



An Analysis and Evaluation of the Damage and Durability Performance of Steel Belted Radial Ply Passenger Tires That Have Experienced Severe Impacts

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ABSTRACT

It is widely known and well understood that a pneumatic tire can be vulnerable to irreparable damage as a result of severe road hazard impacts while in service. A wide variety of vehicle and laboratory test procedures exist to evaluate the effect on tire/wheel assemblies from impacting a road hazard such as a pothole. An example of a standardized procedure is SAE J1981, the primary purpose of which is to evaluate wheel performance. However derivations of this procedure have been used to evaluate tire performance, and to specifically characterize failure modes in tires. This Paper discloses a series of frontal impact tests on tire/wheel assemblies, combined with a series of nondestructive tests, culminating with controlled, fatigue endurance tests, to identify the damage and ultimately confirm the failure modes in steel belted radial ply tires.

INTRODUCTION

The notion of impact testing has been with us for as long as the pneumatic tire. With the advent of a cord reinforced, laminated, pneumatic tire structure, an impact test has proven to be an effective tool for evaluating the basic tire strength. This has been shown to be necessary for even today's highway tires, not only to validate the tire's load carrying capacity, but also to ensure reliable operation on less than perfectly smooth roadway surfaces.

An impact test inevitably involves a sudden and severe disruption to an inflated and rolling tire, in a manner to produce a concentrated and focused amount of kinetic energy that would be primarily directed radially toward the tire's axis of rotation. In addition, whether purposeful or not, the impact will act on the wheel onto which the tire is mounted.

OBJECTIVE

It is easy to envision and acknowledge a road hazard impact with kinetic energy sufficient to produce a tire failure. Furthermore, the tire failure would likely be virtually instantaneous upon impact. However, occasionally the failure can be somewhat delayed, as documented in numerous authoritative references¹⁰. Such a delayed failure would still be expected to be a rupture, just as with an instantaneous failure. However, it is occasionally believed and stated that a delayed failure can take the form of a belt separation.

The objective of this study is to begin by reviewing the history of impact testing. It will be followed by a program designed to run a matrix of tires on a controlled and realistic series of severe impacts. Any immediate damage or failure will be examined and documented with widely used non-destructive tests as well as visual inspections. For all tires which did not experience an instantaneous failure, an extended fatigue endurance test would be run, using an industry developed and approved procedure intended for producing belt separation failures. On this fatigue endurance test, each tire would be run to failure or to a duration wherein

any possible subsequent failure could not be reasonably attributed to the prior impact, whichever came first. Finally, each tire still exhibiting no visible failure would be non-destructively tested once again to verify its structural integrity.

EARLY IMPACT TEST FACILITIES

As tire company proving grounds emerged shortly after World War II, impact test facilities were typically included along with durability, treadwear, traction, ride, and handling courses. An example of such an early impact facility was the Penetration Rupture Course as shown in [Figure 1](#). It featured a machine, imbedded in the roadway, which contained a steel rod with a rounded, hemispherical head, called a rupture pin. Located immediately beyond the pin was a tripping mechanism that, when struck by the tire that had just been impacted, the rupture pin collapsed into the machine. This facilitated the testing of the front tire on the vehicle without testing or otherwise disrupting the rear tire. For this test, the rupture pin height was varied along with the speed of the vehicle, to ultimately determine the conditions under which the tire would fail. This early facility proved to be much more consistent with customer usage than a static test.



Figure 1. Penetration Rupture Course

Nevertheless, for obvious practical and economic reasons, this rupture pin was ultimately incorporated in the static laboratory tests widely found in many Standards, including FMVSS 109. Such a laboratory fixture is shown in [Figure 2](#). While this type of laboratory test obviously evaluates tire strength, it is not generally considered an impact test, because this “plunger pin” is expected to travel rather slowly into the tire structure (typically 2"/minute).



Figure 2. STLSM MACHINERY DIVISION

Another type of impact course that emerged with the tire proving grounds was the Belgian Block Course, as shown in [Figure 3](#). This rough cobblestone road provided an impact type of experience for the tire as well as vehicle components. It was similar to courses which existed at automotive proving grounds and provided for the evaluation of tires in a manner similar to that used by those customers.



Figure 3. Belgian Block

With the advent of the steel belted radial ply tire, primarily in the final quarter of the 20th century, it became apparent that changes would be in order for impact testing. For example, the Belgian Block Course would no longer effectively challenge such a tire with so vastly improved impact protection. The Belgian Block Course seemed to break vehicles and not tires.

An example of an improved test specifically tailored for steel belted radial ply tires featured a 2" diameter steel pipe that was cut at a 45° angle, with the upper edge sharpened. An example of such a pipe is shown in [Figure 4a-4b](#). The pipe was inserted in the same type of roadway machine as with the

penetration rupture machine, and test variables such as pipe height and vehicle speed were carefully managed with the typical and ultimate objective of failing the tire.



Figure 4a.



Figure 4b.

Such a pipe would accomplish a cutting as well as a rupturing action on a tire. Ideally, a pure cut inflicts damage starting at the tread surface, and pure rupture damage starts from the innermost ply, as has been commonly verified in the laboratory plunger energy test. At any rate, the ultimate failure mode, understandably, involves a breaking, cutting, or rupturing of the reinforcing cords and cables in the tire. While it is obviously possible to break some but not all of the layers in a laminate structure such as a tire, even to the point of leaving intact only one or more unbroken rubber membranes to prevent a total breach, such a fragile condition will be understandably short lived. As is widely known, the elongation at break of rubber is several orders of magnitude greater than the cords, while being at a small fraction of the strength. On such occasions, the contained air pressure combined with the other stresses present in a tire in service will result in the breach being completed sooner than later and will be accompanied with a rapid loss of inflation pressure.

RECENT DEVELOPMENTS IN IMPACT TESTING

Arguably, the widespread usage of aluminum wheels with widely varying disk designs and offsets created the need to improve upon the wheel impact test found in SAE J175. Accordingly, SAE J1981 was drafted and adopted. This

laboratory test features a striker mounted at the end of a pendulum, which swings down and strikes the tread of a tire mounted and inflated on a wheel, which is fastened and positioned statically on a test fixture. This machine is shown in [Figure 5a-5b](#).

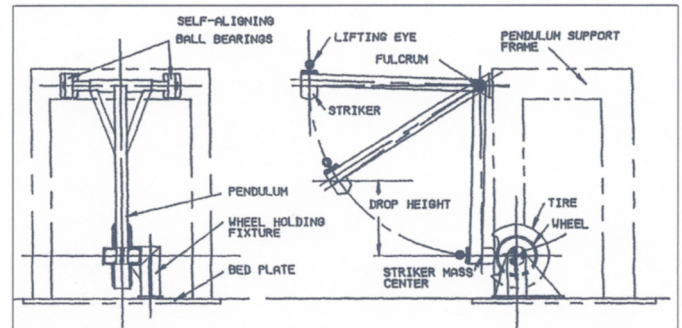


Figure 5a.

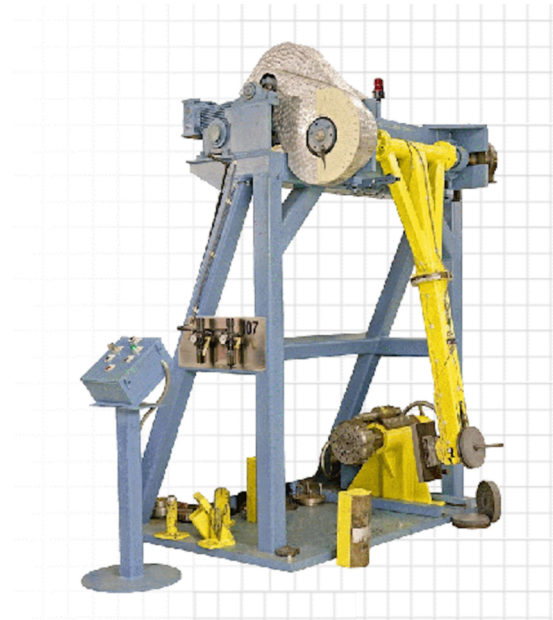


Figure 5b.

A significant variation of the pendulum machine is a straight drop machine, which also is a static test of a mounted and inflated tire/wheel assembly. While there are distinct technical advantages of the pendulum test over the drop test, the latter is nonetheless widely used and has been proven to produce reliable results when care is taken and the test parameters are carefully managed. The drop test machine is shown in [Figure 6](#).



Figure 6.

Notwithstanding these recently developed laboratory tests being intended for wheel evaluations, important revelations and relationships were uncovered regarding the performance and properties of today's steel belted radial ply tires. Specifically, when impact energy values reached the levels sufficient to damage the wheel, the tire remained essentially undamaged. Specifically, it was found that it takes 50% more energy to fail the tire than to fail the wheel¹.

Nevertheless, the SAE J1981 impact test machine has been recently used to produce significant damage and, ultimately, failures in tires. Specifically, the striker head had a variety of steel objects of varying sizes and shapes in an attempt to damage the tire without damaging the wheel and therefore abort the test². Many of the striker designs had shapes and edges that were likely to produce a combination of tire cuts and ruptures, similar to the afore-mentioned pipe test.

At the conclusion of a test matrix involving a variety of tires, strikers, and test conditions, it was reported that numerous examples of damage emerged. Furthermore, the striker design that apparently was the most successful for this purpose involved a small contact area with a rather sharp edge that struck the tire near the tread center (midway between the tread shoulders). While the inferred tire failure modes involved a varied combination of cuts and ruptures, it was nonetheless reported that at least some of the damaged tires had not failed immediately but instead would fail later in service. Such subsequent failures would naturally be expected to take the forms of completed ruptures and associated blowouts. Unfortunately, misconceptions have been created that have led to the beliefs that some subsequent failures can possibly take the form of belt separations. This is despite the fact that the impact damage was located primarily in the center region of the tread, where the belt shear stresses are negligible and actually go to zero³.

THE IMPACT TEST PURPOSE AND PROTOCOL

Accordingly, an impact test program was developed and executed to confirm or refute the notion that such impact damage in tires can lead to a belt separation failure. Furthermore, the impact tests were run dynamically on a roadway, using realistic vehicle components and reasonably foreseen impact hazards.

The test vehicle consisted of a salvaged bed of a half ton pickup truck, complete with its solid rear axle/differential housing and with a normal leaf spring and shock absorber suspension system. A ball hitch receiver was fastened to the front of the "trailer", which was hitched to a towing vehicle consisting of another pickup truck with ball hitch offset 24" from the center of its track width. Such an offset facilitated an impact test on a single tire, with all other tires on the vehicle combination successfully avoiding the hazard. The vehicle combination is shown in [Figure 7](#).



Figure 7.

The tire type chosen for the test program was of size P235/75R15, which is a size commonly found on pickup trucks and SUVs. Its construction featured a 2 ply polyester carcass, 2 steel belts, and a single nylon cap ply. All tires were new (had not been previously in service). The tires were mounted on 15×7J steel wheels with a -6mm offset.

The following objects were chosen for impact hazards:

- 4" × 4" × 24" long wood block
- 6" × 6" × 24" long wood block
- 4" × 8" × 16" long cinder block
- 8" × 8" × 16" long cinder block
- A concrete curb stop 36" long, 5" high × 7.5" wide at the base, tapered to 3" at the top

This collection of impact hazards is shown in [Figure 8](#). All impact tests were run on a closed course in Tucson, Arizona.

Table 1. Impact test Conditions and Locations

Test Tire	Load Per Tire (lbs)	Inflation Pressure (psi) Before	Inflation Pressure (psi) After	Impact Object (in.)	Object Configuration	Test Speed (mph)	Location of Impact (deg.)
1	1725	35.4	36.0	4x4x24 wood block	Perpendicular to road	60	295 to 310
2	1725	34.5	35.9	4x4x24 wood block	Parallel to road	60	250 to 350
3	1725	35.2	36.3	4x8x16 cinder block	Parallel to road	30	20 to 85
4	1735	35.3	36.8	4x8x16 cinder block	Perpendicular to road	60	235 to 265
5	1730	34.9	22.3	8x8x16 cinder block	Perpendicular to road	30	170 to 205
6	1725	34.8	36.0	6x6x24 wood block	Perpendicular to road	30	330 to 355
7	1730	35.4	35.8	5x7.5x36 curb stop	Perpendicular to road	30	300 to 315
8	1720	35.4	36.3	5x7.5x36 curb stop	Parallel to road	30	85 to 230

Paintballs and tire crayon were applied to the impact hazards in order to accurately mark the impacted areas on the test tire tread surface.

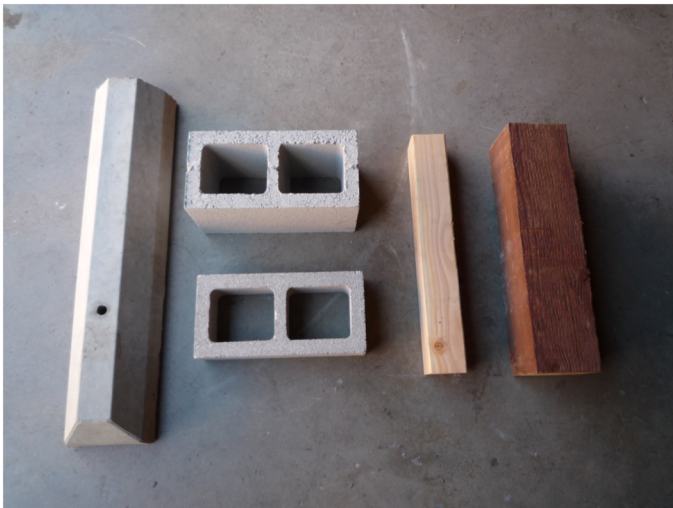


Figure 8.

Each of the test tires was assigned its respective test tire number, mounted, inflated to the rated pressure of 35 PSI, and fitted to the ballasted trailer. An additional two tires were used as control tires and were not run on any of the impact hazards. The matrix of the various test conditions is shown in Table 1.

FATIGUE ENDURANCE TESTING

It is widely known, as well as being verified with an abundance of empirical results, that the failure mode from a road hazard impact is a breach, consisting of a rupture, cut, or a combination. Even on the rare occasion when the tire does not fail immediately upon impact, but instead continues in service for a short but finite period of time before failing, the failure mode is a rupture. However, the belief is occasionally held that it is possible that an impact can directly lead to a belt separation failure later in service, should a complete rupture not occur immediately upon the impact encounter. Regarding the distance traveled from the impact to the final belt separation failure, estimates range from a few hundred to a few thousand miles. However, actual test data is virtually non-existent.

To investigate as to whether such impacts can eventually lead to belt separation failures, these impacted test tires were run on a 67.23" roadwheel at the facilities of Independent Test Services in Canton, Michigan. The test conditions consisted of 35 PSI inflation, 75% of the maximum load, 75 MPH, and an ambient temperature of 100°F. The ASTM Committee F9 on Tires found these roadwheel test conditions to have the highest potential for producing belt separation failures in passenger car and light truck tires through Load Range E⁴. The test duration was 5000 miles, which represented a significant excess of those distance estimates and claims regarding belt separation failures coming from an impact.

NONDESTRUCTIVE TESTING

As a means of precisely evaluating tire damage and corresponding propensity for failure, along with thoroughly establishing a baseline, a comprehensive matrix of nondestructive tests were undertaken at the facilities of NDT and Radiography in Tucson, Arizona. The tests consisted of X-Ray and Shearography, which are widely known and highly regarded equipment and methods⁵ for tire inspection and examination.

X-Ray examination is particularly useful in tires, due to the gross differences in the density of certain components, such as steel belt wires and rubber. Given that an anticipated and ultimate consequence of an impact can be a rupture, an X-Ray will confirm whether steel belt wires have been broken or otherwise significantly damaged.

Shearography, on the other hand, is capable of detecting early separations in a tire. This is accomplished with an interferometric method involving the surface strains in a tire. The basic method entails illuminating the unmounted tire surface inside a closed chamber with a laser light source. A baseline photograph is taken using a camera equipped with a shearing device. A second exposure is taken after the tire has been slightly distorted by drawing a partial vacuum in the chamber. Any separation will be revealed via an interference pattern in the resultant photograph or “shearogram”.

The Shearography and X-Ray evaluations for all tires were scheduled as follows:

1. Before Impact Testing
2. After Impact Testing and before Roadwheel Testing
3. After Roadwheel Testing

The above numbers (1, 2 & 3) identify the sequence shown in [Table 2](#). A thorough visual and tactile examination of all tires accompanied all of these nondestructive tests.

RESULTS

After completion of the impact tests, and upon visual and tactile inspection, none of the tires experienced any ruptures, cuts, splits or tears as a result of any of the impacts. The X-Rays revealed that none of the belt cables were broken, kinked, or otherwise damaged. The shearography tests showed that none of the tires exhibited any early stages of belt separation, belt cable looseness, or belt edge socketing. The shearography tests showed one tire to have some trapped air at one location under one shoulder, but this anomaly was also there at the same location and of the same size before the impact test.

During impact test number 5, the wheel experienced a severe dent in the inboard rim flange and a slight dent in the

outboard rim flange. This rim damage led to a 13 PSI loss of inflation pressure, between the tire beads and the rim flanges, while the tire/wheel assembly continued its subsequent travel over a distance of approximately $\frac{1}{4}$ of a mile. This impact encounter is shown in [Figure 9a, 9b, 9c](#). This damaged wheel is shown in [Figure 10a-10b](#).



Figure 9a.



Figure 9b.



Figure 9c.



Figure 10a.



Figure 10b.



Figure 11b.



Figure 11c.

In impact test number 6, the inboard rim flange of the wheel was slightly bent, which would have probably led to a slight loss of inflation pressure between the bead and the rim flange under loaded, rolling and steering conditions. This particular impact also broke the shock absorber from its mounting on the rear axle housing. This impact encounter is shown in [Figure 11a, 11b, 11c](#), and the damaged wheel is shown in [Figure 12](#).



Figure 11a.



Figure 12.

After completion of the roadwheel tests, and upon visual and tactile inspection, none of the tires experienced any blisters, cracks, splits, or tears. The X-Rays revealed that none of the belt cables were broken, kinked, or otherwise damaged. The shearography tests showed that none of the tires exhibited any early stages of belt separation, belt cable looseness, or belt edge socketing. The shearography tests showed the same

Table 2. Test Results

Tire Test	1	2	3	4	5	6	7	8
X-Ray* (1)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)
Shearography** (1)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)
Impact Object	4X4X24 Wood Block	4X4X24 Wood Block	4X8X16 Cinder Block	4X8X16 Cinder Block	4X8X16 Cinder Block	6X6X24 Wood Block	5X7.5X36 Curb Stop	5X7.5X36 Curb Stop
Rim Damage	None	None	None	None	Yes	Yes	None	None
Immediate Inflation Pressure Loss	None	None	None	None	Yes	None	None	None
X-Ray* (2)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)
Shearography** (2)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)
Fatigue Test Distance (mi.)	5000	5000	5000	5000	5000	5000	5000	5000
X-Ray* (3)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)
Shearography** (3)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)
* (+) indicates ruptured belt cables; (-) indicates no ruptured belt cables								
** (+) indicates separations; (-) indicates no separations								

trapped air in the one tire at the same location and of the same size.

The overall test results are summarized in [Table 2](#).

CONCLUSIONS

Using a representative variety of reasonably foreseeable road hazards under real world vehicle operating conditions, and when impact energy sufficient to significantly damage the wheel was created, no damage to the tire occurred. This confirmed previous findings¹. Furthermore, tires that experienced severe impacts remained totally free of any damage or any incipient separation even after being run for 5000 miles on a test expressly developed to produce belt separation failures⁴.

This test program supported and confirmed what had been found in the development of the laboratory impact testing machines^{7,9}. Should a tire/wheel assembly become unserviceable from an impact, the failure mode will be at the rim flange, which will cause an inflation pressure loss between the tire bead and the rim flange⁸. With even higher impact energy levels, capable of failing the tire as well as the wheel, the failure mode foreseen in a steel belted radial ply tire would be a sidewall rupture. This is commonly referred to as a “rim bruise”, which occurs when the tire momentarily flattens against the rim flange from the impact¹⁰. The folded over sidewall ends up being ruptured or cut by the rim flange.

None of the data or trends in this test program indicated any propensity for the tire to develop a belt separation failure, even later on in service, as a result of the impact.

FUTURE WORK

The possibility remains to test some of the tires to failure on the roadwheel, to confirm the ultimate failure modes as well as the distance to failure. This probably would involve a small matrix of tires that would include tires that were not impacted along with tires of various impact experiences. The roadwheel test program could include some tests with conditions of tire over-deflection, which would be expected to produce sidewall failures⁶, as well as some tests at normal deflection, which are expected to produce belt separation failures.

For such future work, it would be vitally important to isolate impact test influences from the various anomalies that were already present in the tires. In addition to the trapped air in one tire, most of the tires have varying amounts of belt placement anomalies, as revealed in the X-Rays. Such anomalies will skew, if not confound any relationship (or lack thereof) between impact exposure and tire failure later on in service.

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