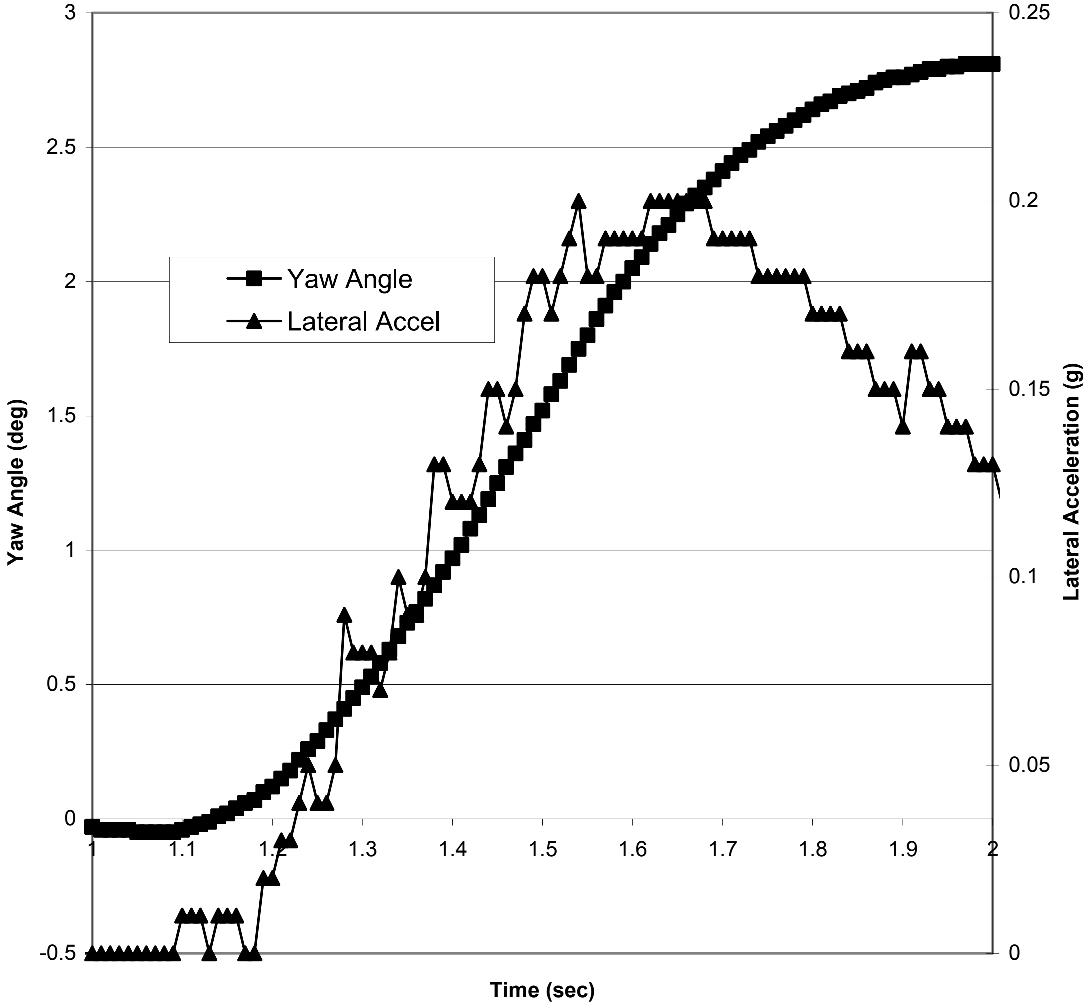

FIG. 6. - *Response of vehicle to tire tread delamination on right rear position. Initial vehicle speed was 112 kph (70 mph); separation begins at 1.0 sec and lasts 0.5 sec.*