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TITLE:

A Validated Test Methodology to Evaluate Radial Ply Tire Road Hazard Impact Failures

1. ABSTRACT:

In-service tire failures are a critical road safety issue. Tire malfunctions were reported to have contributed to seven hundred and thirty-three 2016 US traffic fatalities, and a similar number in 2017; it is therefore important to identify the predominant root causes. For decades tire manufacturers have warned that substantial in-service impacts can cause subsequent tire failure, even in the absence of immediate inflation pressure loss. Such impacts (e.g. with a kerb) are not uncommon, yet the vast majority of affected tires proceed safely to end-of-tread-life removal. A threshold impact magnitude, beyond which precautionary tire removal or close inspection for damage is recommended, appears not to have yet been established. A diversity of approaches has been used in attempting to do so, and in the present work those approaches have been reviewed in the light of measurements of road wheel impact force vectors, which have been validated herein. It was established that static laboratory tests published to date result in tire impact forces which differ very substantially from those confirmed on vehicles in operation, and that post-impact durability testing results in contact and other tire forces which similarly differ. No association between these tests and on-vehicle operating conditions has yet been determined. A suitable alternative test methodology and equipment design has been developed and validated, and a DOE proposed that will enable the determination of a set of impact and operating circumstances comprising a threshold at which damage that compromises the long-term structural durability of the test tire is expected.

2. KEYWORDS:

tire safety; tire durability; tire impact testing; tire failure

3. INTRODUCTION

In-service tire disablements are a significant factor contributing to crashes, injuries and loss of life globally. In 2018, for example, Safety Research & Strategies Inc. reported that tire malfunction was a factor contributing to seven hundred and thirty-three 2016 traffic fatalities in the United States alone1. The United States National Highway Traffic Safety Administration’s website reported seven hundred and thirty-eight fatalities from tire-related crashes in 2017, as recorded in the FARS database.

4. THE CAUSES OF TIRE DISABLEMENTS

It appears undisputed that a puncture through to the inner liner is the most common cause of a tire disablement. In the vast majority of cases the inflation pressure loss is detected (via TPMS or driver perception), the driver takes appropriate action and losses are minimized. Many punctured tires are successfully repaired and returned to service, and in the case of retreadable tires including radial ply truck and bus tires, subsequently retreaded and go on to deliver multiple tread lives.

If the puncture goes undetected the tire may continue in service at reduced inflation pressure. Should the pressure be sufficiently low for the load being carried – because of a puncture or for other reasons - excessive deflection may lead to structural damage to the tire. Such damage may be evidenced by fracturing or discoloration of the inner liner and sidewall [*1*], and potentially permanent distortion of the bead areas at the radii at which they deflect over the rim flange [*2*], although the published literature on the strength of the latter is equivocal [*3*]. Runflat damage alone may render the tire unsuitable for further use; if it continues in service much more substantial (and potentially catastrophic) structural damage may ensue, including (in the case of steel belted radial ply tires) complete detachment of the tread and steel belt package from the body ply or sidewalls as seen below.

Figure 1 - Tire damage caused by grossly underinflated operation. The sidewalls exhibit multiple fractures, and the shoulders have been circumferentially severed [*4*].

Sudden detachment of portions of the tread and belt package is another (if less common) unforeseeable failure mode of steel-belted radial ply tires. It is important that the causes are understood. Various organizations have published information indicating that in-service impacts with “road hazards” may cause tire disablements, including sudden tread and belt detachments that occur well after the impact itself, *having left no externally visible evidence of the event* [*5*]. The purpose of the present work is to analyze the basic physics of tire/road hazard impacts, review the literature that considers this phenomenon, to evaluate (in light of theoretical and real-world tire service conditions) the applicability of the test methodologies employed therein, and to propose an alternative test methodology.

Figure 2 - Typical tread and belt detachment of a steel belted radial ply passenger car tire [*6*]

5. THE DYNAMICS OF A TIRE/ROAD HAZARD IMPACT

5.1. Equivalent Stiffness

The tire in service does not behave in isolation; it is a component of a vehicle system. Road irregularities – including isolated irregularities such as a foreign object ("road hazard") – give rise to momentary spike force inputs to the complete vehicle system. The impact energy is dissipated largely through deflection of the most compliant system elements - primarily the tire, spring and damper and their associated isolators, as well as through displacement of the vehicle body.

Ignoring the displacement of the vehicle body and considering only the tire and suspension spring is a simplified approach, but one that is more severe than in real-world conditions because it requires that the upper end of the spring is solidly fixed. Such a system comprises two springs in series, a well-understood mechanical engineering system. The effective stiffness of the system (spring rate, k_{eq}) is less than the rate of the softer spring and is given by:

$$k_{eq} = (k_1)(k_2)/(k_1 + k_2) \tag{1}$$

Hence, it is clear that on the vehicle, the tire is required to absorb only a portion of the force imparted by a road hazard impact.

5.2. Direction of Impact Forces

Resolution of the forces imparted into a vehicle by a road hazard impact (typically a kerb strike) has been considered by several researchers, including Reimpell et al (2001) who described the influence of suspension spring stiffness on tire load when a wheel undergoes a step change in height (such as a kerb) [*7*], and Brown et al (2002) who described the mathematical relationship between the step height, tire diameter and longitudinal and vertical forces developed in the tire [*8*]. Others whose work generally concurs include Kerchman [*9*], Mousseau & Clark [*10*], Mousseau and Markale [*11*] and Sobhanie [*12*]. A summary of the findings follows.

As can be seen in Figure 3 (Chappuis, 2012), a vehicle wheel striking a solid object gives rise to impact forces initially in the longitudinal (fore-and-aft) direction, progressing to forces in the vertical direction. The compliant nature of a rolling pneumatic tire necessitates that the transition from peak longitudinal force to peak vertical force is indeed progressive rather than instantaneous – the initial longitudinal input is seen to occur well before the vertical force peak.

Figure 3 - Longitudinal and vertical forces when a 205/45R16 tire on a vehicle rolls over a 40mm-high cleat [*13*]

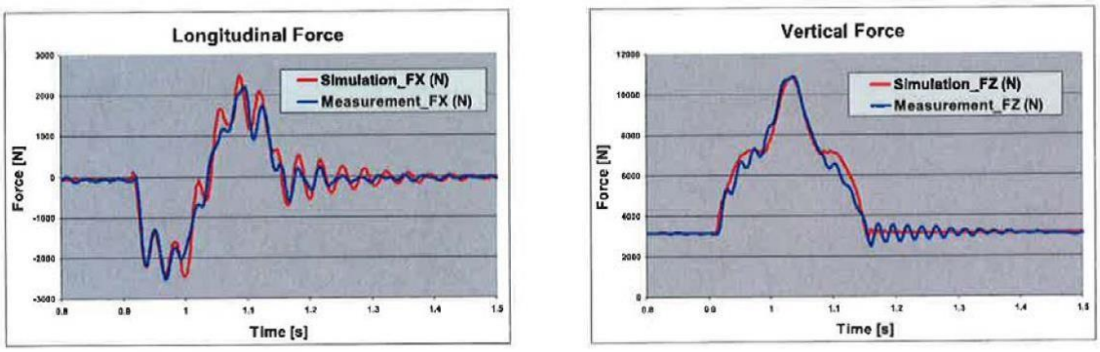
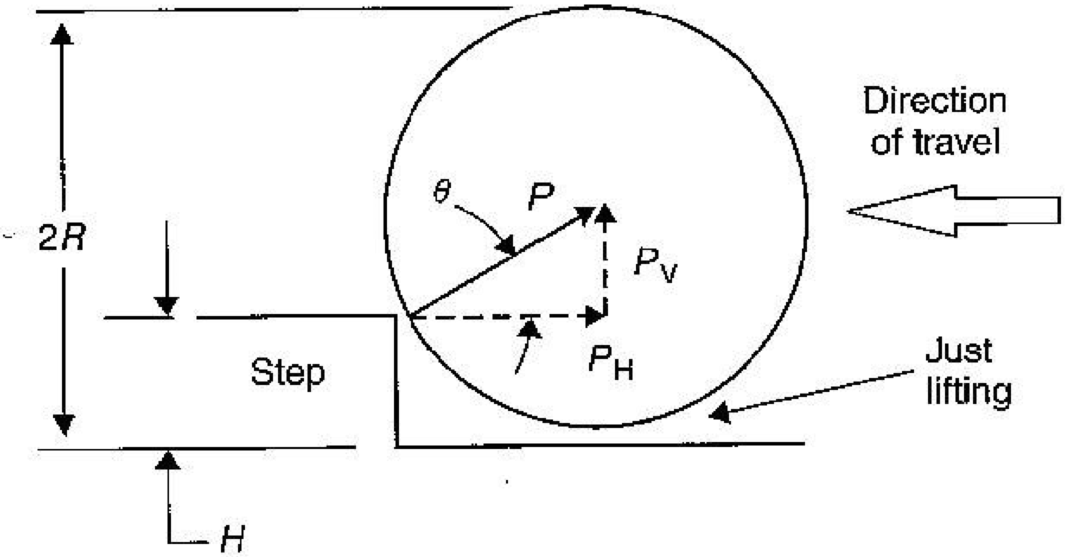


Figure 2.6: Longitudinal (FX) and vertical force (FZ) after cleat crossing at 5 km/h for tyre size 205/45 R16 **[6]**

The magnitude of the peak forces in a static condition is a function of the shape and size *H* of the obstacle, and the tire radius *R* (Brown et al, 2002):

Figure 4 – Free body diagram of a wheel striking a step [*14*]



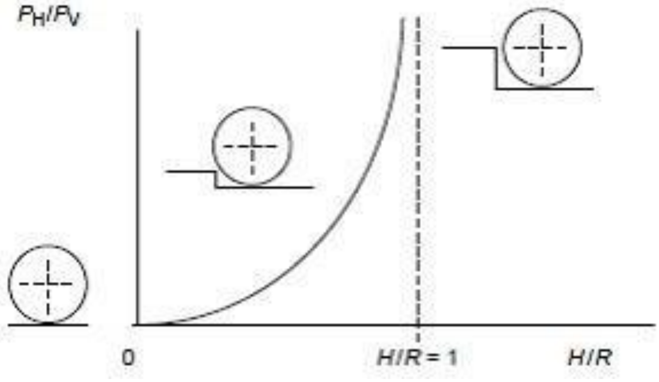
In Figure 4, P_V is the static vertical wheel load, *H* the height of the step and *R* the tire radius. The resultant force *P* (acting through the centre of wheel rotation) can be broken into its component parts as follows:

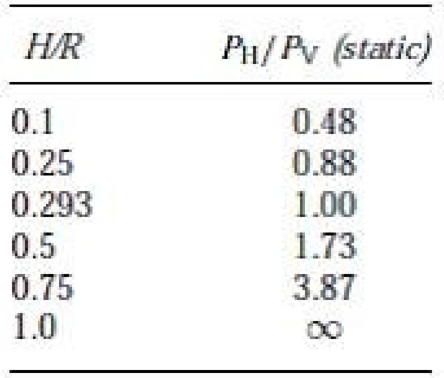
$$P_v = P \sin \Theta \tag{2}$$

$$P_H = P \cos \Theta \tag{3}$$

As can be seen in Figure 5, for a given tire diameter, horizontal forces (relative to the vertical wheel load) increase rapidly with step height:

Figure 5 – Relationship between step height H, tire radius R and static horizontal force [*15*]





H/R	P_H/P_V (static)
0.1	0.48
0.25	0.88
0.293	1.00
0.5	1.73
0.75	3.87
1.0	∞

By definition kerb impacts never occur in a static condition, so a dynamic load factor must be considered. Garrett (1953) suggested a DLF of 4.5 [*16*] which, if applied to the static factors above, yields longitudinal tire inputs that may exceed the vertical forces.

Given the number and range magnitude of these variables, the ability of static tests to reliably emulate any given real-world impact (in which many of the variables are, after the fact, undefinable) must be questioned. This view is echoed by Brown & Wallace (1994) who, in describing the background to the Society of Automotive Engineers SAEJ1981 Road Hazard Impact Test, noted that five of the eight identified impact variables were not accounted for in the final test methodology – including mass, vertical and horizontal suspension compliance, and the direction of the impact [*17*].

6. VERIFICATION

6.1. Dynamic On-Road Testing

In order to confirm the direction and relative intensity of the forces involved in a tire impact with a road hazard, a GCDC-X16-1D 3-axis accelerometer was mounted toward the outboard end of the front lower suspension control arm of a 2006 Holden Commodore utility fitted with 225/55R17 97V tires (static loaded radius = 313mm). The vehicle was ballasted to simulate a driver plus one passenger load condition, and inflation pressure was set to that recommended on the vehicle placard (235kPa). The vehicle was then driven at two speeds over steel square hollow sections of two different heights which had been fixed to the road surface, and the peak impact accelerations in the longitudinal (y) and vertical (z) planes recorded. The results are provided below:

Table 1 – Tire and wheel impact forces measured at 40km/h

40 km/h	**Peak impact force (g) for section height of obstacle (mm)**	
	40	65
Longitudinal	1.9	6.2
Vertical	3.5	10.9
Longitudinal / Vertical	0.54	0.57

Table 2 – Tire and wheel impact forces measured at 100km/h

100 km/h	**Peak impact force (g) for section height of obstacle (mm)**	
	40	65
Longitudinal	5.8	10.2
Vertical	7.5	13
Longitudinal / Vertical	0.77	0.78

6.2. Static Testing

As described in further detail later in this document, nearly all published static impact testing of tires has been conducted in accordance with SAE Recommended Practice J1981 (June 1994) *Road Hazard Impact Test for Wheel and Tire Assemblies*, or some variant thereof. The document Foreword describes the Standard as having been "*prepared to provide a uniform test procedure for evaluating the effect, on wheel and tire assemblies, of impacting a road hazard such as a pothole or kerb"* noting that "*No attempt has been made to simulate the exact conditions encountered when the wheel and tire strike such a hazard*." The Standard then goes on to describe a procedure in which a 406mm wide, 26.3kg radius-nosed striker blade affixed to a 1.83m long pendulum is dropped to instantaneously impact a tire and rim assembly in a purely radial direction (the equivalent of an instantaneous impact on a tire in service; e.g. an impact with a protruding edge at exactly axle height).

In order to demonstrate the tire impact loading differences between this test methodology and those experienced by rolling tires mounted on vehicles in service, a simplified pendulum mechanism, dimensionally equivalent to an SAEJ1981 impact test machine, was constructed (see Figure 6).

Figure 6 – Simple impact pendulum, dimensionally equivalent to an SAE J1981 impact machine

A GCDC-X16-1D 3-axis accelerometer was used to measure the direction and magnitude of forces imparted on a rigidly-mounted wheel and tire (175/70R13 @ 207kPa) assembly that was subjected to an impact by a 26.3kg striker blade released from 90 degrees. The following table provides the results:

Table 3 - Static tire and wheel impact forces (SAEJ1981 directionally equivalent)

	Peak impact force (g)
Longitudinal	0.005
Vertical	8.4
Longitudinal / Vertical	0.0006

By comparing these results with those obtained from a rolling tire in service, it is very clear that the SAE J1981 test methodology – consistent with its own Foreword - imparts very different forces on the tire and wheel from those experienced when a tire and wheel strikes an object in real-world operating conditions.

6.3. Discussion of Results

The results of this verification testing confirm that a significant portion of the loads imposed on a rolling tire when it strikes a “road hazard” are in the longitudinal direction, acting below the centre of wheel rotation. The absolute magnitudes of both forces increase with both vehicle speed and obstacle height, and the relative intensity of the longitudinal force increases with vehicle speed. Its relative increase with obstacle height is not definitively confirmed from this small sample of data, however the work of Brown et al is confirmed at a basic level.

The results further confirm that the SAEJ1981 impact test machine imposes markedly different loads on a tire and wheel assembly from those seen in real-world service; notably, there is basically no longitudinal component that acts below the centre of rotation; rather, the impact simulates a momentary impact at axle height, equivalent to a momentary vertical input to a wheel on a vehicle. The adequacy and relevance of such a test methodology as part of a representative tire impact damage test protocol is yet to be demonstrated.

7. LITERATURE REVIEW

In recent years various parties have published a range of documents pertaining to tire impacts. These range from an expression of opinion to detailed descriptions of impact test methodologies and results. The following summarizes those publications.

In 2001 Tire Technology International published *Impact Simulations in the Lab* by Bolden, Smith and Flood [*18*]. This document described the SAEJ1981 standard, and the modifications Standards Testing Laboratories made to their tire impact machine to enable them to vary the impact conditions. They describe a test protocol that involves running tires on a test wheel under FMVSS (109 or 119) Endurance Test conditions, striking the tires on the impact test machine, then inspecting the tires visually, by x-ray and shearography. If no damage was detected, the tire was struck again. The authors suggest the "*…road hazard impact machine has proven to be a valuable tool by providing a means to simulate field conditions and their resulting failure modes",* although how that conclusion flows clearly and logically from the article thus is not explained. They further suggest that "*Tires that have identifiable damage…resulting from an impact can be run in the laboratory on a dynamometer in order to replicate progressive-type failures",* however no actual test details or results were presented. On "Casing Pressurization", Bolden, Smith & Flood wrote "*Techniques have been developed whereby impacting a tire results in casing pressurization",* but no detail of such techniques is provided, nor about the failed tires shown in the accompanying photographs. The authors note that they were unable to create "localized fracture of the steel cables in only one belt", saying that "*…if steel cables are broken, they break in both belts resulting in immediate tire disablement.*"

In 2002 the Rubber Manufacturers Association (representing tire manufacturers) provided a formal submission to the National Highway Traffic Safety Administration in response to NHTSA's *Notice of Proposed Rulemaking 49 CFR Part 571 – Federal Motor Vehicle Safety Standards, Tires; Docket no. NHTSA-00-8011.* Under the heading *Road Hazard Impact Test* the RMA said "*The tire complaints that led ultimately to the TREAD ACT were related to isolated tread/belt detachment issues – not to pothole damage complaints. Damage from pothole impacts occur more frequently on the smaller height and aspect ratio tires and is, as ODI has ruled in recent cases, generally not safety related."* Commenting on NHTSA's proposal to introduce a Road Hazard Impact test for tires, the RMA said "*The SAE J1981 test was developed as a wheel damage test and has very limited use or experience within the industry as a tire test…".*

In 2003 the National Highway Traffic Safety Administration published a summary of work done in preparation for their revision to the Federal Motor Vehicle Safety Standard for Tires. They reported that they had conducted FMVSS 109 high speed testing on 20 passenger car tires that had been subjected to either a SAE J1981 Road Hazard Impact test or FMVSS 109 Tire Strength test. All 20 tires passed the high-speed testing, with subsequent visual, x-ray and shearography inspections revealing no evidence of damage. The test details were provided in a separate report. Consequently, NHTSA chose not to adopt the SAEJ1981 test.

In 2005 Tire Technology International published an update on Bolden, Smith & Flood's 2001 article [*19*], noting that the impact test machine enabled them to "…*efficiently and effectively select the variables necessary to dynamically simulate tire abuse from impact and produce failures consistent with field experience",* and that "…tires sustaining internal damage resulting from road hazards do not necessarily fail at the moment of impact", although no supporting data is provided. The authors noted that "*mileage alone does not appear to adversely affect a tire's resistance to impact",* and that resistance to impact injury decreases with tread depth. The failure of three tires was described, but no detail about the history of the tires or test methodology was provided. The types of damage observed in two other impacted tires was described, with these tires having apparently not been tested in any way. In conclusion the processes described are said to provide "*…testing techniques that approximate more closely the real-world conditions that can result in tire disablements*".

In 2005 the NHTSA published *The Pneumatic Tire* [*20*]. Chapter 15, entitled *Introduction to Tire Safety, Durability and Failure Analysis* was authored by Bridgestone employees Gardner and Queiser. Writing of "First Principles of Tire Durability", they opine that "*…influences include damage inflicted upon the tire structure from breakage, tearing, puncturing, contamination and intracarcass pressurization. Damage to the tire may accelerate the fatigue process or cause an immediate failure."* Commentary about cuts, punctures and intracarcass pressurization follows, and a description of how tire impact damage might be inferred from laboratory cord pull tests. It is suggested that in some cases "*…the tire will be damaged internally but capable of continued operation until it fails some time after the impact*", going on to suggest that a tread and belt detachment is a possible failure mode.

At the 2006 International Tire Exhibition and Conference Gary Bolden presented a paper entitled *Structural Impact Damage under Varying Laboratory Conditions.* The paper was also published in Tire Technology International magazine [*21*]. The article described the development of new, smaller strikers for the SAE J1981 pendulum impact machine (typically fashioned on the end of 1" diameter steel bar) on which, in use, the penetration depth had to be limited to avoid "…completely destroying the tire." Several P235/75R15 tires at various stages of wear (ip = 40psi) were impacted by these strikers at axle height via a 92lb overweighted pendulum swung through 170 degrees. Subsequent visual inspections revealed damage described as “small bulges, cracks and tears in the tread surface, liner blisters, tears and splits” and “broken steel belt cables”. No further analysis is possible from the information provided.

In 2008 Neves, Micheli and Alves [*22*] conducted experiments in which a 175/65R14 82T passenger car tire on a rigidly mounted steel wheel was subjected to transverse shoulder impacts (E=~138J) by a mass with a round indenter at various combinations of velocity, mass and inflation pressure. Very substantial wheel damage occurred, but tire failure was not considered in the study.

In 2012 SAE International published a paper by Woehrle and Carlson entitled An Analysis and Evaluation of the Damage and Durability Performance of Steel Belted Radial Ply Passenger Tires That Have Experienced Severe Impacts [*23*]. The authors described a test procedure in which they used a trailer offset from the longitudinal centerline of a towing vehicle to facilitate 30mph and 60mph impacts of P235/75R15 tires (load = ~1700lbs, ip = 35psi) with various wooden and concrete blocks. Along with two control tires, the impacted tires were then subjected to 75mph durability testing on a 67” road wheel at 75% of their rated load, for a total distance of 5000 miles. X-ray and shearographic inspections were conducted on the tires before and after impact, and after the durability testing. No failures or damage to any of the tires was detected. In some cases the wheels were damaged, leading to tire deflation.

Woehrle described the same results in a 2016 presentation to the Tire Technology conference [*24*], going on to describe additional laboratory impact testing of light truck tires in which wheel damage occurred in every test, and no tire damage was detected by visual, x-ray or shearographic inspections after 5000 miles on a test wheel at 75mph. Immediate deflation and steel belt cord rupture was noted in a subsequent test in which a rupture pin replaced the SAE striker, and a shoulder/sidewall bulge or immediate deflation resulted from ply cord and inner liner damage when impacted with the tire shoulder. Woehrle then described laboratory rupture pin impact testing of a 4-belt radial ply truck and bus tire that resulted in fracture of the tread and steel belt cords. No signs of failure were then detected following a 5000-mile wheel fatigue endurance test.

In Price & Follen's Influence of road hazard impact on radial car tires (2018) [*25*], the authors opined that road hazard impacts may cause a "…breach in the inner liner", suggesting it "…can be torn without obvious damage to the layers above it…". Describing oxidation and intracarcass pressurization, the authors then suggested "…the tire may eventually fail, typically losing a portion or all of its tread and top steel belts in the process", describing various characteristics they believed may then be in evidence and asserting (without foundation) that these failures initiated in the area of impact. They went on to suggest that impacts may "…break the steel cables within the tire or initiate a large fracture between the steel belts that further develops over time." They then summarized the work of Bolden et al (see above), reporting that they concluded that "…steel belt cable fractures…may lead to subsequent tire failure by tread belt detachment". A review of Bolden's publication does not confirm that such a conclusion was reported. Price & Follen then described "…never before published…testing conducted over a number of years…of tires tested to failure in the area of road hazard impact." The protocol briefly described involves DOT endurance testing, impacting the tires on the pendulum impact machine, then running the tires to failure on a road wheel under diverse (but undisclosed) conditions prior to inspecting them. "One significant constant” was reported to be “…that all tires tested failed proximate to the location of impact from some form of tread belt detachment”. Some detail of two tires that had reportedly been the subject of these test processes is then provided, with the authors concluding that this process provided “…significant scientific evidence that the field tire failed from a road hazard impact like the test tire, given the overwhelming similarities in the forensic evidence”. The “forensic evidence” was described as a radial split; tread flap; loose, bare, nested cords; bare polyester cords; v-shaped tear in the upper sidewall; a detachment initiation site and missing pieces of tread. Finally, a table was presented providing the size, prior condition and miles to failure of twenty-four tires that were tested under the protocol. The article concludes that the “data” shows “…that a severe impact to a steel belted radial tire can and does result in partial or full tread and belt detachment…proximate to the location of the impact”.

A similar version of the same article appeared in Tire Technology International [*26*]. The authors postulated that “Road hazard impact events may not cause immediate failure, but may damage internal components of the tire’s laminate structure”. Relying on the work of Bolden, Smith & Flood they suggest that “…tires that have a history of operating in underinflated and/or overloaded conditions are more susceptible to damage resulting from impact…”, however such a conclusion was not found during a review of the source documents. It is then theorized that an inner liner fracture leads to reduced inflation pressure, higher operating temperatures, intracarcass pressurization, oxidation and a tread and belt detachment, but no testing is conducted or proposed.

In 2019, Woehrle presented *Medium Truck Tire Impacts, R22.5 & R24.5* [*27*]. He first described striking a 16” passenger car tire on an impact test machine, before inspecting and running the tire on a test wheel at 75mph with 1200lbs of load and 35psi inflation pressure. The tire failed after 965 miles, suffering a tread and top belt detachment that commenced where an overlap and offset 2nd belt splice had been detected in the pre-test x-rays, 180 degrees from the impact site (where bent cords were noted). Phase 2 involved striking eight 4-belt radial ply truck and bus tires with a 1” diameter rupture pin using an impact force of at least 15,000lb. The tires were then run at 50mph on a test wheel for 5000 miles at their rated loads. All of the tires successfully completed the test with no failures or signs of separation.

8. CRITIQUE OF THE LITERATURE

8.1. Detail Provided

If the aim of publishing materials such as that described above is to further the industry's knowledge and understanding of tire failures, it is in my view incumbent upon the authors to provide in their reports details sufficient to enable subsequent testers to replicate the processes in order to verify and build upon the reported results. This approach is consistent with the principles of engineering research as described (for example) by Evans & Gruba (2002) who indicated it is important to: "*Include enough data in an appendix to show how you collected it, what form it took, and how you treated it in the process of condensing it for presentation…[28]*". The reliability and usefulness of reports that lack sufficiently detailed methodologies and data is of course limited.

Applying that principle to the aforementioned work confirms that, in the absence of further detail, some is unable to be replicated. The opinions of Gardner and Queiser, for example, are not supported by test details or results. Bolden's 2006 ITEC paper concludes, inter alia, that "*Steel belt fractures can occur without catastrophic failure of the tire at the time of impact, and may lead to subsequent failure."* Bolden does not explain how that conclusion is reached, which is important given none of the impacted tires were subsequently tested, either in the laboratory or on the road. This conclusion is also at odds with his 2001 work, which concluded that "*…if steel cables are broken, they break in both belts resulting in immediate tire disablement*". This important anomaly requires further investigation.

Bolden et al's 2001 TTI article suggests the "…road hazard impact machine has proven to be a valuable tool by providing a means to simulate field conditions and their resulting failure modes" and "proven to be a valuable tool in revealing and validating failure modes in the area of forensic tire analysis”. How those conclusions flow logically from the article thus is not immediately clear; they are particularly curious given that, again, the impacted tires were not subsequently tested, nor any field failure modes comprehensively presented in this work.

Woehrle and Carlson’s 2012 paper provides detail sufficient to enable a subsequent tester to replicate the key elements of the test methodology, as do Woehrle’s 2016 and 2019 presentations.

A conclusion of Price & Follen’s work is that the information provided “…represents the most comprehensive set of impact data known to exist and its publication…makes it available to others interested in the topic”. That being the case, it is reasonable to expect that detail sufficient to verify and replicate the work would have been provided, and that conclusions would flow logically from the data. Obstructions thereto include an unreported basis for the opinion that inner liner breaches can lead to tread and belt separations, and data insufficient to support the outcome that “…all tires tested failed proximate to the location of impact from some form of tread belt detachment”. Their conclusion “…that a severe impact to a steel belted radial tire can and does result in partial or full tread and belt detachment…proximate to the location of the impact” appears to be independent of any of the data thus presented in the article.

Of the twelve relevant articles reviewed, four (NHTSA, Woehrle & Carlson 2012, Woehrle 2016 and 2019) described the way in which impacted tires were subsequently tested on a road wheel to determine their durability. The other authors (Gardner & Queiser, Bolden 2006, Bolden et al 2001 and 2005, and Price & Follen) opined that impact damage can be the root cause of consequent tread/belt detachments in the apparent absence of adequate details of testing to demonstrate the basis of those opinions.

8.2. Pre-impact Tire Condition

Two authors (Bolden et al and Price & Follen) described a test protocol in which tires were first subjected to FMVSS Endurance testing, a high-load, relatively high-speed test conducted in high ambient temperatures that is designed to rapidly fatigue the tire. The following summarizes the passenger car tire (FMVSS 109) test conditions:

Table 4 – Summary of FMVSS109 Endurance Test conditions

Ambient temperature	100° F
Speed	50mph
Inflation pressure	2psi below maximum
Load steps (% of maximum)	4h @ 85%
	6h @ 90%
	24h @ 100%

Some testers elected to subject the tires to this regime prior to the impact tests in order to confirm that the tires were structurally sound. An additional effect is to in fact accelerate fatigue in the tires in a way that is unrepresentative of tires in real-world service conditions. Tire manufacturers do not sell tires that have been through this test. Tires tested under this protocol failed at a rate higher than those that were not, and the influence of the FMVSS test step on the outcome is yet to be quantified.

Whilst the service history of many used tires is unknown, what IS known is that the service history of no tires in the market includes being tested under FMVSS conditions. Proven, alternative non-destructive methods of evaluating tire integrity (shearography and x-ray) are used very effectively in the tire and retreading industries globally. These tests have no effect on tire durability, may highlight alternative factors known to initiate tread/belt detachments, and are therefore processes that should be used to confirm the pre-test structural integrity of impact test tires.

8.3. Wheel Restraint and Impact Methodology

Of all the work reviewed, only Carlson & Woehrle employed a test methodology that represents the real-world conditions of the vehicle system – i.e., with the rotating wheel having tight restraint and very limited initial compliance in the longitudinal direction, and a vertical load applied through a damped spring that provides substantial compliance. All of the other tests were conducted with the wheel rigidly fixed in a static condition, with the tire being – in effect – the only component that deflects in order to dissipate the impact energy. Further, only Carlson & Woehrle employed a test methodology that imposed impact loads on the tires which represent real-world conditions – i.e., with a sequence of longitudinal and vertical loads. All other tests imposed only loads that were radial to the centre of wheel rotation (i.e., at axle height), representing only a momentary vertical force if the wheel was mounted on a vehicle. Force vectors experienced by a wheel and tire in real-world service appear not to have been measured by any of the authors to date.

The representative test conditions were achieved by inflicting the impacts on the tires whilst fitted to a vehicle. The applicability of static, fixed-wheel impact tests to in-service tire impact events has not been explored, and requires further investigation.

8.4. Post-impact Durability Testing

Some of the work reviewed (that of Bolden, and Bolden Smith & Flood) described mechanisms for inflicting damage on tires in a laboratory setting, but made no attempt to then evaluate how tires so damaged might perform in subsequent service. Hence, as support for the notion that in-service impacts may lead to tread and belt detachments, these studies fall short of a reasonable standard.

Some of the work reviewed (that of NHTSA, Woehrle & Carlson, Woehrle, and Price & Follen) involved subjecting the impacted tires to road wheel testing in order to evaluate their propensity to fail. In addition to the benefit of avoiding vehicle and driver costs, road wheel testing provides the tester with the ability to monitor and control load, speed and ambient temperature, as well as to rapidly accumulate distance by running the tests continuously.

However, it is well understood that road wheel tests are far more severe on tires than on-vehicle service in the market. For example Robinson reported that, compared to a flat surface, tire contact with a road wheel results in "*…smaller contact area for the same load, resulting in higher contact pressure; greater deflection and more localized bending of the tread region; higher cyclic stress-strain amplitudes as the tire rotates through the contact area; typically, less cooling airflow on the indoor road wheel results in significantly higher tire internal temperatures. These can lead to… removal conditions, such as tread chunking, which are not prevalent in the field* [*29*]*"*. Stalnaker, Altman, Howland & Popio also reported that end-of-test tire conditions seen on tires tested on road wheels differed from those observed on tires in normal road service [*30*]. Spadone and Bokar reported that tires tested on a road wheel are subjected to "*an increased flex cycle severity, an increased centerline deflection, and a reduced footprint area which results in an increased contact pressure and ultimately in increased tire stresses. As a consequence, local heat generation rates increase and the tire's temperature will be higher, often significantly, when the tire is run on the road wheel at the same load, pressure, and speed as used on the road. Consequently, these more severe test conditions can cause atypical end-of-test, such as tread chunking, which are a result of the testing itself. In such cases, the test termination does not correspond to what would have taken place during normal on-vehicle use. Occurrence of such atypical EOT* *events effectively nullifies the validity of the test and prevents an evaluation of real durability issues that may exist for the tire on the highway*[31]".

The 2002 Rubber Manufacturers Association submission to the National Highway Traffic Safety Administration (in response to NHTSA's *Notice of Proposed Rulemaking 49 CFR Part 571 – Federal Motor Vehicle Safety Standards, Tires; Docket no. NHTSA-00-8011)* said "*The change in predicted running temperature from a flat surface to a 1.7m test road wheel is different for passenger and light truck tires. As tire diameters increase, a 1.7m road wheel becomes less like a flat surface and the severity of road wheel test conditions is increased compared to a flat surface. For example, with the proposed passenger tire conditions, the running temperature on the road wheel is 21% higher than on a flat surface when compared at 38degC. If the same comparison is made for light truck tires, a difference of 25% is seen.*"

The applicability to real-world operating scenarios of road wheel durability tests conducted on impacted tires is yet to be demonstrated. None of the work reviewed subjected impacted tires to subsequent real-world service on a vehicle.

8.5. Failure Observations

The "forensic evidence" described by Price & Follen - a radial split; tread flap; loose, bare, nested cords; bare polyester cords; v-shaped tear in the upper sidewall; a detachment initiation site and missing pieces of tread - is in fact common to virtually every passenger car and light truck tire that has suffered a tread and belt detachment failure, regardless of the root cause. In the absence of indicators uniquely identifying an impact, this work provides little or no support for the notion that impacts may subsequently manifest as tread and belt separation failures.

8.6. Summary of Literature Review

The published literature covers a broad spectrum of verifiability, applicability and relevance. The predominant approach has been to devise a test condition that will inflict damage on a static tire, rather than replicating the real-world conditions under which tires might be impacted, and evaluating the effects of the impact.

Where post-impact durability testing of tires was not conducted, support for the notion that impacts may subsequently manifest as tread and belt separation failures is not available. Tires that were not “pre-fatigued” by the FMVSS testing, and were impacted under real-world conditions, exhibited no failures and no damage when subsequently subjected to durability testing on a road wheel, despite the fact that the road wheel testing is well understood to be more severe than real-world service conditions.

9. A REPRESENTATIVE TEST METHODOLOGY

The most representative protocol involves:

- pre-impact qualification of the tires using non-destructive visual, x-ray and shearographic techniques;
- tires mounted on wheels with vehicle-like vertical loading and vertical and longitudinal compliance;
- an impact that transitions from longitudinal through to vertical accelerations, followed by
- further inspections and distance accumulation under real-world operating conditions.

10. THE PROPOSED SOLUTION

Impacting tires then accumulating substantial distance on an in-service vehicle presents challenges, not the least concerning safety. The author has developed a dynamic test rig that overcomes these issues.

Figure 7 – The on-road tire impact and durability test rig (PSR/LVR version)

A single wheel trailer facilitates impacts with objects while the towing vehicle wheels remain unaffected. Dissipation of impact forces replicates that of a complete vehicle – i.e. through the tire and suspension system, and through vertical displacement of the vehicle. Vertical load and wheel alignment can be adjusted to replicate the required condition. Accelerations in three planes can be continuously monitored and logged, as can inflation pressure, speed, ambient and tire temperature, location and accumulated distance. Continuous visual monitoring of the tire is achieved by three cameras.

Testing that can be accurately and safely conducted on the rig includes:

- impact testing and subsequent structural durability
- durability at low inflation pressures
- bead compression groove development
- durability at zero inflation pressure (e.g. runflat tires)
- tire operating temperature analysis

11. FIGURES

12. TABLES

13. REFERENCES

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