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Tyre Ageing

Its effect on material properties and structural integrity

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Report details

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Executive Summary

The Department for Transport is responsible for maintaining high standards of safety and security in transport and continuing to improve road safety.

The objective of this study was to provide scientific advice on the effect of chronological age on the performance of the elements of a tyre carcass that are critical to its mechanical integrity. The aim was to develop an understanding of whether the material properties of vehicle tyres evolve, due to the passage of time, to such an extent that the integrity of the tyre, and therefore its safety, is compromised.

Key Research Aims

The aim of this project was to:

- Develop an understanding of whether the material properties of vehicle tyres evolve due to the passage of time to such an extent that the integrity of the tyre, and therefore its safety, is compromised.

The purpose of the investigative programme was to provide objective scientific advice regarding the effect of:

- Time (chronological age) on the properties and performance of the elements of a tyre carcass that are critical to mechanical integrity
- Normal road use (including significant under-inflation) on the properties and performance of the elements of a tyre carcass that are critical to mechanical integrity
- Environmental conditions that can affect ageing (e.g. sunlight/temperature/extreme cold)
- The propensity of tyre inner liners to become more permeable and the effect of subsequent air leakage into the structure of a tyre

Literature Review

A literature review was undertaken to provide an objective report based on published scientific knowledge, which also informed the detailed testing to be undertaken.

The literature review revealed the majority of previous published testing in relation to ageing effects had been conducted on light goods and passenger car tyres, not heavy commercial vehicle, bus & truck radial tyres. In general, literature on the ageing of heavy commercial tyres and the effects, if any, is therefore limited.

Stakeholder Data

Stakeholder engagements undertaken as part of this study have highlighted limitations in the service life data retrievable from tyre management companies and the fleet operators of the vehicles. It appears that once a tyre is removed from service, any data in relation to original fitment or removal dates, the driven mileage and chronological age of the tyre is not generally available.

Data was supplied from commercial tyre remanufacturers based on their experience across the industry of the prevalence of defects in tyres submitted for the remanufacturing process, and arising at all stages in that process.

Engagement with the remanufacturers has shown that comprehensive data for all tyres examined in the preliminary casing acceptance process are not recorded, as the examination ceases as soon as the casing is rejected and the remanufacturer's interest lies only in the accepted casings. Reasons for rejection from the retreading process are largely driven by the economic cost of repair needed to meet the requisite UN Regulation and may be defined by a combination of the tyre condition, brand, model, size, manufacturing facility or period of manufacture. Not all remanufacturers record the date of manufacture of rejected casings, thus limiting the availability of data to inform this research. In practice, there are a number of barriers and commercial sensitivities; however, the remanufacturers' data indicates an overall conversion rate of about 52% with most rejections occurring on their initial visual inspection before Shearography examination (as depicted in BTMA data Figure 6). Some of the defects identified at visual inspection may already be obvious from routine maintenance inspections of the tyre when in service e.g. external damage, punctures.

Members of the British Tyre Manufacturers Association have varying positions regarding the maximum age of casing they will accept for retreading, some members may have seven or eight years as a maximum but none more than 10 years, as determined from the regulated tyre marking code on the tyre sidewall. Commercial experience and economic considerations have to be considered and also, each would not want to be too different to other companies. Adopting an older maximum age may give some financial benefit but would deviate from the industry norm. Adopting a younger age limit restricts commercial opportunities.

Test Programme

In order to provide further information on the effects of ageing on different tyre characteristics, 31 tyres were subjected to laboratory testing including five new and thermally/dynamically aged tyres used as controls. A suite of assessments, measurements and laboratory tests were undertaken to assess the material properties and structural integrity of the selected tyres.

The tyres chosen for testing were from one manufacturer and originating from in-service use within the UK vehicle fleet. In accordance with the project specification the tyres were sized 295/80 R22.5, of first life (not re-treaded) and aged between 3 and 19 years.

Following acquisition of the used (first life) truck & bus radial tyres, each tyre was inspected and the carcass evaluated to ensure that each tyre fell within the scope of the study and did not harbour pre-existing defects; of which any external defects should be discernible by routine maintenance inspection.

The testing provides some data to suggest that the physical properties of the tyre are affected by the length of time that the tyre is in service. The hardness of the sidewall compound appears to show an increase with time. It was noted that the majority of the observed changes have occurred within the first 3-4 years of service life.

Reductions in interfacial peel forces at several interfaces within the tyre were noted; however whilst these reductions were observed after service, no data is available to indicate the critical limitations on peel force at each interface relative to the structural integrity of the type of tyre being studied. It is therefore not possible to comment further on the significance of this result.

Examination of the peel adhesion test samples revealed that a number of the samples exhibited corrosion of the steel cords themselves. Of the 26 tyres returned from service, 16 exhibited corrosion of one or more of the steel belts, with the corrosion being most prevalent (but not exclusively) in belt 4, the uppermost belt in the tyre's structure. This evidence supports the hypothesis that this corrosion is due to penetrations through the tread of the tyre and into the outer layers that were not deep enough to penetrate the lower layers or to puncture the tyre, although the data available does not definitively prove the relationship. The presence of this corrosion would be expected to adversely affect the bond between the steel cords and the adhesive rubber compound with which they are coated, although no obvious effect on peel strength or ply strength was observed in this test series. This is important to consider as loss of integrity at belt 4 can be associated with separation of the tread and deflation of the tyre. In this test series all tyres eight years old or older showed corrosion.

Some of the physical property changes observed in tyres that had been in service were found to be less marked than those observed with the laboratory-aged controls tyres, whilst some were more marked than those of the aged controls. This would indicate that prediction of a tyre's material & physical property changes as expected in service, through laboratory testing, is not straightforward and suggests the oven ageing procedure for commercial tyres would need to be refined before it could reliably be used as a benchmark.

Conclusions

Little relevant information was available regarding the effects of ageing on heavy vehicle tyres, either from the literature, from fleet companies, or from the retreading industry. Nevertheless, some members of the industry (Continental/Uniroyal/Michelin) have published recommendations on the maximum age of a tyre in use; as do the BTMA in relation to retreading age limits.

The test programme identified an increased tyre rubber compound stiffness with age, with an associated reduction in elasticity with increasing age.

The cut section inspections revealed a number of tyres with anomalies associated with the steel belt package. All of the anomalies were found in the tyres returned from service, whereas there were no anomalies of note in any of the new or new/thermally aged tyres. The revealed anomalies were not identifiable from the shearography inspections; therefore the findings from this sector of the work suggest that shearography may not be able to detect all of the internal anomalies that may be present in a tyre following service use. Smithers Rapra indicate that the observed looseness of the belts, which is a breakdown of the steel-cord and rubber compound, reveals limitations in shearography. At what point such looseness would cause a rejection in the retreading process would be for the opinion of the retreading business.

Peel force reduction appears in the first three to four years of tyre life. Despite scatter, the data reveals there is a marked reduction in peel force within this age range, for belt 2 to 3, belt 3 to belt 4 and between the casing and sidewall, when compared with a new tyre; however following the initial drop there does not appear to be any further significant reduction over the age range of the tested service tyres.

The thermally aged tyres also showed a reduction in peel force compared to the control tyre, however this was not as marked as observed in the service tyres. Further data would be needed to compare those changes with the critical limits for each of the properties as designed and specified by the original tyre manufacturer.

Examination of the peel adhesion test samples revealed that a number of the samples exhibited corrosion of the steel cords themselves. Of the 26 tyres returned from service, 16 exhibited corrosion of one or more of the steel belts, with the corrosion being most prevalent in belt 4, the uppermost belt in the tyre's structure. This evidence supports the hypothesis that this corrosion is due to penetrations through the tread of the tyre and into the outer layers that were not deep enough to penetrate the lower layers or to puncture the tyre, although the data available does not definitively prove the relationship.

The presence of this corrosion would be expected to adversely affect the bond between the steel cords and the adhesive rubber compound with which they are coated, such that, it could affect the integrity of the tyre in service in such a way that disablement may result, although no obvious effect on peel strength or ply strength was observed in this test series.

The project has:

- Compared evidence from physical inspection of older tyres with rejection and failure statistics from the commercial vehicle tyre remanufacturing process
- Provided an objective report based on published scientific knowledge, together with the understanding gained from this investigative programme, which explores the effect of chronologic age on the structural integrity of a tyre
- Discussed the scientific evidence to inform consideration of a control of the use of tyres on the basis of their chronological age

Limitations

Given the limited number of tyres involved in this research compared to the number in use in the UK, statistically valid conclusions may not be made without an increased sample size; the in-service conditions such as under-inflation (to any degree), overloading and the heat history of each tyre during its lifetime were unknown, thus it was not possible to conclude whether the observed changes were a result of only service use, age alone, or a combination of both.

The results do provide data to suggest, that some of the physical properties of a tyre are affected by the length of time that the tyre is in service and the type of service that the tyre experiences. There is considerable scatter of the data with variability observed between tyres of similar age, therefore the particular service use and the employed maintenance regimes are considered likely to impact on the data.

It should be noted that only a single tyre brand was tested. Differences in rubber compound formulation and steel cord construction that exist between tyres, of different manufacturers, types and ages may affect the results and conclusions of this analysis.

Table of Contents

Table of Figures

1 Introduction

1.1 Why was this research commissioned?

In September 2012, a catastrophic failure of a tyre, fitted to the front axle of a large coach, led to the loss of three lives. The accident investigator concluded that the tyre failure was as a direct result of its age but no forensic evidence was presented to explain or characterise the degradation of the tyre's construction resulting from the passage of time.

Following the inquest, and on the basis of the precautionary principle, the Secretary of State for Transport issued advice to coach owners and operators that tyres aged 10 years or older should not be used on the front (steering) axle of buses and coaches and, if used at all, should only form part of a pair in a twin wheel arrangement on a rear axle[1].

The Government is committed to the use of evidence to support the development of policy. At that time, it had not been able to identify any research that supported the argument that a tyre is liable to failure purely on the basis of its chronological age.

1.2 Key research aims

The aim and objective of this project was to:

- Develop an understanding of whether the material properties of vehicle tyres evolve due to the passage of time to such an extent that the integrity of the tyre, and therefore its safety, is compromised.

The purpose of the investigative programme was to provide objective scientific advice regarding the effect of:

- Time (chronological age) on the properties and performance of the elements of a tyre carcass that are critical to mechanical integrity.
- Normal road use (including significant under-inflation) on the properties and performance of the elements of a tyre carcass that are critical to mechanical integrity.
- Environmental conditions that can affect ageing (e.g. sunlight/temperature/extreme cold).
- The propensity of tyre inner liners to become more permeable and the effect of subsequent air leakage into the structure of the tyre.

To identify tyre properties that could affect the integrity of the tyre in service in such a way that failure may result.

To compare evidence from physical inspection of older tyres with rejection and failure statistics from the commercial vehicle tyre remanufacturing process.

[1] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/266915/dft-tyre-guidance.pdf

To provide an objective report based on published scientific knowledge, together with the understanding gained from this investigative programme that explores the effect of chronologic age on the structural integrity of a tyre.

To discuss the scientific evidence to inform consideration of a control of the use of tyres on the basis of their chronological age.

2 Commercial vehicle tyres in the UK

2.1 UK Vehicles

As of 2018, the Society of Motor Manufacturers & Traders (SMMT)[2] reports there are some 39.6 million vehicles on the road in the United Kingdom (UK); of these there are 602,799 trucks and 86,607 buses and coaches, representing a percentage of about 1.5% and 0.2% of the total.[3]

Road use statistics[4] from the DfT suggest that, when considering vehicle miles travelled, HGVs are the most intensively used vehicles; travelling on average further than cars or vans and representing 5% of all vehicle miles travelled, with bus & coaches under 1%[5] of all miles travelled.

Department for Transport published 'Road Traffic Forecasts 2018', predict that road traffic at a national level is set to grow from an earlier 2015 forecast by between 17% & 51% by 2050 with the strongest growth on the Strategic Road Network. A modest increase in demand for goods leads to a forecast of less growth in HGV traffic with an increase, by comparison, of 5%-12% by 2050.

In 2017, 17 people were killed and 147 people were seriously injured in road traffic collisions where illegal, defective or under inflated tyres were recorded as a contributory factor in the collision[6], these factors represent 1% of the contributory factors reported. The age of the tyre or further data in relation to the tyre is not statistically recorded therefore no association in relation to the vehicle defects, as recorded, can be made with the effects of ageing on the tyre.

It is important to note that the contributory factor system is based upon the identification of such a factor by the attending police officer who may not be in a position at that time to identify all factors.

2.2 Commercial tyres

The basic function of a tyre is to provide adequate friction, to support the dynamic forces at the vehicle to road interface and to absorb the mechanical loads caused by any road irregularities whilst supporting the vehicle, occupants and load.

[2] https://www.smmt.co.uk/wp-content/uploads/sites/2/SMMT-Motor-Industry-Facts-June-2018.pdf

[3] DfT stats for the previous year 2017 suggest, 523,300 licensed Goods vehicles and 74,600 buses & coaches not including minibuses

[4] https://www.gov.uk/government/statistics/road-use-statistics-2016 p8

[5] https://www.gov.uk/government/statistical-data-sets/road-traffic-statistics-tra#traffic-volume-in-miles-tra01

[6] https://www.gov.uk/government/publications/reported-road-casualties-great-britain-annual-report-2017

Commercial tyre manufacturers apply technical knowledge and experience in producing reliable role specific tyres (examples of variations in expected service life are shown in Figure 1), including consideration of anticipated vehicle speed, load, grip, weather and wear resistance, fatigue resistance and longevity of service life. The lowest tread wear may be observed on long distance vehicles on trunk roads or motorways. The most severe tread damage may be observed on vehicles used on loose surfaces and unpaved roads. Accelerated wear from accelerating, braking and turning may be observed in vehicles operated in the urban environment.

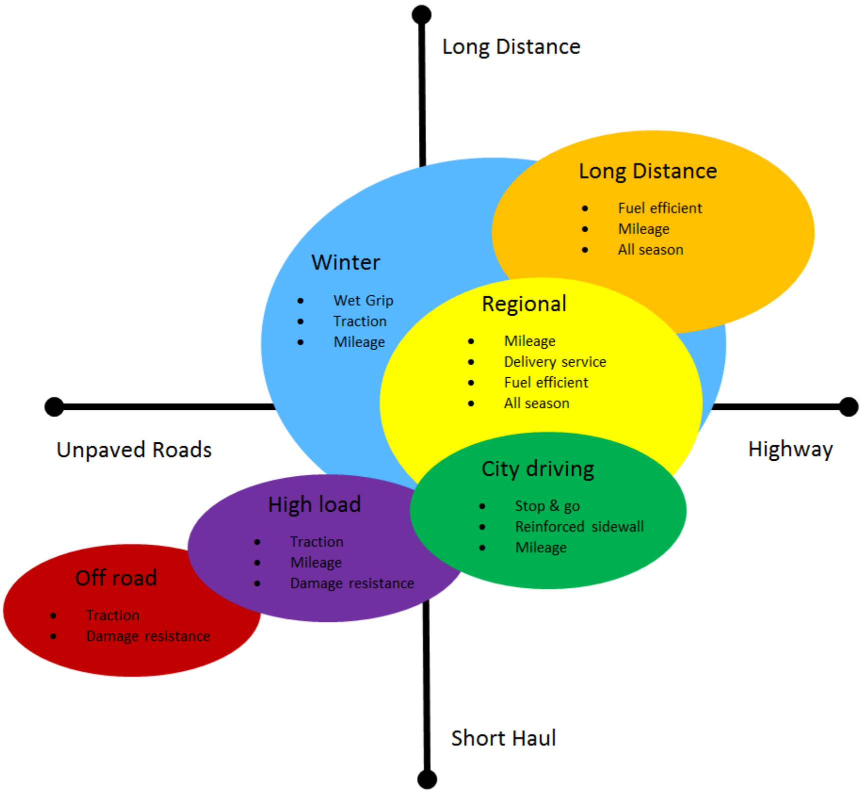

Figure 1: Tyre service applications[7]

Whilst engaged in dynamic service use, the tread and carcass are under continuous loading and undergo repetitive deformation as the tyre rotates. A manufacturer is not able to oversee a tyre throughout its service life; it is thus the vehicle operator who is responsible for a tyre's in-service usage and continued fitness.

Maintaining correct inflation is one of those operator responsibilities, however this aspect is greatly influenced by the effectiveness of the inner liner acting as a barrier to loss of air pressure; inner liner will be discussed later in this report. Atmospheric air compressed by mechanical means to inflate tyres generally contains approximately 78% nitrogen (N_2) 21% oxygen (O_2) and 1% other gases and contains a widely varying amount of water vapour.

Road conditions can vary between smooth asphalt, concrete, unpaved gravel and dirt roads. In extreme international climates a tyre can be exposed to ambient temperature anywhere

[7] Based on Goodyear Truck Tyres Technical Data book application map

from + 38°C to -26°C although the UK mean daily temperature value for 2018 is shown in the +12 to +5 range (daily period 0900-0900 GMT)[8] – see Figure 2. Despite this small ambient range, the operating temperature of a typical commercial tyre can vary greatly depending on the type of driving, inflation pressure and vehicle load.

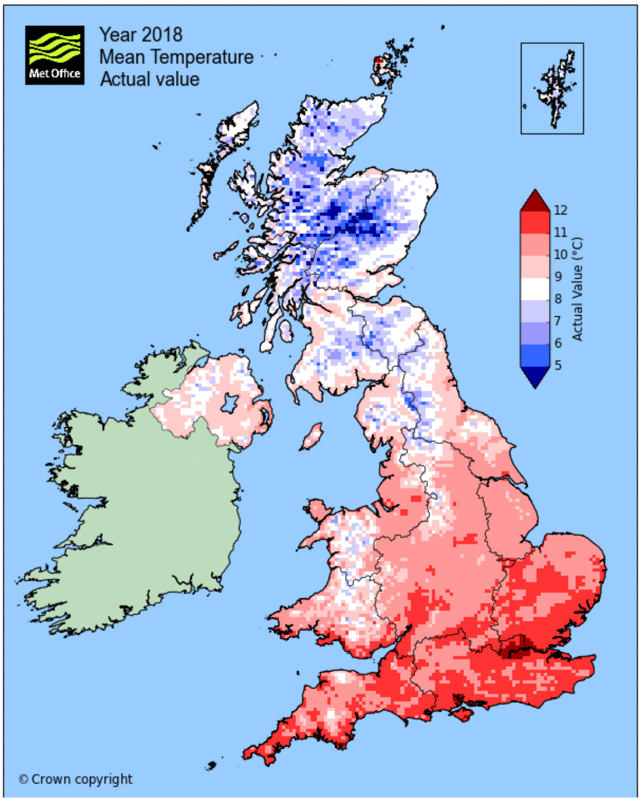

Figure 2: Mean daily temperature UK 0900-0900 GMT

The sidewall of a tyre gives structure, strength, support and shape to a tyre; it provides lateral stability whilst deflecting during normal use. Any under-inflation of the tyre allows greater deflection of the sidewall and carcass and produces higher running temperatures. A factor that also impacts on a sidewall is its resistance to environmental conditions, the weather.

There is legislation within the Road Vehicles (Construction and Use) Regulations 1986 which requires, in use, tyres to be fit for purpose at all times, although these regulations generally refer to: a tyre's markings, noise level, mixing of type, inflation pressure, tread depth and maintenance.

[8] https://www.metoffice.gov.uk/climate

2.3 Current guidance from Driver and Vehicle Services Agency (DVSA)

In November 2018 the DVSA updated its ‘Guide to maintaining roadworthiness; Commercial goods and passenger carrying vehicles’[9]. Within this guidance, it is stated that professional vehicle operators should ensure:

> *“that tyre age is monitored and that tyres aged more than 10 years old should not be used except on a rear axle as part of a twin wheel arrangement. Where tyres more than 10 years old are used, their age should be recorded and a specific risk assessment, that considers the speed and loading conditions that the vehicle will operate under (for example, operating only in urban areas) is done”*.

2.4 Date code / tyre identification number

The markings on a tyre sidewall are required by United Nations Economic Commission for Europe Regulations that are applicable in the United Kingdom and more widely in Europe. They provide manufacturing information, comprising of the manufacturing plant where the tyre was produced, along with the week and year in which it was made (see Figure 3)[10]. The last four characters of the markings are the date code, in the format W W Y Y (week number / year number) i.e. 4117 is the 41st week of 2017 (week commencing 7 October 2017).

Figure 3: Regulated tyre markings

[9] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760818/guide-to-maintaining-roadworthiness-commercial-goods-and-passenger-carrying-vehicles.pdf

[10] This production date is generally only visible on one side of the tyre

3 Literature review

This chapter presents the results of a literature review carried out to understand the current published knowledge in relation to the effect of ageing on tyres, service use, vehicle tyre construction and material analysis techniques.

3.1 Literature databases

The databases searched on behalf of this literature review are outlined below.

TRID (Transport Research International Documentation) is a database that combines ITRD (OECD's International Transport Research Documentation database) and the US-based database TRIS (Transport Research Information Service). Together they form one of the most comprehensive transport research databases available today which covers more than 900,000 records of references to books, technical reports, conference proceedings, and journal articles in the field of transportation research.

http://trid.trb.org/

Science Direct is a leading full-text scientific database giving access to 6.5 million journal abstracts on all topics, book chapters from more than 2,500 peer-reviewed journals and over 11,000 books.

http://www.sciencedirect.com/

IMechE (Institution of Mechanical Engineers) provide an online library and digital resource with access to engineering publications from key publishers, including McGraw-Hill, Springer and Elsevier. All ASME journal papers published from 2000 and conference papers published since 2008.

https://www.imeche.org/

TRIMIS (Transport Research and Innovation Monitoring and Information System) is an online platform for researchers to share and discuss innovation in mobility in Europe. It analyses technology trends, research and innovation capacities and developments in the European transport sector, providing open-access information.

https://trimis.ec.europa.eu/search/site/tyre

The Transport Research & Innovation Portal (TRIP) is the one single portal for all transport research conducted at European and national levels and in ERA (European Research Area) countries. Providing the most up-to–date information on transport research projects, programmes and activities, TRIP aims to increase awareness, understanding and the take-up of transport research results. TRIP showcases over 7,300 projects and their associated documents and more than 300 national, European and international transport research programmes. It also provides background information on the organisation of transport research in the 30 ERA countries and in Europe as a whole.

https://ec.europa.eu/transport/themes/research/trip_en

ARRB Knowledge Base is a free full text searchable resource of ARRB (Australian Road Research Board) publications from 1962 to present, including conference papers, reports and bulletins. There are over 5,000 items in the resource with more being added as they are scanned.

http://arrbknowledge.com

Regulations.gov is a searchable database for US federal research papers including NHTSA documents. At the time of writing there are 60,740 results for the search term 'tire' narrowing to 404 results for 'aged tire'.

https://www.regulations.gov/

CARE database / CaDas is a common accident dataset based on the identification of the data required for accident analysis through the input of experts participating in the CARE research project. The level of detail of the variables and values corresponds to all data useful for macroscopic data analysis and not for detailed reconstruction of the scene of the accident, which is of local interest. The glossary for the variables included in CARE (v3.6 2017) can be found here:

https://ec.europa.eu/transport/road_safety/sites/roadsafety/files/cadas_glossary_v_3_6.pdf

UMTRI University of Michigan Transportation Research Institute have a searchable database focusing on crash/injury data collection management and analysis. They issue a census on trucks and buses involved in fatal accidents. The Truck in Fatal Accidents (TIFA) and Bus in Fatal Accidents (BIFA) files contain records for all heavy trucks buses and coaches that are involved in a fatal accident in all 50 of the United States.

http://www.umtri.umich.edu/

Google Scholar is a freely accessible web search engine that indexes the full text or metadata of scholarly literature across an array of publishing formats and disciplines. The Google Scholar index includes most peer-reviewed online journals of Europe and America's largest scholarly publishers, plus scholarly books and other non-peer reviewed journals.

http://scholar.google.co.uk/

3.2 Source selection criteria

After identification, source documents were then screened for relevance with selected sources included for a detailed review of the full manuscript. Finally, the bibliographies of all the sources that were selected for full text review were recursively searched for further relevant sources.

The keywords that were used in the search were as follows:

- Tyre / tire
- Fail / failure / blow out / materials
- Vehicle components / wheels / rolling contact
- Age / aged / aging / ageing

There were some limitations present in the current literature review as some literature was not always freely accessible in English. This was the case for some potential research areas conducted in countries such as Norway[11].

Papers that met the search criteria, and abstracts of these papers were reviewed to identify those relevant to this study's aims. Full copies of the publications selected for inclusion by the literature review were obtained. The Bibliography provides the titles of these publications, to include the year and country where the research was based.

A number of publications originated in North America, and particularly from the US National Highway Traffic Safety Administration, which has been historically active in conducting tyre studies. Their tyre website[12] provides a repository of useful research findings, however, the concentration of testing conducted has been on light goods and passenger car tyres as opposed to commercial vehicle bus and truck radial tyres.

In general, literature on the ageing of commercial tyres and the effects, if any, is therefore limited. Furthermore, the literature review did not identify any existing research correlating the aged effects of tyres with that of tyre disablement or collision risk.

3.3 Tyre ageing definition

Ageing occurs in a tyre which is exposed to environmental conditions and occurs whether a tyre is fitted or not, driven upon or not; a non-service use, a spare tyre or a stored tyre are expected to age to some degree.

It is currently thought that the mechanism of ageing that is most likely to affect the performance of a tyre is a combination of dynamic mechanical (in service) ageing and chemical properties ageing.

Tyre ageing reasonably refers to any changes or degradation in a tyre's properties over a period of time, that may or may not affect the structural integrity and/or its material properties.

NHTSA defines tyre ageing as *"the reduction or loss in a tyre's material properties, which over time leads to a reduction of its performance capabilities"* (NHTSA, 2007).

Whilst not the only mechanism, the ASTM International definition of thermo-oxidative ageing states "*the process whereby chemical and physical material properties of a tyre change with exposure to heat and oxygen"* (ASTM, 2017).

[11] https://www.vegvesen.no/en/Professional/Publications/Library

[12] https://www.nhtsa.gov/research-data/vehicle-research-testing

3.4 Ageing of rubber

3.4.1 *Effects of storage and service on tyre performance*

Kataoka *et al.* reported on the effects of storage and service use on a tyre's performance. Their results "*confirmed a marked deterioration in performance with both increasing storage time and mileage. The rate of change of these properties was accelerated by the extra stimuli provided by service [use], as demonstrated by comparing tyres of a similar age but different mileage*". (Kataoka, 2003)

Gent comments on the work of Kataoka *et al*. and says "*Rubber undergoes profound changes on storage that are accelerated at higher temperatures. Harmful changes occur in tyre properties after storage at ambient temperatures for five years or after use on cars for similar periods. They [the changes] are caused by a variety of chemical reactions"* (Gent, 2006). (Similar to the early three to four year deterioration described later in this report.)

Veirh (1992) distinguishes wear mechanisms into five categories:

- Adhesive wear – removal of material caused by high transient adhesion
- Abrasive wear – caused cutting-rupture action of sharp angular asperities on the sliding interface
- Erosive wear – cutting-rupture action of particles in a liquid (fluid) stream
- Corrosive wear – from direct chemical surface attack
- Fatigue wear – caused by rapid or gradual material property changes that give rise to cracks and with their growth, a loss of material

3.4.2 *Ozone reaction*

The natural amount of ozone in the lower atmosphere is generally around 0.04 parts per million (ppm)[13], although such a concentration is small, ozone reacts rapidly and ably with the compounds commonly used in tyre sidewalls.

Gent reported that such an ozone reaction takes place at the exposed surface of the tyre and produces a relatively innocuous thin degraded surface layer; ozone in its isolation however cannot penetrate deeply into the rubber material.

If tensile strain is present in the rubber surface, then scission reaction with ozone can form characteristic sharp cracks in the surface which grow inwards, continuously exposing new material to further reaction.

Gent says ozone related cracking is problematic in tyre sidewalls where tensile stresses are commonly present.

[13] Air quality fact sheet Department of the Environment and Heritage, 2005 Aus.

Anti-ozone additives/waxes, when introduced to the tyre compound during manufacture, inhibit and retard the degradation and formation of such cracks; with brominated polyisobutylene[14] being much less susceptible to the influence of ozone than a natural rubber.

3.4.3 Oxidation

A reported cause of material change is a result of compound reactions with oxygen in the atmosphere. Oxidation does not itself cause cracking although the tyre material may become harder and brittle and then crack upon flexing.

Depending on the relative rates of diffusion, oxidation rates are found to be highly dependent on the ambient operating temperature. Oxidation is regarded by Gent as the normal mode of ageing of tyre components.

A laboratory test method to assess the sensitivity of a rubber compound to oxidation is to expose samples for various test periods at elevated temperatures and then measure the remaining strength and extension at room temperature. An approach to accelerated ageing, based on elevated temperature, was also used within the experimental testing employed by Smithers Rapra and described later.

3.5 European research outcomes

3.5.1 TNO R11423 v2 Final Report issued 2016

In 2016 the Netherlands Organisation for applied scientific research (TNO) reported a 'Study on some safety-related aspects of tyre use'. Within the TNO report (pg.17) one of the main tyre safety aspects considered was:

> *"The risk of tyre blow out failure is related to inflation pressure being too low and tyre damage (including effects of ageing) which are strongly linked to tyre maintenance."*

Tyre ageing is discussed (Task 3), whereby TNO identified *"the mechanical properties of rubber change due to exposure to the environment resulting in less strength, less flexibility, and in general less resistance to heat and mechanical damages"*.

However, this statement was balanced with the assertion that *"ageing is difficult to quantify as the extent of exposure is a mix of meteorological conditions specific to use of the vehicle and tyre age".*

3.5.2 TNO stakeholder engagement

Some 130 stakeholders were sent questionnaires for the TNO research project and there were 50 replies from 15 of the EU member states.

[14] Other types such as polyisobutylene itself and chlorinated polyisobutylene can be used but are less likely as brominated polyisobutylene which offers the best barrier properties. Inclusion levels in the rubber compound can vary.

In relation to the ageing of tyres, the stakeholders emphasised the need for inspections and identified that the only current method to get indications about tyre ageing was currently by visual inspection. The Stakeholders considered that in real world use *"most vehicle tyres wear to the minimum tread before the effects of ageing can be noticed".*

It was suggested that the effects of tyre ageing are typically assessed from a visual inspection into any tyre defects, rather than by checking the tyre production date.

Within the report on Stakeholder engagement TNO summarises:

> *"Stakeholders do not consider tyre age to be a safety issue. The only meaningful concept of ageing is 'tyre service life' which depends on many different factors and it is therefore too complex to be regulated". [pg. 91]*

When asked should tyre labels inform about tyre ageing performance?

> *"There was consensus amongst stakeholders that tyre age is not a safety issue. Agreement was also general that age is only a component of 'tyre service life' which depends on various factors such as storage time, exposure to environment, speed, inflation pressure, use pattern etc. Therefore the safety issue is more related to proper tyre maintenance than 'tyre service life'."*

Michelin Tyres and the ETRMA provided additional evidence to TNO after the initial 2014 stakeholder engagement, where the industry suggested: *"Periodic inspections are the best way to check for tyre inflation pressure, tread depth, damages, ageing effects"*.

In the cost-benefit analysis for the EU, Task 11, TNO reported on page 8:

> *"As a result of preparatory work done in the current study, it was indicated that tyre age and ageing effects are of relatively little importance towards road safety and are difficult to objectify. In contrast, tyre damages play a more important role but precise quantification remains an issue. Therefore no specific measures on tyre ageing and tyre damage were analysed".*

3.5.3 TNO commercial vehicle deficiency rates

Deficiency rates following commercial vehicle roadside inspections during 2007-2008 found that, on average, 20.1% of the inspected vehicles in Europe had tyre defects; the table indicated the UK was at 20% - see Table 1 (from (Jansen *et al.*, 2016) Table 2.4).

Table 1: Percentage of vehicles inspected with tyre defect (Jansen *et al.*, 2016)

	Wheels/ tyres defects	
Austria	2164	13.6%
Belgium	866	14.6%
Bulgaria	335	29.9%
Cyprus	214	16.8%
Czech Republic	12224	20.6%
Germany	29511	16.6%
Denmark	13	5.7%
Estonia	356	21.3%
Finland	368	6.4%
France		
Greece	2291	45.4%
Hungary	990	5.1%
Ireland	545	15.9%
Italy		
Lithuania	1353	17.5%
Luxembourg	193	17.6%
Latvia		
Malta	778	17.2%
Netherlands	188	11.3%
Poland	15464	28.2%
Portugal	154	20.7%
Romania	5503	42.9%
Sweden	4595	13.9%
Slovenia		
Slovakia	404	23.3%
United Kingdom	19325	20%

It should be noted that the table title actually relates to wheels and tyres rather than tyre defects in isolation. A review of the original data source[15]does not allow further interpretation and does not differentiate between the manner of defect nor specifically mention ageing of tyres. It is felt this percentage may overstate the number of tyre defects found.

However, the percentage of deficiencies detected highlights the importance of roadside inspections for road safety. Any visiting foreign registered vehicles would be subject to UK legislation.

3.5.4 GIDAS

TNO also reviewed the GIDAS (German In-Depth Accident Study) database for tyre failures (the GIDAS database contains in-depth records of accidents in defined areas of Germany that may be interrogated for collision causation factors); however, the number of records was too small to quantify tyre specific conditions of the trucks involved in the study: only two records

[15] COM(2010) 754 final The technical Roadside Inspection of Roadworthiness of Commercial Vehicles Circulating the Community 2010 Table 7 (European Commission, 2010)

from the 1,130 truck collisions were related to tyre quick deflation as the cause and were recorded without further explanation.

In summary the TNO 'Study on some safety-related aspects of tyre use', identified that tyre damage and ageing can lead to tyre blow out failure. A safety improvement could be achieved by more inspections between regulated periodic ones. Any increase in such inspections would increase consumer awareness. Whilst the TNO cost-benefit analysis did not show a compelling economic impact, actions such as; voluntary basis inspections, or if regulated, inspections between Periodic Technical Inspection intervals would be associated with a safety improvement benefit.

To place this in context, it is an existing requirement within the UK that licenced Goods Vehicle operators keep a vehicle safe and maintained in good condition at all times. Records of all safety inspections and maintenance should be kept for a period of 15 months. The records should include:

- Vehicle details
- A list of all items to be inspected
- When and by whom the inspection is carried out
- The result of the inspection
- Details of any work carried out
- A declaration that any defects have been properly fixed

There is also a requirement for a recommended 24-point walk-around check of the vehicle before the commencement of driving at the start of the day (or at least once every 24hrs), including the inspection of the tyres and wheel fixings[16].

3.5.5 TÜV final report 'Survey of motor vehicle tyres & related aspects'; ECE DG ENTR/F/5 (Reithmaier and Salzinger, 2003)

TÜV Rheinland Group is a provider of technical services worldwide (TÜV). In a report commissioned by the European Commission, TÜV reported on motor vehicle tyres and related aspects; specifically on the subject of tyre age and ageing they reported:

> *"The problem of different aging performance by various tyres must not be analysed simply in terms of their age in years. Attention must be paid especially to operating conditions (e.g. including earlier damage caused by driving with inadequately inflated tyres), external influences and consumer behaviour, but also to visible signs of old age such as damage and tread depth".*

TÜV progressively suggest a basic minimum age, up to which a (car) tyre and trailer tyre may be used, would be a sensible preventative safety measure:

[16] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/755764/heavy-goods-vehicle-walkaround.pdf

> *"From a technical perspective, a maximum of eight years is recommended in this context, a period, as from the date of manufacture, over which the tyre can be operated without giving rise to fears of any serious loss of the properties previously described".*

It is noted that after this expiry period, TÜV suggest mandatory inspections are carried out since it is known that ageing and wear performance of tyres differs from one make to another. The technical perspective is not expanded upon and no explanation of this chronological period is forthcoming within the report.

The TÜV report considers that clear information on tyre age and ageing behaviour, exceeding the current regulated tyre sidewall codes, is a necessary tyre marking.

TÜV identified a feasible cost-benefit saving in the range of 2 billion Euros by intensification of tyre inspections. This was not a CBA for commercial tyres.

3.6 US research outcomes

3.6.1 NHTSA 'The Pneumatic Tire'

The US National Highways Traffic Safety Administration (NHTSA) sponsored an authoritative review on the principles of tyre design and use (Walter, 2006).

Ageing of rubber is addressed in Chapter 2 where Professor Gent (2006) discusses oxygen and ozone as the primary agents responsible for the ageing and weathering of rubber. Gent regarded the contributory factors as heat, light, humidity and mechanical stress and strain arising during in-service use.

Prof Walter supported Gent's view of contributing factors, either alone or in combination, as being causes of ageing and that they are responsible for the loss of physical properties of a tyre component.

He identifies two long-term trends that he considers exacerbate tyre ageing:

> a) *The number of years tyres remain in service has increased considerably due to the high mileage attained by many current products;*
>
> b) *Weight reductions achieved by employing thinner sidewalls, etc., have tended to produce cooler running tyres, albeit a small effect, allowing for reduced levels of anti-oxidants and anti-ozidants.*

Walter suggests a simple "expiration date" moulded on the tyre sidewall, after which use would be prohibited, could be included at a future date by NHTSA who have indicated that a laboratory tyre ageing standard could be in included within Federal Motor Vehicle Safety Standard (FMVSS) No. 139 (Department of Transportation, 2006).

A review[17] of FMVSS No. 139 does not reveal the adoption of an expiration date, nor a notice of proposed rulemaking.

[17] https://www.law.cornell.edu/cfr/text/49/571.139

3.6.2 *Rubber Oxidation and Tire Aging – A Review*

Baldwin *et al.* (2008) state, *"The oxidation that leads to the chemical and physical changes in the belt skim is termed "tire aging". Unlike tread wear (the traditional measure of tyre life) or other damage (punctures, ozone cracking, etc.), the rubber oxidation that leads to tread separations is typically not visible to the average consumer".*

Analysing earlier research by Ford Motor Co. Baldwin *et al*.'s interpretation is that mileage was a relatively unimportant factor in ageing compared to time, *"Thus time, not mileage is the correct metric for tyre ageing"*.

Baldwin *et al.* conclude that despite the variability on ageing effect in tires it *"is possible to derive reasonable estimates of aging rates for key rubber properties in tires*". The variability of oven ageing is much less than that for field ageing.

3.6.3 *SANDIA Final Report on Reliability and Lifetime Prediction*

This report was originally prepared in 1999 by Sandia National Laboratories California, by way of a cooperative research and development agreement with the Goodyear Tyre and Rubber Company; but restricted from open distribution under a 5-year protection clause, being approved for unlimited public release in 2012. The overall objective of the project was to establish the chemical and physical basis for the degradation of tyres.

Test sampling included cross sectional pieces from laboratory aged and in-service aged tyres from automobile and truck tyres. Un-aged materials were also tested and modulus measurements showed that the un-aged modulus can change significantly with time while resting at room temperature. It also highlighted that different batches of the same material gave differing initial modulus values.

The report concluded:

> *"When oxygen is present during the aging of tire materials, oxidation effects are important contributors to degradation. Oxidation will often result in modulus increases (material hardening), which can be an important underlying factor in crack initiation".*

In relation to oxygen permeability measurements, testing for diffusion-limited oxidation (DLO), the conclusion reached was:

> *"…important DLO effects occur across real tire cross-sections and that the interior layers of truck tires are likely to age {even when initiated} under anaerobic conditions".*

3.6.4 *NHTSA Research on Tyre Ageing*

In August 2007 the US Department of Transportation, National Highway Traffic Safety Administration (NHTSA) submitted a tyre ageing report to the US congress, the report defined safety problems and included a summary of research into tyre ageing (NHTSA, 2007).

It identified tyre ageing as *"referring to the reduction or loss in a tire's material properties, which over time leads to a reduction of its performance capabilities".*

In February 2014 NHTSA published a report summarising its work on tyre ageing (NHTSA, 2014). A primary aim of the project was to understand service life degradation that could serve as the ‘real world’ baseline for the development of a laboratory-based, accelerated service life test. Ford contributed research and recommended oven ageing tyres would accelerate the ageing process by speeding up chemical reactions and thus material property changes in a tyre. Such an oven aged tyre *“may then be studied for material property changes, or physically evaluated, such as run on a road wheel to determine any change in structural durability”.*

Soodoo in 2014 reported on Phase iii of the testing program and indicated oven temperature was refined to 65°C (149°F) and time in oven refined to 5 weeks resulting in *“Material properties of new tyres after oven ageing closely matched 4-6 year old service tyres”* (Soodoo, 2014).

In summary NHTSA suggest oven ageing of a tyre in a laboratory is a scientifically valid method to artificially accelerate the tyre ageing process and thus simulate a naturally aged in-service tyre on a vehicle. It should be noted the NHTSA research does not discuss truck and bus radial tyres.

3.6.5 Oven Ageing

The following literature review section discusses oven ageing of a tyre in a laboratory being a scientifically valid method to artificially accelerate the tyre ageing process and simulate in-service tyre ageing; the research does not discuss truck and bus radial tyres as presented in this project.

3.6.5.1 Literature review support for oven ageing

The NHTSA Research Report to Congress on Tire Ageing 2007 p 18 states, *“The oven ageing protocol was the only method successful at replicating the overall material properties of the used tire”*.

Research by Professor Gent (2006) agreed that a way of assessing the sensitivity of a rubber compound to oxidation is to expose samples for various periods at elevated temperatures and then measure the remaining strength and extensibility at room temperature.

3.6.5.2 Oven ageing method

The oven ageing process itself is thermal and not mechanical. However when a tyre is run it does get hot, therefore the thermal ageing is believed to be a significant factor to consider.

Ford, in the course of its own tyre ageing research, had sufficient data to recommend that NHTSA (2014) use a method in which the tyre is inflated using the 50% oxygen air mixture mentioned below, and heated in an oven for a period of time to accelerate the ageing process by speeding up chemical reactions, and thus material property changes. The tyre may then be studied for material property changes or run on a road wheel to determine any change in durability.

Also in oven aged tyres, the modulus increases and the tensile strength and elongation decrease with increasing temperature and/or time in the oven, consistent with general expectations for organic chemical reactions.

Shearography analysis performed by Waddell (2007), supported significant changes, in essentially all chemical and physical properties, as a function of the %-oxygen in the filling gas, the inflation pressure of the tyre, ageing time in the oven, and the oven temperature.

3.6.5.3 Using high levels of oxygen

Research by Ford Motor Company, NHTSA and ASTM as described by Baldwin (2008), indicates that because of the higher oxygen pressure inside tyres, most of the oxidation occurs due to permeation through the inner liner from the inside air cavity.

A cause of tread separations has been found, by Baldwin, to be the oxidative ageing of a tyre. When rubber oxidises, it loses elasticity and peel strength. During normal operation, cracks form inside the tyre at the edge of the steel belts. Crack growth rates increase dramatically in oxidised rubber, so as mileage and chronological age increase, the cracks can propagate between the belts, potentially resulting in a tread separation.

This oxidation process can be accelerated and is independent of tyre size or field ageing rate; the test with the highest acceleration factor will lead to the shortest laboratory testing time.

For that reason, research has mostly focused on varying the temperature, pressure and fill composition. The proposed acceleration factor will depend on both temperature and oxygen concentration; a 50/50 blend will accelerate at ~40%.

As a general consideration the regular refilling of oxygen prevents oxygen-deprived ageing, which could be undesirable, as without the correct level of oxygen, the actual ageing process would not be representative of normal conditions.

3.6.5.4 Literature review support to oxygen replenishment ratio

Dr Baldwin of the Materials Research & Advanced Engineering (Ford) found that the use of the 50/50 blend effectively doubles the concentration of O_2 in the cavity. This leads to an increase in oxidation rate of ~40%. The acceleration that results from using the 50/50 blend is independent of test temperature or tyre type.

NHTSA (2014) highlighted that after 6 weeks of oven ageing, the oxygen-enriched tyre inflation gas had decreased from an initial average of approximately 45% O_2 to approximately 35% O_2, resulting in the onset of oxygen-deprived ageing (i.e. not representative of service ageing and thus undesirable). Therefore, future oven ageing test development would include periodic venting and re-inflation of the tires with fresh oxygen-enriched gas.

Oven ageing tyres at 55°C to 65°C while pressurized with an oxygen-rich inflation gas has been identified as the primary candidate for the thermal ageing of tyres.

At long exposure times at a higher temperature of 70°C, there is some evidence for deviation from aerobic oxidation in a tyre. Finite element modelling and measurements of cavity air composition suggest that this deviation is a result of oxygen depletion in the tyre air cavity.

For this reason, more recent oven ageing studies have identified the need for periodic replenishment of the oxygen in the air cavity.

Whilst there were some concerns discussed in a Diffusion Limited Oxidation (DLO) study (NHTSA, 2010) that the level of oxygen required by the accelerated reaction rates within the tyre rubber at the higher oven temperatures would exceed the supply of the oxygen diffusing to the rubber components.

To understand the effect of temperature on tyre size and type, the oxidation rates in twenty-four tyre models were predicted using a one-dimensional DLO computer model. The result showed that, the 65°C oven ageing temperature was not expected to significantly limit oxidation in any component of the tyre shoulder region.

The benefit from a testing perspective to using 65°C for oven ageing would be a dramatically shorter test time than at 55°C.

The most successful method at replicating the overall material properties of used tyres was the one provided by Ford to NHTSA (2014) who recommend the use of a method in which the tyre is inflated using the 50% nitrogen and 50% oxygen (50 % N_2 / 50 % O_2) mixture, and heated in an oven for a period of time to accelerate the ageing process by speeding up chemical reactions, and thus material property changes.

3.6.6 NTSB Special Investigation Report NTSB/SIR-15/02 PB2016-100009

In 2014, the NTSB hosted a tyre safety conference to learn more about the tyre-related issues discovered during its crash investigations and to gather expert opinion on the factors that lead to tyre failure.

The NTSB (2016) identified the following general areas of concern:

- Poor tyre maintenance practices by consumers
- Barriers to technological innovation that could prevent or mitigate tyre-related crashes
- Failure to establish the current level of crash risk posed by tyre ageing and a lack of consumer guidance on this issue
- Problems with the tyre registration and safety recall system

3.6.7 Registration of new tyres

In the US, the Code of Federal Regulations (49 CFR Part 574) requires that each tyre manufacturer compiles a list of the individuals or entities that have purchased its tyres, so the user can be contacted in the event of any recall. The success of the tyre recall process depends on the effectiveness of a tyre registration process.

3.6.8 Improving the registration process

The NTSB concluded that a computerised system would encourage dealers to register tyres at the point of sale. Scanning technologies that allow dealers to electronically read barcodes and (RFID) tags affixed on a tyre could speed up the registration process.

Collecting the vehicle identification number (VIN) of the vehicle on which the tyres were installed would allow tyre manufacturers to perform searches to identify owners, the same process as vehicle manufacturers do for vehicle recalls.

The NTSB asserted that by not providing the complete tyre identification number which includes the date code, on both sides of the tyre, hampers any recall process.

3.7 Industry recommendations regards age / service life length

3.7.1 Guide to tyre management on heavy vehicles

First published in October 2015 (revised Oct 2016) authored by the Tyre Industry Federation and prefaced by Ms Beverley Bell the Senior Traffic Commissioner for Great Britain (Tyre Industry Federation, 2016).

The published guidance offers advice to operators of heavy vehicles including trucks, trailers, buses and coaches, about tyre safety and maintenance including consideration about the physical condition and age of tyres (p.8):

> *"Tyre ageing is not a function of the passage of time alone but rather the cumulative exposure to adverse environmental and operational factors. Prolonged exposure to ozone or ultra-violet light can lead to degradation of the natural and synthetic rubbers used in tyres. Tyre manufacturers incorporate additives to reduce this phenomenon.*
>
> *The flexing of the tyre in normal use helps the diffusion of these additives to the surface of the tyre where they act against the adverse effects of exposure to ozone and ultra-violet light.*
>
> *This diffusion process is greatly reduced in tyres fitted to vehicles that are used infrequently. Consequently, such tyres are more susceptible to degradation caused by adverse environmental factors than tyres on vehicles that are frequently used".*
>
> *"As a precaution, the Department for Transport strongly recommends that tyres over 10 years old should not be fitted to the front axles of buses and coaches and that such tyres should only be fitted to the rear axle as part of a twin tyre combination. DVSA will issue an advisory notice at annual test if this recommendation is not followed".*

The Tyre Industry Federation comprises the British Tyre Manufacturers' Association, the Imported Tyre Manufacturers' Association, the National Tyre Distributors Association and the Tyre Recovery Association.

The DVSA has been monitoring compliance with the guidance; since 2017 they have inspected 136,263 buses and coaches and found 82 to be non-compliant, a non-compliance rate of 0.06%[18].

[18] https://www.gov.uk/government/speeches/consulting-on-options-to-ban-old-tyres

3.7.2 RSA Ireland

'Your guide to tyre safety' as issued by the RSA Road safety Authority Ireland[19] when referring to the National Car Test (NCT), the equivalent of an MOT in the UK, states:

> *"A tyre that is six years old is a 'pass advisory' item at the NCT. This will not cause your vehicle to fail its NCT, but it is to advise you that your tyres may soon need to be changed".*

3.7.3 Tyre Manufacturers (Passenger Cars) – advice on replacement of tyres

Continental[20] recommends *"All tyres including spare produced more than ten years ago should be replaced".*

Uniroyal[21] tyres state, *"We recommend that all tyres are replaced when they reach ten years old, regardless of the depth of tread".*

Michelin[22] offers advice in its UK safety guide regarding product life: *"The older a tyre the greater the chance that it will need to be replaced due to the service-related evolution or other conditions found upon inspection or detected during use. While most tyres will need replacement before they achieve 10 years, it is recommended that tyres in service 10 years or more from the date of manufacture, including the spare, should be replaced with new tyres as a simple precaution".*

Pirelli 2019 US market limited warranty document states:

> *"The mere passage of time (age) does not cause tires to deteriorate, but rather exposure to outside forces. The service life of a tire is a function of service and storage conditions.*
>
> *For each individual tire, this service life is determined by many factors such as temperature/weather, storage conditions, and service conditions (e.g. load, speed, inflation pressure, maintenance, and road hazard damage, etc.) to which a tire is subjected throughout its life. Since service and storage conditions vary widely, accurately predicting the service life of any specific tire based on chronological age is not possible.*
>
> *There is no scientific or technical data that establishes or identifies a minimum or maximum service life, but the longer a tire has been in service, the greater the chance that it will need to be replaced due to service-related conditions".*

[19] http://www.rsa.ie/PageFiles/5206/Tyre_Safety_Information_Guide_.PDF

[20] https://www.continental-tyres.co.uk/car/technology/tyre-knowledge/lex-1-2

[21] https://www.uniroyal-tyres.com/car/tyre-guide/tyre-knowledge/the-importance-of-tyre-age-as-well-as-tread-depth

[22] www.michelin.co.uk/content/pdf/TC_Safety_Guide_UK.pdf

3.7.4 *Tyre Manufacturers (Commercial) – advice on replacement of tyres*

Michelin Trucks UK & ROI Guidance[23] states:

> *"Tyres are constructed using various types of material and rubber compounds, having performance properties essential to the proper functioning of the tyre itself. These component properties evolve over time. For each tyre, this evolution depends upon many elements such as weather, storage conditions and conditions of use (load, speed, inflation pressure, maintenance, etc.) to which the tyre is subjected throughout its life. This service related evolution varies widely so that accurately predicting the serviceable life of any specific tyre in advance is not possible.*
>
> *That is why, in addition to regular inspections and inflation pressure maintenance by operators, Michelin recommend that tyres, including spare tyres, should be inspected regularly by a qualified tyre specialist, such as a tyre dealer, who will assess the tyre's suitability for continued service. Tyres which are in use for 5 years or more from their date of manufacture should continue to be inspected by a specialist at least annually".*

Technical Information Michelin: Truck and Bus Tyres - Edition 24, 2014 states, *"It is recommended that tyres 10 years or older should be fitted only on Drive or Tag/Trailer axles".*

3.7.5 *The European Tyre and Rubber Manufacturers Association (ETRMA)*

The ETRMA is an organisation consisting of individual manufacturing companies and national tyre associations; informing policy and educating consumers about safety and tyre performances.

They provide the opinion that a tyre's service life is affected by the wide variety of conditions in which it may be used; thus, accurately predicting the service life of a tyre from new is not possible.

Within their publication 'Tyreaware'[24] they reason that *"Although the older a tyre, the greater the chances it will need to be replaced due to service-related conditions, or just through wear"*, and recommend consumers should *"inspect tyres on a monthly basis - checking for inflation pressure and tread wear as well as implementing recurring rotation, balancing and alignment. Consumers should also use their hands and eyes to look out for signs that a tyre may need replacing. These recommendations and guidelines cannot ensure that a tyre does not exhibit an undetectable internal condition that may render them unacceptable for continued service"*.

[23] https://trucks.michelin.co.uk/Advice/Legislation

[24] http://www.tyreaware.org/pdf/brochure/9133-CR-ETRMA-UK.pdf

3.8 Consumer awareness

Early work by Cowley *et al.* (2006) indicated that when asked to list all contributory factors which could cause tyre problems, very few people (4% of 225 respondents) identified aged tyres, or more correctly tyre ageing as a potential cause of tyre failure; the highest response being that of poor or worn tread (69.8%).

Wogalter & Laughery (2012) discussed consumer awareness in relation to tyre ageing and any safety related concerns. They proposed that it is not easy to decode the date of manufacture on a tyre sidewall.

> *"A 2006 BMW manual states "BMW recommends that you replace all tires after 6 years at most, even if some tires may last for 10 years." The wording reduces the potential impact of the message because it allows for people to consider that their tyres might last 10 years. Later in the 2006 manual, it says "BMW recommends tire replacement after no more than 6 years, regardless of the actual wear of the tires." Note that this warning is simply a recommendation, i.e., a suggestion. The manufacturer is not saying that it is mandatory to replace the tyres after 6 or even 10 years. More importantly safety is not directly stated as the reason".*

3.8.1 RAC

On tyre age the RAC[25] refer to a Kwik-Fit survey 2013 where it is reported that:

> *"More than half of the UK motorists questioned (59%) were unaware that their tyres displayed the information required to calculate the date of manufacture. In addition, 24% were aware the information existed but didn't know how to interpret it. In total, this means that 83% of drivers cannot assess the age of their tyres".*

3.8.2 The Automobile Association

The AA offer advice on tyre life and age[26]:

> *"Tyres will normally wear out before they become unserviceable due to ageing.*
>
> *Tyres degrade naturally through exposure to heat, sunlight (Ultraviolet/UV) and rain. The amount of damage depends on the exposure and the severity of the weather.*
>
> *Damage through ageing is more common with caravans, trailers and other vehicles only used occasionally.*
>
> *There are no hard and fast rules on age.*

[25] https://www.rac.co.uk/drive/news/motoring-news/tyre-age-poses-motoring-risks/

[26] https://www.theaa.com/driving-advice/safety/tyre-life-and-age

Check for signs of cracking on the sidewalls of tyres four or five years old if your car is parked outside and get them replaced if cracking is severe.

Any tyre specialist will be able to give you advice if you're not sure".

3.9 Vehicle Safety Inspections in other countries

3.9.1 *Review of tyre standards & safety – Australia Technical Working Paper No 12, September 1994*

With regards to tyre defects in collisions, early research in Australia compared the role of tyre defects in accidents.

The research suggested that whilst a heavy vehicle collision was 2.5 times as likely to be caused by a vehicle defect as a passenger car collision, a heavy vehicle collision-involved defect was only half as likely to be a tyre related defect compared to a passenger car. Based on the New South Wales data, it is estimated that, in Australia, approximately 1.4% of heavy vehicle accidents involved tyre defects. These tyre defects appear to be primarily related to excessive wear or improper inflation in the case of trucks and the additional factor of incorrect tyre fitment to the rim in the case of trailers.

The study reported the first life average service life before retreading for city buses was 30,000-60,000 km and 70,000-100,000 km for coaches.

3.9.2 *DEKRA ROAD SAFETY REPORT HGV 2009*

DEKRA Automobil GmbH operates in 28 countries in the field of technical monitoring of vehicles and is one of Europe's largest organisations in this field. Over all inspected age classes, DEKRA identified 29% of trucks had defects or failures when inspected after collisions.

Among the trucks between three and five years, the inspected / identified failure rate was 30.2% being slightly above the average. Failures were identified in 46.2% of vehicles aged between seven and nine years. In vehicles above nine years old, the rate was 59.1%. Three failure categories, brakes, tyres and steering parts were the greatest identified reasons for failure.

They reported maintenance defects, in particular operational overloading and/or under-inflation of the tyre were statistically responsible for damage to tyres, with approximately 50% of tyre failures attributed to such conditions.

DEKRA state *"pre-existing damage in the tread area in particular means that moisture can penetrate as far as the steel belt causing it to corrode. This reduces the adhesion between the steel cord and the rubber below the surface of the tread to such an extent that the protector suddenly detaches from the tyre carcass together with parts of the belt".*

3.9.3 *University of Michigan Transportation Research Institute UMTRI*

The UMTRI BIFA factbooks for Buses Involved in Fatal Accidents for 2008 (Jarossi *et al.*, 2011) recorded 'tire blowout or flat' in zero instances for the 120 fatal bus incidents and for nine of a total of 1546 fatal incidents involving trucks, a percentage of 0.6.

3.10 Contributory factors in Reported Road Casualties GB 2017

In 2017, the Department for Transport statistics published[27] that there were 14 fatal accidents and 115 serious accidents where 'illegal, defective or under inflated' tyres were recorded as a contributory factor in the collision (Table 2, Table 3 and Table 4). These factors relating to tyres represent 1% of the contributory factors reported.

Table 2: RAS 50001 - Contributory factors in reported accidents by severity, 2017

	Fatal		Serious		Slight		All	
	No.	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**
Vehicle defects	**32**	**2**	**359**	**2**	**1,148**	**2**	**1,539**	**2**
Tyres illegal, defective or under inflated	14	1	115	1	343	0	472	1
Defective lights or indicators	1	0	37	0	115	0	153	0
Defective brakes	9	1	129	1	432	1	570	1
Defective steering or suspension	4	0	67	0	196	0	267	0
Defective or missing mirrors	1	0	5	0	13	0	19	0
Overloaded or poorly loaded vehicle or trailer	4	0	29	0	86	0	119	0

Data records that in those road traffic accidents, 17 people were killed and 147 people were seriously injured.

[27] https://www.gov.uk/government/publications/reported-road-casualties-great-britain-annual-report-2017

Table 3: RAS 50007 - Casualties in reported accidents by contributory factor and severity, 2017

	Fatal		Serious		Slight		All	
	No.	%	No.	%	No.	%	No.	%
Vehicle defects	**35**	**2**	**411**	**2**	**1,753**	**2**	**2,199**	**2**
Tyres illegal, defective or under inflated	17	1	147	1	555	1	719	1
Defective lights or indicators	1	0	38	0	152	0	191	0
Defective brakes	9	1	139	1	654	1	802	1
Defective steering or suspension	4	0	75	0	312	0	391	0
Defective or missing mirrors	1	0	5	0	16	0	22	0
Overloaded or poorly loaded vehicle or trailer	4	0	33	0	125	0	162	0

Further breakdown of the vehicle involved, by type, for these accidents indicates that one bus or coach and six Heavy Goods Vehicles were identified, where the contributory factor of illegal, defective or under inflated tyres were recorded.

Table 4: RAS 50005 - Vehicles in reported accidents by contributory factor and vehicle type, 2017

	Pedal cycle		Motor-cycle		Car		Bus or Coach		Van/Light goods		HGV		All	
	No.	**%**	**No.**	**%**	**No.**	**%**	**No.**	**%**	**No.**	**5**	**No.**	**%**	**No.**	**%**
Vehicle defects	**183**	**2**	**145**	**1**	**970**	**1**	**20**	**1**	**109**	**1**	**57**	**1**	**1,543**	**1**
Tyres illegal, defective or under inflated	7	0	39	0	384	0	1	0	25	0	6	0	473	0
Defective lights or indicators	59	1	20	0	54	0	1	0	4	0	2	0	154	0
Defective brakes	114	1	60	0	316	0	16	0	40	0	13	0	570	0
Defective steering or suspension	8	0	30	0	204	0	3	0	9	0	4	0	267	0
Defective or missing mirrors	0	0	3	0	12	0	1	0	0	0	2	0	19	0
Overloaded or poorly loaded vehicle or trailer	4	0	5	0	29	0	0	0	31	0	33	1	119	0

It is important to note that the contributory factor system is based upon the identification of such a factor by an attending police officer who may not be in a position, at that time, to identify all relevant factors. The age of the tyre or further data in relation to the tyre is not statistically recorded therefore no association in relation to the vehicle defects, as recorded can be made with the effects of ageing on the tyre.

3.11 Summary of literature review

The review of literature highlighted that existing knowledge on the ageing of commercial tyres and the effects, if any, is limited. Furthermore, it did not identify any existing research correlating the aged effects of tyres with that of risk of disablement.

Data for commercial vehicle accidents involving tyre defects is generally sparse; an early 1994 study in Australia identified a 1.4% correlation. DEKRA identified that tyre failures occurred in 8.4% of accidents, whereas the UK Reported Road Casualties GB 2017 records 14 fatal accidents and 115 serious accidents where illegal, defective or under inflated tyres were recorded as a contributory factor in the collision. These factors relating to tyres represent 1% of the contributory factors reported.

Previous work has defined tyre ageing as *"the reduction or loss in a tyre's material properties, which over time leads to a reduction of its performance capabilities"*.

Service use of the tyre accelerates the rate of change of properties. Research in the Netherlands identified poor service use (under-inflation & damage) including the effects of age as increasing the risk of a failure. Thus, the mechanical properties of rubber change; resulting in less strength, flexibility and resistance to both heat and mechanical damage.

TNO stakeholder views suggested the only meaningful concept of ageing is 'tyre service life' which depends on many different factors. Periodic inspections are described as the best way to check for pressure, tread depths, damage and ageing effects.

An alternate view was raised by Baldwin *et al*. in a review of 'tire aging' whose interpretation is that mileage was a relatively unimportant factor in ageing compared to time; *"Thus time, not mileage is the correct metric for tyre ageing".*

Oxidation causes material changes to a tyre, at rates dependent on ambient temperature and rates of diffusion.

Research by Professor Gent (2006) agreed that a way of assessing the sensitivity of a rubber compound to oxidation is to expose samples for various periods at elevated temperatures and then measure the remaining strength and extensibility at room temperature.

A primary aim by NHTSA was to understand service life degradation that could serve as the 'real world' baseline for laboratory-based accelerated service life test. NHTSA and Ford suggested that *"The oven ageing protocol was the only method successful at replicating the overall material properties of the used tires"*.

Whilst NHTSA suggest oven ageing of a tyre in a laboratory is a scientifically valid method to artificially accelerate the tyre ageing process and simulate in-service tyre ageing; the NHTSA research did not discuss truck and bus radial tyres as presented in this project. It is acknowledged, therefore, that a similar approach for providing baseline / control tyres for truck and bus tyres may need to differ. However, no such evidence was found in relation to a defined approach, so the NHTSA research was carried forward to the experimental design for this project, with minor adaptation as employed by Smithers Rapra.

Tyre manufacturers for passenger cars (Continental, Uniroyal and Michelin) recommend that a tyre in service 10 years or more is replaced. Pirelli state the mere passage of time does not cause tyres to deteriorate but rather the service use and conditions, however they also add the longer a tyre has been in service the greater the chance it will need to be replaced.

The European Tyre and Rubber Manufacturers Association indicate that accurately predicting the service life of a tyre from new is not possible but recommend consumers inspect tyres on a monthly basis, however they also recognise a tyre may exhibit an undetectable internal condition that may render it unacceptable for continued service. Consumer awareness in relation as to how to identify the age of a tyre from the regulated tyre date code appears poor, the RAC reported 83% of drivers could not assess the age of their tyres.

For car tyres, TÜV recommends a safety measure of a maximum of 8 years, although no explanation of this chronological period was forthcoming. However, commercial tyre advice on replacement is less widely available, TÜV made no recommendations in relation to a maximum age for commercial tyres.

The Senior Traffic Commissioner for Great Britain, in the documents 'Best Practice Guide for Bus & Coach Tyre Maintenance' and the 'Guide to tyre management on Heavy Vehicles' adopts the current DfT guidance of strongly recommending that tyres over 10 years old should not be fitted to the front axles of buses and coaches and that such tyres should only be fitted to the rear axle as part of a twin tyre combination.

Michelin in their Technical Information on Truck & Bus Tyres say, *"tyres which are in use for 5 years or more from their date of manufacture should continue to be inspected by a specialist at least annually"*. They recommend; *"that tyres 10 years or older should be fitted only on Drive or Tag/Trailer axles".*

4 Rubber Tyre – Mechanical Properties

As a result of tyre manufacturers' extensive research and development, rubber compounds and components used in modern tyres are predictably effective and durable for the variable service life.

As taken from UN Regulation No. 109 (UNECE, 1998), the following structures are distinguished in a pneumatic-tyre relating to the technical characteristics of the tyre's carcass.

"Diagonal" or "Bias ply" describes a pneumatic-tyre structure in which the ply cords extend to the beads and are laid at alternate angles substantially less than 90° to the centreline of the tread.

"Bias belted" describes a pneumatic-tyre structure of diagonal (bias-ply) type in which the carcass is stabilised by a belt, comprising two or more layers of substantially inextensible cord material laid at alternate angles close to those of the carcass.

"Radial" describes a pneumatic-tyre structure in which the ply cords extend to the beads and are laid substantially at 90° to the centreline of the tread, the carcass being stabilised by an essentially inextensible circumferential belt.

"Bead" means the part of a pneumatic-tyre which is of such shape and structure as to fit the rim and hold the tyre on it.

"Cord" means the strands forming the fabric of the plies in the pneumatic-tyre.

"Ply" means a layer of "rubber" coated parallel cords.

"Belt" applies to a radial ply or bias belted tyre and means a layer or layers of material or materials underneath the tread, laid substantially in the direction of the centre line of the tread to restrict the carcass in a circumferential direction.

"Breaker" applies to a diagonal ply tyre and means an intermediate ply between the carcass and tread.

"Protective breaker" applies to a radial ply tyre and means an optional intermediate ply between the tread and the belt to minimize damage to the belt.

"Chafer" means material in the bead area to protect the carcass against chafing or abrasion by the wheel rim.

"Carcass" means that structural part of a pneumatic-tyre other than the tread and outermost "rubber" of the sidewalls which, when inflated, supports the load.

"Tread" means that part of a pneumatic-tyre which is designed to come into contact with the ground, protects the carcass against mechanical damage and contributes to ground adhesion.

"Sidewall" means the part of a pneumatic tyre between the tread and the area designed to be covered by the rim flange.

"Tread groove" means the space between the adjacent ribs or blocks in the tread pattern.

"Chunking" means the breaking away of pieces of rubber from the tread.

"Cord separation" means the parting of the cords from their rubber coating.

"Ply separation" means the parting of adjacent plies.

"Tread separation" means the pulling away of the tread from the carcass.

Figure 4 below illustrates the features of a typical tyre[28].

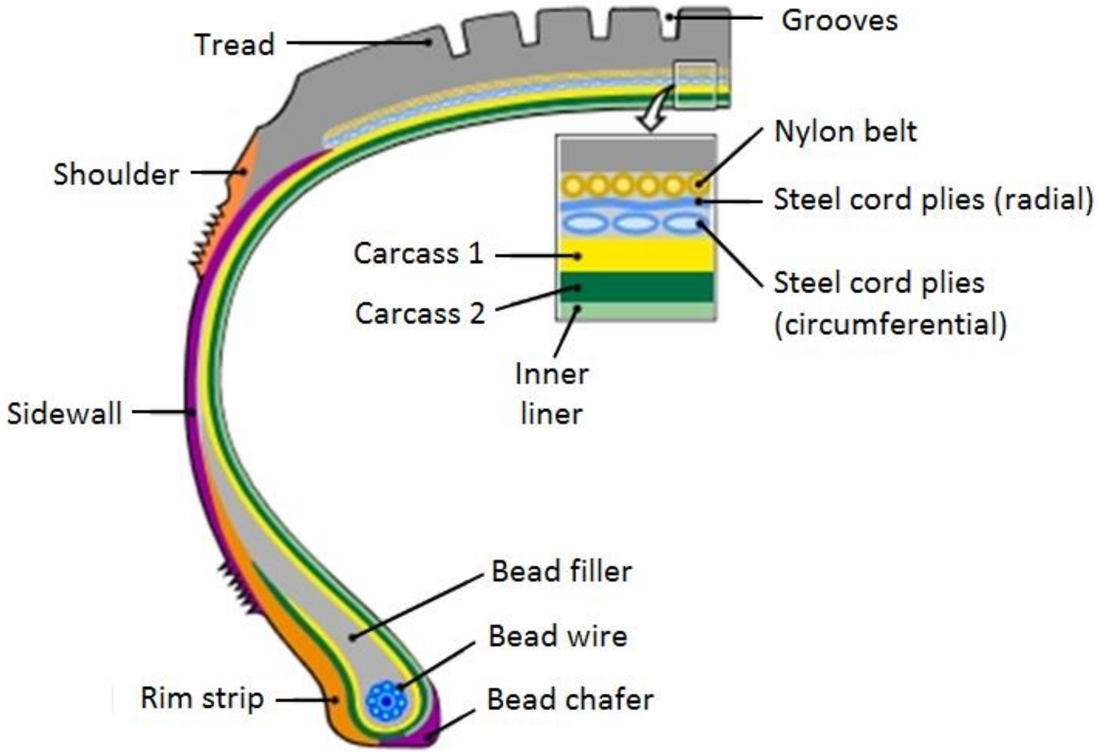

Figure 4: Tyre features

Chemical bonding mechanism

The adhesive properties between the rubber and cords must be stable throughout the service life of the tyre otherwise there becomes vulnerability to shortened service and/or failure (Niziolek *et al.*, 2000).

Steel cords and rubber compounds have little affinity in their adhesive properties; however adhesion to the rubber interface is improved when the steel is coated in a layer of brass. This brass coating deposited on the steel provides a strong and robust adhesion (Buytaert, 2009) between the steel and adjacent rubber; reportedly formed from reaction of the sulphur contained in the adhesion rubber with the copper of the brass (other adhesion promoters are also employed).

Vanooij *et al.* (2009) discussed the adhesion of steel tyre cord to rubber; and state *"it is known that with ageing the sulphide layer continues to grow thicker and thus becomes weaker, leading to a drop in adhesion…Ageing of the rubber-brass bond generally leads to a loss in*

[28] Adapted from https://commons.wikimedia.org/wiki/File:Radial_Tire_(Structure).svg - created by MagentaGreen

adhesion primarily due to corrosion of part of the brass layer that has not been converted to a sulphide film".

Any penetrative damage caused to or weakness in the brass coating may lead to the wicking of moisture along the internal interfaces and the risk of such moisture and oxygen causing corrosion thereon.

4.1 Inner liner

Air pressure retention is critical to tyre performance; the inner liner is a thin layer of rubber laminated to the inside carcass of a tubeless tyre to ensure retention of air. Air is a mixture of 78% nitrogen (N_2) 21% oxygen (O_2) and 1% other gases and contains a widely varying amount of water vapour. NHTSA research to establish the effect of differing ratios of oxygen & nitrogen inflation gases recorded an average 90-day pressure loss rate for new tyres inflated with air of 2.13 % per month (NHTSA, 2008).

Niziolek *et al.* (2000) indicate that an efficient inner liner preserves the tyre carcass integrity, restricts oxygen and water vapour migration and prevents separations and failures due to degradation and loss of adhesion. The migration of O_2 through the tyre is determined to a large extent by the butyl rubber liner which acts as a barrier.

Waddell (2006) adopts the same view; he found correlations between liner permeability, on intra-carcass pressurisation, belt edge separation, and time to failure in road wheel durability tests among tyres of the same design but with varied inner liner formulations. He proposes increasing the percentage of halobutyl rubber in the liner from 60/40 to 100/0 and indicates by adopting Bromobutyl Rubber (BIIR) rather than natural rubber (NR), as a liner, reduces both air and moisture permeability.

Halobutyl polymers offer the best performance in this respect (both chloro and bromo butyl polymers are used). Bromobutyl based inner liner compounds have the best air retention properties and are widely established today as the optimum rubber for use in tyre inner liners. However, halogenated butyl polymers are more expensive than standard polyisobutylene, so variations are seen between manufacturers (and within their own product ranges) in the amount of butyl polymer used in liner compounds.

The bromobutyl content of the inspected tyres (within this DfT study) is not specifically known, however by way of example, a compositional analysis performed by NHTSA (2010) looking at different tyre brand manufacturers (performed on light vehicle tyres) specifically looked at polymer identification and highlighted the percentage differences in the composition of the inner liner.

> *"The Bridgestone tires were estimated as an 85/15 bromobutyl/natural rubber compound. The Continental tires were approximately a 65/35 bromobutyl/natural compound. The Cooper tires were approximately 85/15 halobutyl/natural formulations, with chlorobutyl or bromobutyl rubber, varying by plant. The Goodyear tires were approximately a 90/10 bromobutyl/natural rubber formulation. Finally, the Michelin tires were approximately 100-phr bromobutyl compound, containing a high styrene resin".*

Waddell (2006) indicates that 100-phr bromobutyl compound, as found in the NHTSA Michelin tyres, is the most age resistant (phr is an indicator of concentration i.e. parts per hundred resin/rubber).

The inner liner is a key tyre component during service life, as it slows the diffusion of oxygen from the interior through to the tyre structure. A reduction of air and moisture vapour migration into the tyre structure will minimise development of intra carcass pressure, which may adversely lead to belt edge separation, rusting of steel tyre cords and adhesion failures.

According to Waddell 100phr Bromobutyl Rubber reduces both air and moisture permeability. However NHTSA identified in the 2010 report ‘Tire Inner liner Analysis’ that the overall thickness and construction of a tyre is a factor in permeation rates and that even when *“using identical inner liners of the same compound, the thicker construction of a truck tyre may have a lower inflation pressure loss rate than a thin high performance passenger tire …”.*

Thus whilst the inclusion of a high performing low permeability liner is shown to lessen pressure loss and the migration of gases into the tyre structure; tyre manufacturers clearly determine their individual balance of composition and performance when deciding on the differing liner bromobutyl/natural rubber compound proportions and blending.

4.2 First life tyre regrooving

Regrooving is the process of extending the mileage of a casing by carving out material from the base of the tread pattern to provide a similar pattern. Regrooving is permissible where there is sufficient thickness from the bottom of the original tread to the top of the uppermost belt. An indication of whether a casing can be regrooved is branded on the casing sidewalls at the time of original manufacture and generally involves the removal of 3-4mm of rubber. The regrooving principle is shown in Figure 5.

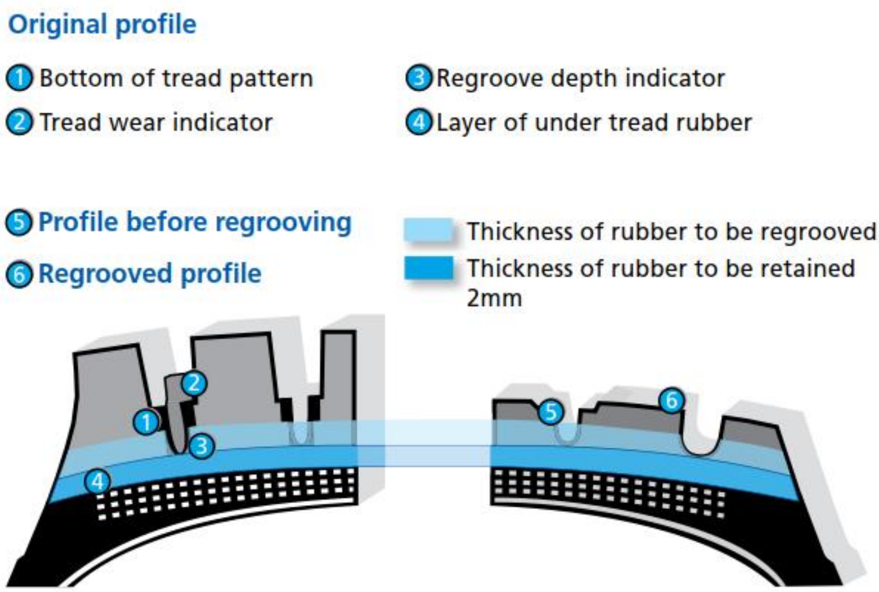

Figure 5: Regrooving profile

There are no restrictions on fitting correctly regrooved bus and truck radial tyres within the UK; the Motor Vehicle (Construction & Use) Regulations allow most bus/coach and goods vehicles over 2.5 tons unladen weight to be fitted with regrooved tyres. However, other countries vary in restriction. By way of example Germany allows regrooved tyres to be fitted except on the front axle of coaches operating at a speed of 100 km/h (62mph) (Michelin, 2014). (A public service vehicle (PSV) must get approval to travel up to 100 kilometres per hour (km/h) in Germany by having a 'Tempo 100 examination'.)

The terminology of a first life tyre includes one which has been regrooved; the sample of tyres inspected for this project included both regrooved and non-regrooved tyres.

4.3 Tyre retreading

Following first life, which may include regrooving, a tyre could be subject of a retreading process. Retreading is generic term for processing or re-engineering a worn tyre casing which receives a new tread. The safety, performance and structural integrity of a retreaded tyre depend largely on the condition of the original casing (Tyre Industry Federation, 2016).

Commercial vehicle tyres are often designed to be retreaded two or three times, whilst a car tyre may only be retreaded once.

Two methods generally describe the retreading process: either ‘cold cure’ retreading where a pre-cured tread strip is applied to the prepared casing. The casing and tread are vulcanised together in an autoclave using a special rubber compound; or ‘hot cure’ retreading whereby an uncured rubber compound is applied to the prepared casing. The new tread pattern and sidewall markings are formed during vulcanisation in a curing press.

The Motor Vehicle (Tyres) Safety Regulations 1984[29] require the retread process to be carried out in accordance with UN ECE Regulations relating to the “type approval” of retreaded tyres: UN Regulation 108 for car tyres and 109 for commercial vehicles tyres. This became mandatory in the UK with effect from January 1st, 2004. Common terminology from Regulation 109 is included below.

"Bead to bead" - replacement of the tread and renovation of the sidewall.

"Buffing" is the process of removing old material from the casing to prepare the surface for the new material.

"Casing" is the worn tyre comprising carcass and remaining tread and sidewall material.

"Cement" is an adhesive solution to hold new materials in place prior to the curing process.

"Cure" is the term used to describe the change in physical properties of the new material which is brought about usually by the application of heat and pressure for a set period of time under controlled conditions.

"Cushion gum" is a material used as a bonding layer between new tread and casing and for repairing minor damage.

[29] http://www.legislation.gov.uk/uksi/1994/3117/contents/made

"Pre-cured" is a previously formed and cured tread applied to the prepared casing. The new material must be bonded to the casing.

"Re-capping" is the replacement of the tread with the new material extending over part of the sidewall.

"Repair" is the remedial work carried out to damaged casings within recognised limits.

"Sidewall veneer" is a material used to cover the sidewalls of the casing thereby allowing the required markings to be formed.

"Top capping" is replacement of the tread.

Retreaded tyres must bear the marked 'RETREAD' on at least one sidewall.

Regrooving followed by retreading offers cost efficiencies for fleets when compared to the purchase of new tyres after the first life of an original fitment tyre. Mileage is also increased; offering fleets a reduction in overall operational costs. There are some limiting factors with regards to the acceptance criteria for a tyre to be retreaded, that are stipulated by UN Regulation 109 as listed in Table 6. The intention of these criteria is to ensure that no tyre with component deficiencies is kept in service. One of the criteria is that the age of the tyre does not exceed 10 years age from the date of manufacture.

5 Stakeholder engagement

5.1 British Tyre Manufacturers Association (BTMA)

The BTMA represents: Apollo Vredestein (UK) Ltd, Bridgestone UK Ltd, Continental Tyre Group Ltd, Cooper Tire & Rubber Company Europe Ltd, Dunlop Aircraft Tyres Limited, Goodyear Dunlop Tyres UK Ltd, Hankook Tyre UK Ltd, Michelin Tyre plc and Pirelli UK Tyres Ltd. All are tyre manufacturers supplying the UK market from Europe-based factories. On 1 April 2018 members of the Retread Manufacturers Association joined with the BTMA to create one voice representing retread manufacturing in the UK. BTMA members account for over 90% of UK retread tyre production.

The BTMA engages with Government and Industry trade associations. BTMA has addressed a number of questions regarding the remanufacturing process with the aim to gain insight into common defects found within tyres that are subject to remanufacturing processes and compare industry data relating to defect identification / rejection as part of the study.

BTMA engaged in this project with a meeting between their members and representatives from the DfT and TRL on 6 February 2019 in Leamington Spa, UK. The questions posed to the BTMA and the answers provided are documented in the following section.

Tyre assessment

Q. It is our current understanding that a tyre will have several inspections prior to being received by the tyre remanufacturer, i.e. by the casing management firm, fleet operator, casing agent. Is the data recorded in these inspections made available, alongside the tyre, when it is received for remanufacture?

BTMA stated their general opinion that, generally, such data was not recorded; whilst some casing agents offered a comprehensive inspection service, the remanufacturers relied upon their own independent inspection at the factory prior to the commencement of the retreading process.

Q. Do all tyres go through the same inspection process prior to being considered for remanufacture?

Yes, however, the factory inspection process would cease as soon as a tyre was rejected.

Q. Are all brands of tyres included within the remanufacturing process or are some brands automatically rejected/excluded?

BTMA highlighted that some brands of bus and truck radial tyre are only designed for single life rather than being originally designed for the retreading process. Single life lightweight casings are not suitable for retreading.

BTMA members know who such manufacturers are and stated that the tyres are designed to be commercially cheaper at initial purchase. Whilst all tyres generally have the same amount of tread to start with, with some possible small savings on the compound mixture, the real difference in price can be gained from savings in the structure of the casing.

This is an interpretation by the BTMA members, not tested or researched, but based on experience and deduction. There was general agreement that cheaper products were less likely to be able to withstand long life.

Importers of single life tyres have not been consulted within the framework of this project and have not commented or offered a viewpoint on the suitability of their products in relation to retreading.

Tyres may display other traits that also make them unsuitable for retreading, with excessive porosity and the inability to maintain inflation pressure being an aspect highlighted in response. Retreading is a commercial activity and therefore BTMA members aim to retread only those tyres that will repay their investment in the remanufacture process.

A question was posed on whether there are any known problematic inner liners specifically in relation to porosity / permeability. BTMA indicated that casings undergo a high voltage 'Hawkinson' test looking into the porosity of the liner, this test may occur at the beginning or later in the process.

'Hawkinson' pinhole detection is non-destructive testing using an electrostatic generator to produce a very low current static pulse (50,000 Volts at micro amps) which will arc between the probe brushes and a conducting roller on the inspection spreader. When a pinhole is detected a static spark is produced between the two conductors pin-pointing the otherwise invisible injury; the operator marks the spot if suitable for repair.

Thus, reason for rejection and the timing of that rejection during the inspection process can be variable across the industry.

Q. If some tyre brands are excluded, is there data or reasoning to ascertain why?

BTMA provided the opinion that casing fatigue life is a key factor. Tyres designed for a single life of only 80 – 100,000 miles have lighter casing plies than tyres designed for multiple lives potentially totalling in excess of 400,000 miles.

The BTMA quite rightly would not discuss amongst themselves and thereby do not create a list of excluded brands, as competition law and commercial position would prohibit such discussions. However, they acknowledge they all independently analyse rejections and perhaps have a list of casings that are excluded from remanufacture, but do not share that list.

Members may also just purely reject a specific casing based on not having a mould of the correct size or type; but then another remanufacturer could accept if it better suited their own equipment.

Furthermore, since the structural casing of the tyre frequently increases in diameter through use, a casing could be slightly oversize (perhaps by millimetres) possibly such that the remanufacturing mould would not fit well, and, given the cost of £20-30k per mould, this will skew any processing data.

Remanufacturers analyse the 'rejections' and if they find a particular trend, they will decide whether to retread or not at all; as there are plenty of other casings available, it is not necessary to consider problematic casings. Any exclusion may not be the whole range of an original manufacturer but may be just a specific model type.

Table 5: Data for truck tyre arisings and outcomes UK

Tyres inspected by retreaders in relation to all UK used truck tyre arisings

Data from UTWG 2017 mass balance

UK used truck tyre arisings

	Tyres
UK replacement tyre sales New	1,793,677
UK replacement tyre sales Retread	758,698
Recovery of tyres from dismantled vehicles	333,228
Imports of used tyres	154,471
Total arisings	**3,040,074**

Recovery outcomes

	Tyres
Reused in UK as part-worn tyres	78,039
Exports of used tyres (whole)	196,529
Retread production by UK manufacturers	913,169
End-of-life recovery	1,852,337
Total outcomes	**3,040,074**

Tyres inspected by retreaders (units)*	1,756,094
Tyres inspected by retreaders (% Total arisings)	58%

** Assumes 52% conversion rate*

The information above in Table 5 is provided by the BTMA from the annual mass balance prepared by the joint Defra / tyre industry Used Tyre Working Group. The table only discusses truck tyre data and is a simplified extraction. It was offered for scale purposes and is acknowledged as being a best estimate in the face of incomplete data. The BTMA believe there is a shortfall in recovery outcomes in the original source but it is not clear from which categories e.g. tyre crumb manufacturers, and it is unknown which are from car/truck etc.

The principal recovery outcome is to retread, then followed by rubber crumb (bigger sections of tread and magnetic wire make them more appealing for recovery and can be used for bin wheels, synthetic play surfaces etc.)

It was the general opinion of the BTMA that a significant proportion of the 1.85 million 'end of life recovery' figure will be cheaper, single life, casings.

Are there any pre-set conditions for a tyre to be excluded from the process?

Q. For example prior remanufacture (not first life)

BTMA response: "No, tyres in the right condition are frequently retreaded more than once. Aircraft tyres are commonly retreaded six times. Some manufacturers refuse tyres previously retreaded by another retread manufacturer." This may be based on commercial positioning and the desire to have knowledge of the casing history. It is more about knowing the exact history of how and when it was retreaded, rather than any issue with another retread manufacturer. Refusal is to do with commercial considerations and risk management. There are plenty of casings, thus BTMA members can easily be selective.

Q. Exclusion due to age

BTMA members apply a maximum age limit for retreading, largely for economic reasons. They stated that *"Older casings have a much higher rejection rate at visual inspection, making them less economically attractive"*. Equally, in the case of bead-to-bead retreads, older casing designs are unlikely to be a suitable starting point to produce a latest generation 'as-new' tyre.

The positions of BTMA members vary as to the maximum age of casing they will accept for retreading but the maximum value adopted is **10 years**, as determined from the regulated marking (DOT code) on the tyre sidewall. Furthermore, a lower limit may be applied to particular tyre types for other economic reasons (see further discussion below).

A further question was posed as to **why might different BTMA members choose a different maximum value with there being possibly a lower 'maximum' value?**

Some members may have seven or eight years as a maximum but none more than **10 years**. Commercial experience and economic considerations have to be considered and also each would not want to be too different to other companies.

Older casings often have more visible damage. Why inspect all of those casings only to accept a few? Again, as there are so many casings available, the incremental gain of altering selection criteria reduces.

Any differences in construction over the years may also mean an older casing does not fit their reprocessing equipment any more. NB: Rubber compound changes would not affect the retread process.

The responses highlight that, given the number of available tyres in the 1-8 year age, there would be little economic reason to spend time and effort on casings over that age.

Q. Rejection due to obvious physical damage

BTMA replied in the affirmative and referred to the UN Regulation No. 109 truck tyre acceptance criteria regarding identification of physical damage. The list below and Table 6 overleaf list the casing performance specification requirements of the regulation.

> *Tyres shall be clean and dry before inspection.*
>
> *Before buffing, each tyre shall be thoroughly examined both internally and externally to ensure its suitability for retreading.*
>
> *Tyres, where damage is visible which has resulted from overload or under inflation, shall not be retreaded.*
>
> *Tyres showing any of the following damage shall not be accepted for retreading:*
>
> *General: (a) non-repairable rubber cracking extending through to the casing; (b) casing break up; (c) appreciable oil or chemical attack; (d) damaged or broken bead core; (e) previous repairs of damage outside specified injury limits.*

Table 6: BTMA limiting factors drawn largely from UN Regulation 109

Tyre Component	Limiting Factor	Units	Limit Value / Maximum
Casing Contamination	Burnt Areas	Presence	No burnt areas that cannot be removed by buffing process
	Hydrocarbon contamination	Presence	No evidence of hydrocarbon contamination
Bead wire	Deformation	Presence	No bead wire deformation >6 mm
	Visibility	Presence	No visible bead wire
	Rubber Damage	Number	Maximum of 8 rubber damages >80 mm
	Cable damage	Presence	No damage to cables in wrap around zone
Sidewall	Stone Trap Damage	Presence	No visible stop trap damage (Note- unless confirmed acceptable through additional x-ray procedures)
	Cable Damage	Presence	None ≥ 20 mm circumferential
	Crazing/multiple diagonal cracks depth	Presence	None ≥ 3 mm
Crown	Holes greater than 35 mm	Presence	None
	Crown ply damage Crown centre	Presence	No damage to crown ply > 45mm (inclusive of regrooving damage)
	Crown ply damage Crown Edge	Presence	No damage to crown ply > 30 x 180 mm
	Maximum number of repairs in Crown edge area	Number	8
	Ply rusting exposure	Presence	No more than 20% of casing exposed to ply rusting
Shearography	Crown centre	Presence	Maximum separation 60 mm diameter in Crown centre
	Crown Edge	Presence	Maximum separation 15 mm diameter in Crown edge
Liner	Radial splits/ cracking	Presence	None
	Liner splits/cracking with visible radial ply	Presence	None
	Visible run flat damage	Presence	None (note: unless confirmed acceptable by additional x-ray procedures)

Q. Exclusion based on knowledge/experience, e.g. carcass weakness due to type of use, or brand of tyre?

BTMA agreed that some pre-selection may occur and referred back to their previous replies regarding single life tyres, casing fatigue resistance.

Q. The DfT asked whether they should be considering the longevity of a 'single' life and chronologically old tyre compared to 'longer' life tyre of the same age?

The BTMA response was that they would be unable to lay down a specification for single/multiple life tyres, as it is more to do with individual service history. They indicated the ETRTO have discussed creating a standard for retreading but suggested there may be too many variables for example, what if a 'retreadable' tyre is then assessed for retreading but its *usage* makes it not suitable?

The BTMA reasoned that the biggest influence on longevity is operational life, specifically whether a tyre has been subjected to hard or soft miles, under-inflated or over-loaded, on a vehicle or stored outside in a pile, etc.

Q. Economic reasons to exclude a tyre type/brand?

Clearly, tyres that have suffered excessive damage, e.g. off-road tyres, will be uneconomic to repair prior to retreading. Equally, tyres that present an excessive rate of rejection post-buffing are commonly excluded for economic reasons. Thus, they would effectively be pre-excluded because of repeated learning and knowledge gained for that particular tyre. Such tyres may be defined by brand, model, size, factory or period of manufacture. Remanufacturers make informed decisions rather than carry out a full investigation of every tyre looking at brand and mileage etc. as they will not know in-service mileage.

It should be noted that the purpose of the casing selection process is to secure the production of retreaded tyres that comply with UN Regulation 109 at an economic cost.

Exclusion from the retreading process cannot be interpreted as a judgement of a tyre's safety performance.

Q. At what point during the inspection / remanufacture process are most rejections made?

Relating to inspections taken at the retreading factory, rejections rates were offered by the BTMA from common agreement between its members:

- Initial visual assessment ~ 20 - 50%
- Shearography testing ~ 5 - 10%
- During the buffing process ~ 4 - 10%
- Remanufacture process ~ 1 - 3%

This results in a worst-case rejection range of between 30-73%, with an average of about 52%.

By comparison to the initial triage inspection of the subject tyres for this project, TRL and Smithers Rapra inspections resulted in similar rejection figures, at a level of about 34% on visual assessment.

Some BTMA members offered that for the post-buffing rejections this was generally due to visual damage becoming noticeable after this abrasive process; also if there was a high level or likelihood of repeated rejections then they would probably add that tyre to an exclusion list from the start. This was justified again on economic reasoning; however, there was no commonality across the industry.

It was also highlighted that a tyre's date of manufacture regulated tyre marking (DOT code) is the first thing to be checked, so if found to be over the 10 year (or in some cases a lower 7-8 year) age, the inspection process would not carry on even if a tyre could probably satisfy the rest of the selection criteria.

What are the reasons for rejection and is this recorded?

Q. Is data held identifying the reasons for rejection for each tyre?

In general, "No."

Q. Is data relating to each rejected tyre kept (e.g. manufacturer, age, mileage)?

This varies between retreaders.

Q. Is statistical data available to determine percentage rates for rejection in terms of overall totals?

BTMA presented the chart below:

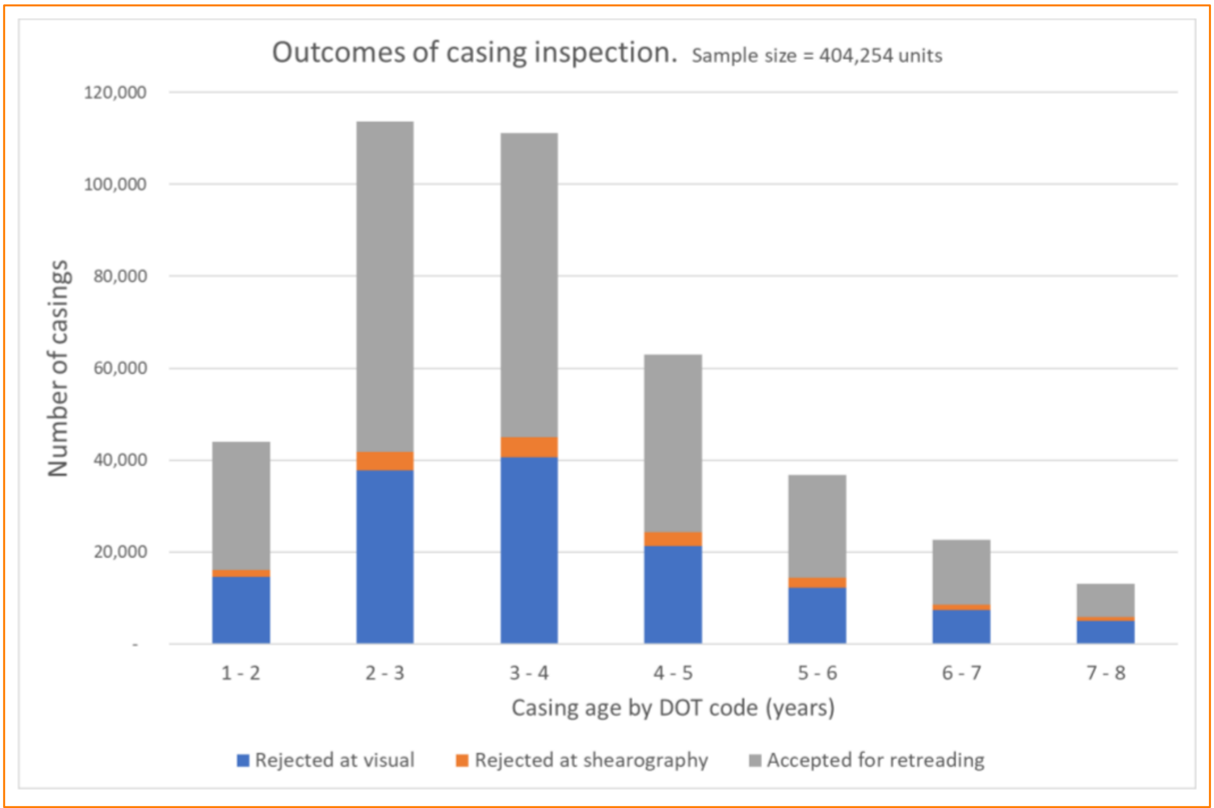

Figure 6: Casing rejection and acceptances by DOT code (years)

Figure 6 above represents 404,254 casing inspections. These are data of the rejection outcomes at the visual and shearography inspections and with those accepted for retreading. It is, however, only based on data from three BTMA members who record the regulated tyre marking date code of all tyres inspected, and not from all members. The age range is noted from 1-8 years.

TRL asked if further approaches could be made towards those members that record this data; however, the response was that the provision of any additional information would depend on the nature of data requested. At the moment, this chart is collated of high-level, unidentifiable data.

Even if data is obtained, it was highlighted that any inspection or retreading process would always stop as soon as an issue was identified; the factory would not know of any other potential reasons for rejection. The regulated tyre marking date code is not, generally, kept for casings that are rejected.

The process is all about the economic production of a tyre that is compliant with UN Regulation 109. The retreader will want to make the remanufacturing process as efficient as possible, so will stop the process as soon as possible in the event of a defect being found, not recording anything else nor retaining data.

The assessment processes are not designed to look at whether the tyre is roadworthy at the time of presentation, or even at the end of the re-treading process, but whether it will be roadworthy at the end of its unknown next life based upon a prudence and precautionary principle.

In 2015 the BTMA Tyre Technical Advisory Committee reviewed and republished their recommendations in relation to car, 4x4, van and commercial vehicle tyres including spare tyres.

> *"The serviceability of a tyre over time is a function of the storage conditions (temperature, humidity, position etc.) and service operating conditions (load, speed, inflation pressure, road hazard damage, climatic conditions, terrain etc.) to which a tyre is subjected throughout its life.*
>
> *Since these conditions vary widely, accurately predicting the serviceable life of a tyre in advance is not possible. The longer the tyre has been in service, the greater the chance that it will need to be replaced, due to service-related deterioration, or other conditions found upon inspection or detected during use….*
>
> *… Tyres that have been in use for a number of years should be regularly inspected by a tyre specialist (at least annually)".*

It is noted that UN Regulation 109 makes no comment on the date of manufacture code. During 'hot cure' the original DOT code would be removed in the process; whereas in 'cold cure' only the crown is renewed however a retreader may still choose to buff off the DOT code. The legal regulations only stipulate a new code should be placed on one side of the tyre. It is mainly for economic reasons that BTMA members do not place on both sidewalls as they are not required to.

An RFID chip can store information about when and where the tyre was made, its maximum inflation pressure, size etc. Information can be retrieved with a handheld reader. UK regulations require that commercial vehicle tyres be regularly checked for air pressure and overall condition. Fleet operators are required to maintain a record of these maintenance activities whether completed by their own staff, or by a service provider. In the future RFID may expedite this activity.

RFID tagging is likely to be wider spread throughout the tyre industry in the next 5-10 years. However, mandatory adoption would require UNECE regulation. If another significant non-UNECE regulatory jurisdiction decides to implement a requirement for RFID tags, then it may speed up the process in other countries. ISO/DIS20909[30] sets the standard in relation to RFID tags for tyres, covering the format of codes, longevity.

[30] A revision to ISO/DIS 20909 in now under development and has not be reviewed as part of this work.

6 Tyre selection and tyre service history

The selection criteria ensured the tyres were taken from UK vehicles and that they were available in sufficient quantity to compensate for potential rejections. Service history and the removal date from service were sought where available.

6.1 Selection

6.1.1 Casing selection

Each tyre underwent a triage assessment based up on the technical specifications and guidance within DVSA Heavy Goods Vehicle and Public Service Vehicle Inspection Manuals. This was to ensure that the casing selected exceeded the requirements as laid out within the project sponsor's scoping document, namely that the tyre be examined:

- Externally to ensure that there are no defects that could be readily identified when fitted to a vehicle and using typical roadworthiness inspection techniques (with the exception of tread wear limits).
- Internally to determine if there are any signs of damage, misuse or repair.
- To identify pinholes, flaws of the tyre liner.
- To determine whether there is any separation of any layer or element of construction of the tyre carcass.

Tyres that failed this initial inspection were rejected from the work and were not included in any further aspect of the test programme or analysis.

6.1.2 Casing supply

Following consultation with the British tyre industry's Retread Manufacturers Association (RMA), industry support was made available to supply casings in order to fulfill the project requirements.

A leading and recognised casing agent provided support to enable the selection of an initial batch of 25 used 295/80 R 22.5 first life casings aged between three and seven years old. They also supplied a further 13 casings for the secondary phase of testing and supplied the five new casings that were subject to ageing techniques and provided the control samples.

The sourcing of casings for the secondary phase, the scope of which included tyres older than seven years, was challenging due to the major casing agents having a high-turnover of casings, with very few identified that were older than seven years. The casing agents stated, in common with the knowledge gained during the stakeholder engagement, that there is a 10-year old cut-off for the remanufacture of a casing, therefore, it is not economically viable for a casing agent to retain casings older than 10 years. This resulted in the limited availability of older tyres.

Additionally, the husbandry practices used by the casing agents were such that older casings were more difficult to locate and, if identified, were more likely to have defects that prevented them from entering the remanufacturing process and therefore, being unsuitable for inclusion within the scope of this project.

Thus, to assist in the sourcing of tyres for the secondary phase of this project, further support was provided by the project sponsor by way of Driver and Vehicle Standards Agency (DVSA) vehicle examiners identifying old casings that were of interest and relevance to the project scope.

6.1.3 Triage inspection

Prior to inclusion within the project each tyre was subject of two triage inspections. These consisted of an initial inspection by the TRL project team, with a further inspection made by the members of the project team at Smithers Rapra. The secondary inspections made by Smithers Rapra were conducted alongside the TRL project team, a factor that benefitted the sharing of acceptance and rejection data.

The technical criteria for inclusion into the project, to meet the DVSA Annual Test requirement and that a casing may not be subject to any prior repair, resulted in an initially high rejection rate.

In identifying the initial batch of 25 casings that were selected for secondary inspection by Smithers Rapra, there was a rejection rate of around 34% (13 casings being rejected). Of these 13 casings the Reasons for Rejection (RfR) are shown in

Table 7: Reasons for rejection at triage (initial batch)

Reasons for Rejection – Initial Phase	Number
Penetration to cords – Central tread	7
Penetration to cords – Shoulder	2
Regrooved to deeply to expose cords	2
Plugged repair	1
Damage to shoulder to expose cords	1

The rejected casings were then removed from the project, having been photographed and the RfR noted.

The secondary inspection of the 25 tyres, conducted in unison with Smithers Rapra and TRL project team members, found that to enable 20 used casings to be taken forward into the scientific analysis stage of the project there was just a single rejection, the RfR being a penetration to the casing’s liner (casing ref TRL: 295/80R220.5_024).

In relation to the triage inspection for the secondary phase of the project, in identifying casings older than seven years of age and younger than three years of age, the triage inspections identified a similar technical rejection rate for the older casings.

As part of the secondary phase, 18 casings were initially sourced, 14 from casings agents and/or tyre remanufacturers, with four casings sourced from coach operators (the latter examples being with the assistance of DVSA inspection staff).

Of the 18 casings, only nine progressed beyond the joint triage assessments of TRL and Smithers Rapra and into the next phase of the test programme. The technical RfR for this phase were as follows:

Table 8: Reasons for rejection at second inspection (secondary phase)

Reasons for Rejection – Second Phase	Number
Heat damage from vehicle exhaust	1
Hydrocarbon damage and liner cracks	1
Penetration repair	4

Table 8 above illustrates that for the secondary phase of the tyres, just six were rejected due to the casings displaying technical flaws that would render the casing un-roadworthy, and therefore fall below the minimum standard acceptable for a DVSA annual inspection. The technical RfR rate for the second phase of tyres was 33.33%, similar to that seen within the initial phase.

As shown in Table 8 the older casings obtained for inclusion in the secondary phase included a number of casings that were rejected due to them being previously repaired following penetrative damage. All repairs appeared to be consistent with the standards as laid out in BS AU 159, however, as the presence of prior penetrative damage could introduce inconsistencies within the project samples, they were rejected. It was noted during the selection process for each phase of the project, that the older casings were more likely to have defects to them that rendered them unsuitable for inclusion into the project, as well as unsuited for use on the UK road network. There is therefore a potential linked argument, that restricting the maximum age of a casing has the added benefit of potentially reducing the usage of previously repaired casings.

An important point to note is that although 18 casings were initially sourced for this secondary phase, with a technical rejection rate of six, only nine casings progressed to the material analysis phase. This was due to the project sponsor wishing to have as large a range of casing production dates as possible therefore duplication of production years was avoided, hence the omission of three further casings from the study. The casings taken into the second phase had age span of 16 years, the oldest included casing being produced in 2000, with the youngest being 2016.

6.1.4 Casing usage history

The availability of the prior usage data for all, or as many of the selected casings as possible, was outlined within the initial meeting with the RMA. It was their opinion at the time, that this would prove challenging to obtain, as mostly it remains with the vehicle operator or with a casing management firm operating on their behalf.

During the initial selection of casings, the TRL project team were made aware that whilst the casing supplier physically held the casing, they had no associated data linking individual casings to a fleet operator or, at a deeper level, to the casing's position on the vehicle, date of fitment and removal, or its covered distance.

The above, therefore, reinforces the prior opinion of the RMA that the availability of the prior usage data for any of the tyres included within the project scope would be difficult to obtain.

During the triage assessments of the initial batch of casings it was noted that some casings (six of the 20 selected) had hand-written information on the casing that identified the vehicle, by way of registration number, from which it had been removed. Using openly available resource techniques, attempts were made to identify what vehicle this was, alongside the fleet operator.

For the initial batch, a number of casings were identified that originated from vehicles used by three major UK fleet operators. Three casings were identified as having originated from vehicles used within Fleet Operator 1, two casings having originated from Fleet Operator 2 and one casing from Fleet Operator 3.

Investigations were commenced with the fleet operators to source prior usage history for each casing, the requested information being:

- Vehicle – make/model/age
- Tyre position
- Fitment date and odometer recording
- Removal date and odometer recording
- Reason for removal
- Vehicle usage – primarily motorway/regional, UK/European networks, etc.

Despite initial protracted enquires made with the fleet operators usage data was not forthcoming.

Further enquires were made with the tyre management company that provides tyre support for Fleet Operators 1 and 2. These enquiries indicated that although data may be available it would only be provided with the consent of the fleet operator. After many attempts to progress the situation, and gain prior usage data, consent was obtained from Fleet Operator 2 for information to be shared by the tyre management company to the TRL project team; the information provided was minimal (reproduced, in part, in Table 9 and Table 10).

Table 9: Usage data example – tyre 25

For DAF CF - (Tyre 25)	
Tyre position	Unknown
Fitment date and odometer recording	Unknown
Removal date and odometer recording	30 July 2014 (odometer unknown)
Reason for removal	Worn Out
Vehicle usage	Unknown

Table 10: Usage data example – tyre 14

For DAF CF - (Tyre 14)	
Tyre position	Unknown
Fitment date and odometer recording	Unknown
Removal date and odometer recording	10 July 2014 (odometer unknown)
Reason for removal	Worn Out
Vehicle usage	Unknown

As can be seen in the above examples, the information returned from the tyre management company was limited and provided no tangible value to the project.

Having obtained data from the tyre management company, further enquiry was made with Fleet Operator 2's fleet management. For the identified tyres, both of which were fitted to vehicles that were no longer in the operator's fleet, no further data specifically related to the identified casings was available, thus the limited data previously identified was all that was available for Tyres 14 and 25.

The fleet data returned for Tyre 14 was slightly more comprehensive and contained odometer readings for some tyre changes later in the vehicle's service life. However, as there was no information as to the Tyre 14's fitment position, no direct reference could be made in relation to estimated usage for any of the replacement tyres.

Despite repeated and on-going enquires with Fleet Operator 1, no information regarding prior usage has been obtainable for any of the casings previously used on vehicles within their fleet.

For the secondary phase casings, prior usage proved an equally difficult factor to obtain. Initially it was anticipated that the four tyres sourced directly from coach operators may provide any easier source of the data, however this was not to be the case.

When the TRL team collected the casings from the coach operators, it was apparent that the casings sourced were originally fitted to vehicles that had been brought, as used vehicles, into the fleet and that the two operators implemented no documented tyre management strategy.

It would appear that the tyre management policy of the coach operators, where the casings were sourced, was to fit the newest tyres to the vehicle that did the most mileage (typically a touring coach) then, as the tread depth reduced, refit the casings to older vehicles that do less distance, prior to being retained on a low mileage vehicle as a spare wheel. Therefore, it was not possible to obtain an indication of fitment position, distance covered, or typical usage for any of these casings.

The information regarding older casing usage as a spare wheel was reinforced during the triage inspection of two of the casings sourced from the coach operators. One of the triaged casings (Tyre 32) had hydrocarbon contamination reportedly caused from the tyre being stored beneath the vehicle’s auto-lube dispenser. A second casing (Tyre 31) had heat damage caused by the spare wheel position being too close to the vehicle’s exhaust pipe.

Of the other casings selected for progression in the secondary phase, only one casing (Tyre 46) had any identification markings to it, this relating to a DAF XF vehicle, being operated by Fleet Operator 4; at the time of writing, despite protracted efforts to obtain usage information none has been forthcoming.

It can therefore be summarised, that the data retrieved from tyre management companies and the fleet operators of the goods and public service vehicles is very limited in being able to ascertain a casing’s prior usage.

6.1.5 Prediction of wear rates

In the absence of the prior usage data from either the tyre management company or fleet operator, research papers were reviewed to identify formulae that could be used to provide predictive comparison on tread wear rates; the purpose being to establish, in the absence of any meaningful usage data, an appreciation for the potential mechanical wear each casing may have been exposed to, i.e. an indication of the theoretical distance each casing may have travelled.

Three papers were identified that provided predictive formulae for estimating expected tyre life based on wear rates only, these being by Lupker *et al.* (2002), Deierlein (1992) and Chatti *et al*. (2012).

Using the known tread erosion of each used casing within the project sample, it was possible to use these research papers to provide an estimate on the expected service life of the project casings. To reduce error, any casing that had been subject to tread regrooving was eliminated; therefore estimates based on the upper and lower predictions for tyre wear were calculated for each of the 14 casings that had not been regrooved.

The first paper provides an upper and lower wear rate for steering axle tyres fitted to large goods vehicles (this based on kilometres per mm of eroded tread depth), with the higher wear rate being 15,000 km/mm and the lower wear rate being 30,000 km/mm of tread wear.

Using the Lupker *et al.* formula, estimates for the distance covered by each of the non-regrooved tyres included within both phases of the project have been calculated (Table 11).

Table 11: Calculated tyre wear estimate using Truck Tyre Wear Assessment and Prediction

Tyre #	New depth	Measured tread depth	Eroded tread	Prediction, lowest wear rate (30,000 km/mm)	Prediction, highest wear rate (15,000 km/mm)
Tyre 7	14.5	2.51	11.99	359700	179850
Tyre 9	14.5	2.1	12.4	372000	186000
Tyre 10	14.5	3.73	10.77	323100	161550
Tyre 11	14.5	2.7	11.8	354000	177000
Tyre 13	14.5	4.78	9.72	291600	145800
Tyre 14	14.5	1.5	13	390000	195000
Tyre 15	14.5	4.33	10.17	305100	152550
Tyre 17	14.5	1.38	13.12	393600	196800
Tyre 18	14.5	0.71	13.79	413700	206850
Tyre 21	14.5	2.56	11.94	358200	179100
Tyre 23	14.5	5.24	9.26	277800	138900
Tyre 25	14.5	1.36	13.14	394200	197100
Tyre 43	14.5	6.1	8.4	252000	126000
Tyre 46	14.5	2.9	11.6	348000	174000

The second paper by Deierlein (1992)[31] discussed an early Goodyear investigation into the mileage per 1/32nd inch (0.8mm) of tread wear for varying operating regimes, considering a Heavy Goods Vehicle. Converting to comparative kilometres attained per mm of wear revealed wear rates for Long haul use of 30,525 km/mm, Regional use of 19,851km/mm and Delivery & Collection use of 16,561 km/mm (see Table 12).

[31] As referenced in (Woodrooffe *et al.*, 2008)

Table 12: Calculated tyre wear estimate using Deierlein research

Tyre #	New depth	Measured tread depth	Eroded tread	Prediction, Long Haul (30,525 km/mm)	Prediction, Regional Use (19,851 km/mm)	Prediction, Delivery and Collection Use (16,561 km/mm)
Tyre 7	14.5	2.51	11.99	365995	238013	198566
Tyre 9	14.5	2.1	12.4	378510	246152	205356
Tyre 10	14.5	3.73	10.77	328754	213795	178362
Tyre 11	14.5	2.7	11.8	360195	234242	195420
Tyre 13	14.5	4.78	9.72	296703	192952	160973
Tyre 14	14.5	1.5	13	396825	258063	215293
Tyre 15	14.5	4.33	10.17	310439	201885	168425
Tyre 17	14.5	1.38	13.12	400488	260445	217280
Tyre 18	14.5	0.71	13.79	420940	273745	228376
Tyre 21	14.5	2.56	11.94	364468	237020	197738
Tyre 23	14.5	5.24	9.26	282661	183820	153355
Tyre 25	14.5	1.36	13.14	401099	260842	217612
Tyre 43	14.5	6.1	8.4	256410	166748	139112
Tyre 46	14.5	2.9	11.6	354090	230272	192108

The variance in the wear rate/mileage driven results, highlights that real-world tread wear is directly proportional to the rate of stopping and starting and manoeuvring of the in-service specific use.

The third paper (Chatti and Zaabar, 2012) provides a wear rate as a percentage per kilometre, the wear rate being between 0.0006%/km to 0.0021%/km. As with the previous wear rate examples, Table 13 uses the same known tread wear to calculate an expected distance that each non-regrooved tyre would be expected to have travelled, based on the provided formula.

Table 13: Calculated tyre wear estimate using Estimating the Effects of Pavement Condition on Vehicle Operating Costs

Tyre #	New depth	Measured tread depth	Eroded tread	Prediction, lowest wear rate (0.0006%/km)	Prediction, highest wear rate (0.0021%/km)
Tyre 7	14.5	2.51	11.99	137667	39333
Tyre 9	14.5	2.1	12.4	142500	40714
Tyre 10	14.5	3.73	10.77	123833	35381
Tyre 11	14.5	2.7	11.8	135667	38762
Tyre 13	14.5	4.78	9.72	111667	31905
Tyre 14	14.5	1.5	13	149500	42714
Tyre 15	14.5	4.33	10.17	116833	33381
Tyre 17	14.5	1.38	13.12	150833	43095
Tyre 18	14.5	0.71	13.79	158500	45286
Tyre 21	14.5	2.56	11.94	137167	39190
Tyre 23	14.5	5.24	9.26	106500	30429
Tyre 25	14.5	1.36	13.14	151000	43143
Tyre 43	14.5	6.1	8.4	96500	27571
Tyre 46	14.5	2.9	11.6	133333	38095

Comparison between the predictive methods show there is a significant difference in the calculated estimated distances. Taking Tyre 7 as an example, the quoted examples of lowest wear rate show that the tyre has difference in estimation of 228,228 km, between the highest value (Table 11) and the lowest value (Table 13); approximately 62% variance.

Keeping Tyre 7 as the example, but using the highest wear rate, the range in estimated travelled distance is lower at 159,223 km, however in percentage terms the variance is increased to approximately 80%.

It would therefore seem that the formulae provided within the research papers is unhelpful in being able to make a meaningful estimate regarding the wear rate each tyre was exposed to, and therefore, being able to estimate with any degree of accuracy the distance travelled.

To quantify the above, reference is made to the usage data provided in relation to Tyre 14. The data shows project Tyre 14 was replaced on 10 July 2014, subsequent to this date, the next replacement front tyre for this vehicle occurred on the 29 July 2015, which, if the annual usage remained constant, could suggest that the steering axle tyre on this vehicle had a service life of around 163,000 km.

7 Tyre test programme

7.1 Introduction

A wide range of industry-standard tyre tests were performed to investigate the potential effects of tyre age. The testing regime looked at material properties, permeability of the inner liner, and adhesion between the layers of the tyre. All testing was performed by Smithers Rapra at their Ravenna, US laboratory, which has been a provider of testing services to the National Highway Traffic Safety Administration (NHTSA) since its inception in 1968. They have been a provider of compliance testing as well as research and development testing for the National Highway Traffic Safety Administration's Vehicle Research and Test Centre and Office of Vehicle Safety Compliance. The laboratory is accredited to ISO 17025.

7.2 Selection of tyres

A total of 49 tyres, consisting of five new tyres and 44 used tyres returned from service were selected as potential candidate test samples. A detailed description of the tyre selection process is given in Section 6. All of the investigated tyres were a single premium brand front axle specification and sized 295/80 R22.5. This particular Truck & Bus Radial (TBR) tyre size was selected because it has been established in UK vehicle fleets for many years. Test tyre selections were limited to first-life (TBR) tyres, 3 to 19 years in age, with new tyres utilised as comparative test samples. All test tyre samples were obtained in the UK.

The used tyres were subjected to a detailed visual examination by TRL and Smithers Rapra, with their general condition and any physical damage being recorded photographically using high resolution digital images. Any tyres that exhibited evidence of significant physical damage, under-inflation, penetrations or repairs were rejected from the study (and retained by Smithers Rapra for reference). A total of 26 used tyres were selected for inclusion in the test programme, as well as five new tyres, some of which were artificially aged as described in Section 7.3.1.

Sidewall data from each of the test tyres was collected and recorded for reference.

It should be noted that it is possible that the tyre manufacturer could have modified the tyre design over the 17-year age period due to product or process development; however, exemplar samples were from the same manufacturer and of the same designed usage and size. In addition, three different tyre models were used in this study, which may have differing material properties. The use of three models was necessary as no single model spanned the complete age range of the tyres selected for the study.

7.3 New tyres

A control sample of five new tyres was obtained for a base-line inspection and to investigate the effect of artificial ageing methods on the material properties and structural integrity of new tyres.

It was reported from earlier NHTSA testing on passenger car tyres (as shown in Section 3.6.4) that during service, oxygen migration through the structure of the tyre leads to attack on the sensitive adhesive boundary layers. This was also supported by Smithers Rapra historical research. However, the literature review did not identify similar testing on heavy duty commercial tyres. In order to address this limitation in the available literature, a limited programme of tests was developed to replicate a change in tyre characteristics and provide a set of control data.

7.3.1 Artificial ageing

Four out of the five new tyres were artificially aged: all four underwent thermal oxidisation ageing at an elevated temperature in an oxygen-rich atmosphere and two of these additionally underwent mechanical ageing on a dynamometer, as described in the following sections. The four tyres were then subjected to the same tests as the new tyre and the used tyres.

7.3.1.1 Oven ageing in an oxygen-enriched environment

As mentioned in the previous paragraph, four of the new, unused tyres were thermally aged, with inflation gasses replaced at regular intervals. This controlled thermal oxidation ageing process provides a set of comparative data (in addition to that obtained from the new tyre and the used tyre samples).

Smithers Rapra indicated that the chemical process of oxidation creates reactions and material property changes within tyres. Smithers Rapra therefore kept the tyres at a normal inflation pressure for service tyres, but with greater oxygen levels i.e. 50/50 (N_2/O_2), which was replenished at regular intervals and kept at a temperature of 65°C. Each tyre was maintained in these conditions for eight weeks.

This data is intended to provide information which is valuable in determining the importance of differences observed between the physical properties of the new tyre controls, and those tyres returned from service.

7.3.1.2 Dynamometer

Two of the new tyres that were subjected to the thermal ageing regime were additionally subjected to dynamometer tyre exercising, in general accordance with FMVSS 119. Each tyre was run on a dynamometer for 47 hours at 225 revolutions per minute, which is the higher drum speed adopted in UN Regulation 54. This additional test was conducted in order to determine the effect of dynamic inputs on the aged properties of the tyre's materials.

This test is designed to operate a wheel and tyre assembly under load as specified in FMVSS 119, as appropriate for the vehicle. For a 'heavy truck' this load is specified as 8000 lbs, or 3,629 kg. The assembly is mounted on an axle and pressed against a flat-faced steel drum (referred to as a "test wheel" in the standard) that is 1,708 mm in diameter and at least as wide as the tread of the tyre. The load is applied and the test wheel is rotated at the required speed.

7.4 Test methods

The test programme subjected the selected tyres to a very wide range of tests, as defined in the following sections. Initially, each tyre was subjected to non-destructive (shearography) testing to provide information on the status of the internal structure of the tyre. Each tyre was then cut into sections to provide test samples for each of the remaining test types, and the dimensions of the cut sections was recorded.

Note on tyre belt numbering: In this report the steel belts of each tyre are referred to by numbers from 1 to 4. In the context of this report, belt 1 is that which is positioned closest to the tyre inner liner, belt 4 is that closest to the tread.

7.4.1 Shearography

Shearography is a non-destructive optical measurement technique. It is a tool commonly employed in the retreading industry for identifying separation defects (internal detachments of the tyre structure that cannot be seen externally) and is the key non-destructive tool for detecting this type of defect.

The tyre is subjected to a low pressure differential inside a vacuum chamber. The pressure differential induces deformations in the tyre carcass and causes any internal detachments to become evident. Laser holography is used to detect and view the detachments; where it sees metal it reflects a bright appearance and where it does not impinge on metal it will not reflect and dark areas will be displayed.

As an example, the dark anomalies in the image for 'Scan 1 Sector 7' in Figure 7 are described by Smithers Rapra as *"One damage-area anomaly at 220-230° in upper sidewall".*

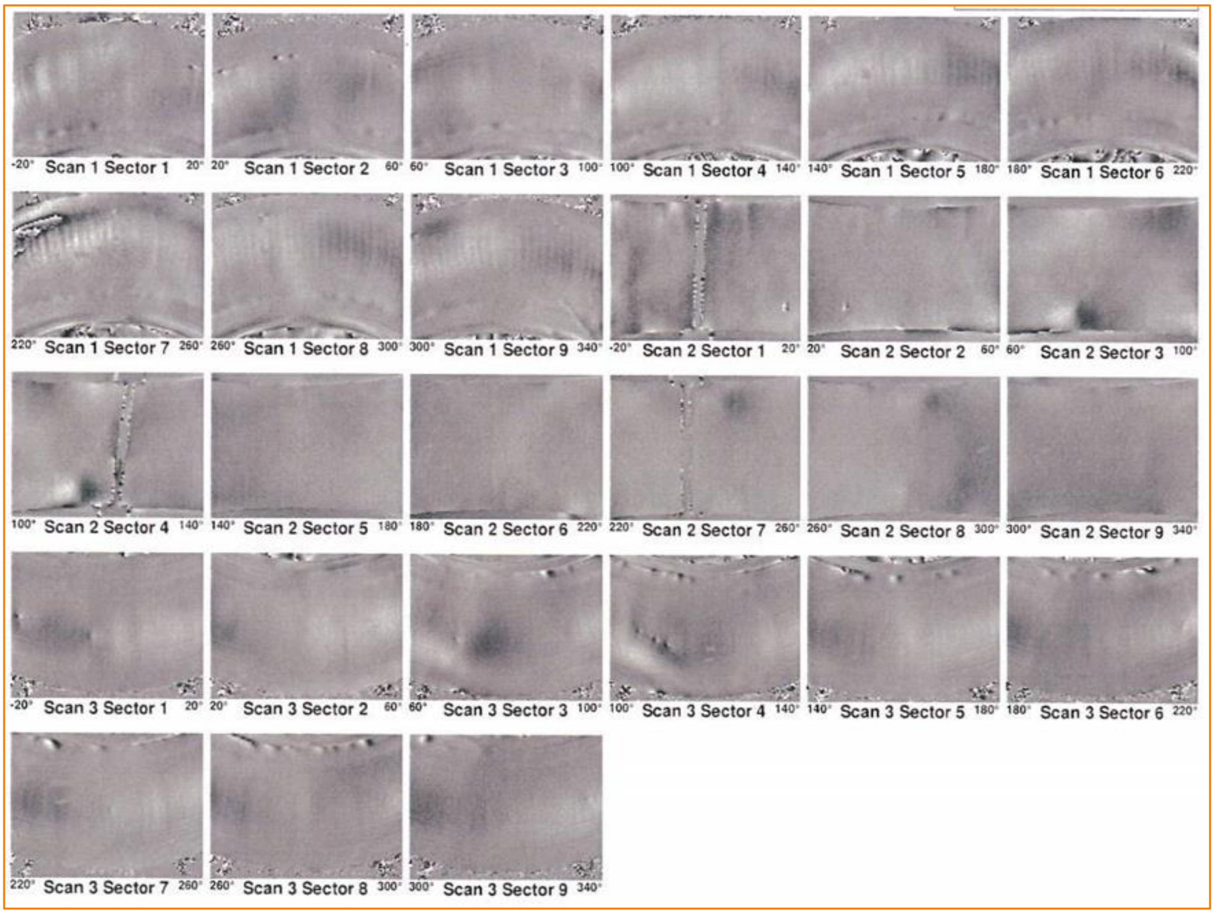

Figure 7: Shearography example, Tyre 20

7.4.2 Rubber compound hardness

The hardness of the rubber compound was tested to ASTM D2240. Tests were performed on components from five areas on each tyre including the tread, sidewall and inner liner plus two further areas selected from the working belts, bead filler or bead turn-up.

This test method relates to hardness measurements based on either initial indentation or indentation after a specified period of time, or both. The test is based on the penetration of a specific type of indentor when forced into the material under specified conditions. The indentation hardness is inversely related to the penetration and is dependent on the elastic modulus and viscoelastic behaviour of the material.

The measuring apparatus includes a durometer with operating stand, and a presser foot, which has a centrally located orifice (to allow for the protrusion of the indentor) of a specified diameter.

7.4.3 Rubber compound tensile properties

The tensile strength, modulus of elasticity and elongation of the rubber compound were tested to ASTM D412. Tests were performed on components from five areas on each tyre including the tread, sidewall and inner liner, plus two further areas selected from the working belts, bead filler or bead turn-up.

The test procedure specifies that determination of tensile properties starts with test pieces taken from the sample material and includes the preparation of the specimens and the testing of the specimens. Specimens may be in the shape of dumbbells, rings or straight pieces of uniform cross-sectional area.

Measurements for tensile stress, tensile stress at a given elongation, tensile strength, yield point, and ultimate elongation were made on specimens that had not been pre-stressed. Tensile stress, yield point, and tensile strength are based on the original cross-sectional area of a uniform cross-section of the specimen.

Tension tests were made on a powered machine equipped to produce a uniform rate of separation for a set distance. The testing machine has a suitable dynamometer and an indicating or recording system for measuring the applied force (and may be placed in a temperature-controlled chamber for specific tests, if required).

Unless otherwise specified, the standard temperature for testing is 23 ± 2°C, with specimens conditioned for at least 3 hours. If the material is affected by moisture, relative humidity is maintained at 50 ± 5 % and specimens are conditioned for at least 24 hours prior to testing.

7.4.4 Residual ozone resistance in the tread and sidewall

The ability of the tread and sidewall compounds to resist attack by atmospheric ozone, and any changes in such performance due to ageing, were assessed using tests defined in ASTM D1149. This test method specifically relates to un-aged rubber compound and not tyres; therefore, the tests described in this report were conducted in general accordance with the Standard and the results should be considered comparative only.

These test methods are used to estimate the effect of exposure, under surface tensile strain conditions (either dynamic or static) in an atmosphere containing specified levels of ozone concentration.

7.4.5 Interfacial peel force

These tests quantify the adhesion levels at key material interfaces within the tyre, measured in accordance with ASTM D413. Tests were conducted at room temperature at five interfaces (these being: belt 2 to belt 3 (Working belts), belt 3 to belt 4, belt 4 to tread, casing to sidewall, and casing to innerliner) and at an elevated temperature (100°C for 1 hour prior to testing) at interfaces belt 2 to belt 3 and belt 4 to tread.

The tests cover the determination of the adhesion strength between plies of fabric bonded with rubber, or the adhesion of the rubber layer in articles made from rubber attached to other material.

The methods used consist of applying to a test specimen, under specified conditions, a measured force sufficient to strip from the specimen at a measured rate, a layer of moderate thickness with separation at the adhered surfaces. The numerical value of the adhesion is expressed as the average force required to maintain separation at a definite rate, or the average rate of separation caused by a known or specified force.

The separation force can be applied by using the weight of known mass, although in these tests, a power-driven, tension testing machine (or tensometer), accurate to within ±1 %, was used to apply and measure the force required to separate the layers of the test specimen.

7.4.6 Tensile properties of ply cords

Key physical properties of the ply cords (including tensile strength and modulus) of each tyre were determined for comparison. This testing was conducted in general accordance with ASTM D2969, which is intended for application to new, unused cords; however, the steel tyre cords here remained partially coated with rubber because they had to be extracted from the test tyres prior to ply testing. The effect of the rubber residue is expected to have been insignificant.

These test methods cover the testing of cords made from steel that are specifically designed for use in the reinforcement of pneumatic tyres. They include:

- Visual appearance, residual torsion, straightness and flare
- Linear density
- Tensile properties or cord breaking force (strength) and elongation at break
- Elongation between defined forces

In this case only tensile properties were tested, for which a tensile testing machine that provided a constant rate of extension with an automatic force-extension recording system was required.

7.4.7 *Innerliner Permeability (Oxygen Gas Transmission Rate)*

The liner permeability test was conducted in accordance with ASTM F1927-14, using Oxtran 2/21 test apparatus with computer control. This test measures the oxygen gas transmission rate through the liner samples. Test conditions were 23 ± 2°C, 50 ± 5% Relative Humidity (RH).

This test method covers a procedure for determination of the rate of transmission of oxygen gas at steady-state and at a given temperature and %RH level, through film, sheeting, laminates, co-extrusions, or plastic-coated papers or fabrics.

The specimen was mounted as a sealed semi-barrier between two chambers at ambient atmospheric pressure. One chamber was slowly purged by a stream of nitrogen at the temperature and RH given above, and the other chamber was purged by a stream of oxygen at the same temperature as the N2 stream. As oxygen gas permeates through the film into the nitrogen carrier gas, it is transported to a coulometric detector where it produces an electrical current, the magnitude of which is proportional to the amount of oxygen flowing into the detector per unit time.

7.5 Test matrix

Table 14 shows the test matrix for the test programme undertaken by Smithers Rapra. In addition to a large number of visual inspections and measurements, over 1100 tests and over 800 scans were performed.

Table 14: Test matrix, showing all tests performed by Smithers Rapra

Test programme	Test standard	No. tyres tested
Initial sidewall data collection, non-destructive tyre examination, selection and photography		31
8 weeks thermal ageing at 65°C using an oxygen enriched inflation gas mixture		4
Dynamometer test	FMVSS 119	2
Shearography		31
Physical properties of 5 areas/components of rubber compound of each tyre – hardness (5 tests per tyre)	ASTM D2240	31
Physical properties of 5 areas/components of rubber compound of each tyre – tensile strength, modulus and elongation (15 tests per tyre)	ASTM D412	31
Residual ozone resistance tread and sidewall (2 tests per tyre)	ASTM D1149	31

Interfacial peel force tests of 5 tyre interfaces at room temperature and 2 at elevated temperature (7 tests per tyre)	ASTM D413	31
Physical properties of ply cords – tensile properties (strength, modulus and elongation) (3 tests per tyre)	ASTM D2969	31
Inner liner air permeability (Average of 4 tests per tyre)	ASTM F1927-14	31
Cut section measurements/examinations of 2 sections per tyre		31

8 Test results

Smithers Rapra have produced a Technical Report (CTR 62526, The Effect of Ageing on Tyre Material Properties) which is an Annex to this report. This section summarises some of the test results, including reproduction of charts; for a complete understanding the Smithers Rapra document should be read in full and in conjunction with this report.

Thirty-one first life tyres were subjected to laboratory testing including new and thermally/dynamically aged tyres used as controls. A suite of assessments, measurements and laboratory tests were undertaken to assess the material properties and structural integrity of the selected tyres. The following observations were made following laboratory testing.

8.1 Artificial ageing

As discussed within the literature review section NHTSA identified oven ageing as a suitable method for artificially ageing light vehicle tyres (in a controlled and accelerated manner); however, with reference to the commercial tyres tested here, the laboratory results do not support oven ageing as a wholly suitable method to age the tyres to an identifiable chronological age.

Some of the physical property changes observed in the thermally aged tyres were either more or less marked when compared to the service tyres. The reasoning is not fully understood but may be as a consequence of the differing properties found within commercial tyres when compared to those in passenger vehicles upon which most previous laboratory testing had been based.

Figure 8 shows the peel strength between belt 2 and belt 3 at the elevated temperature test condition. It can be observed that the thermally aged and dynamometer run tyres showed comparable peel strength to the un-aged new tyre and all new, thermally aged and dynamometer run tyres had markedly greater peel strength than any of the service returned tyres.

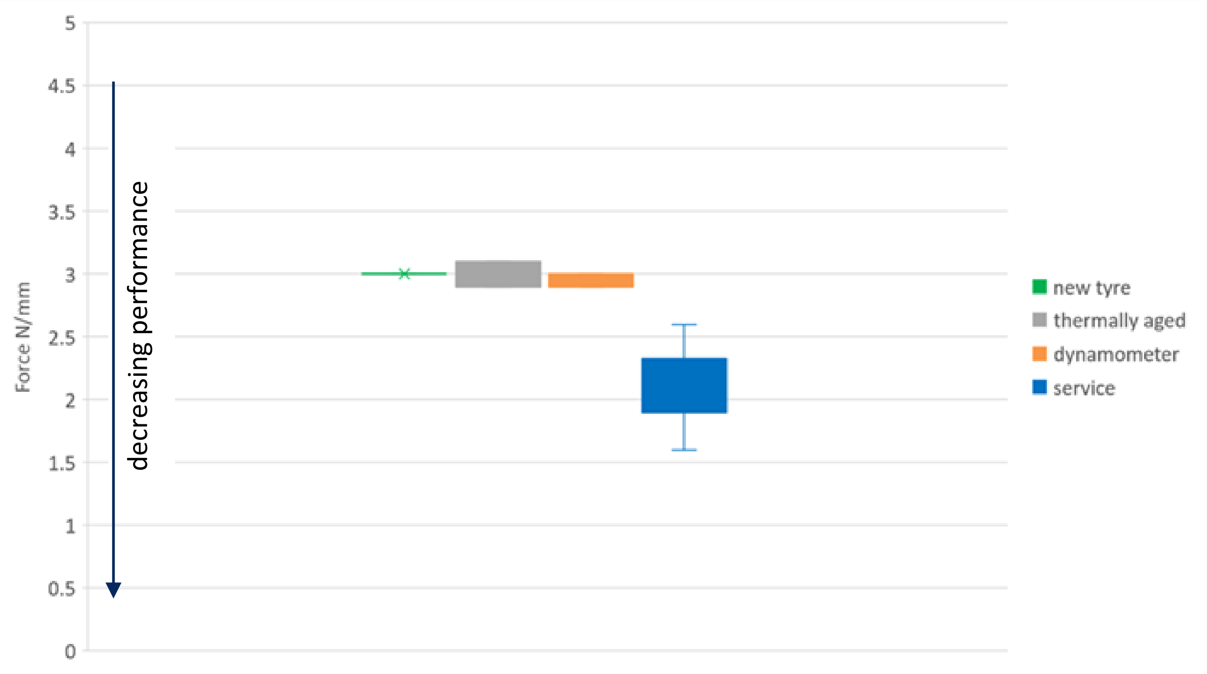

Figure 8: Interfacial peel force, belt 2 to belt 3 (elevated temperature)

The interfacial peel force data for belt 2 to belt 3 (room temperature) shows that the thermally aged and dynamometer tyres are closer in peel-strength performance to the service tyre data (Figure 9). Nevertheless, they do not demonstrate peel strength as low as that observed for the service tyres.

Figure 9: Interfacial peel force, belt 2 to belt 3 (room temperature)

There are in some cases modest correlations between the data resulting from thermally aged tyres and that from the tyres taken from service, such as that seen in Figure 10. However, there is very little correlation between the dynamometer aged and service tyres.

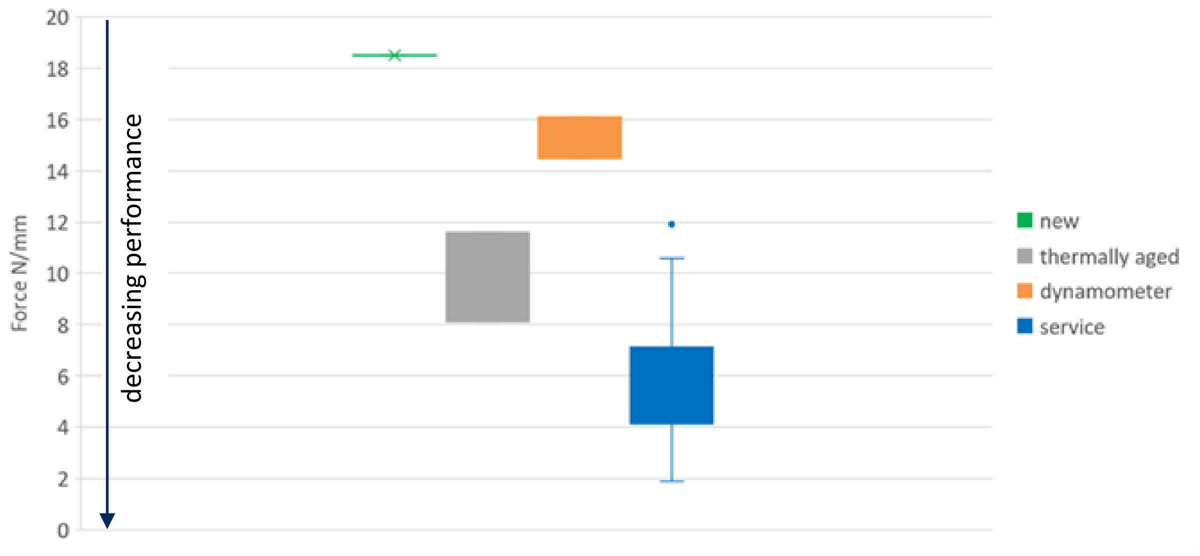

Figure 10: Interfacial peel force, belt 4 to tread (elevated temperature)

At the belt 4 to tread interface (room temperature), the thermally aged and dynamometer run tyres (orange data) showed an increase in peel force compared to the new control tyre (green) - Figure 11. This was unexpected and is difficult to explain; more investigation would be needed to form any firm conclusions.

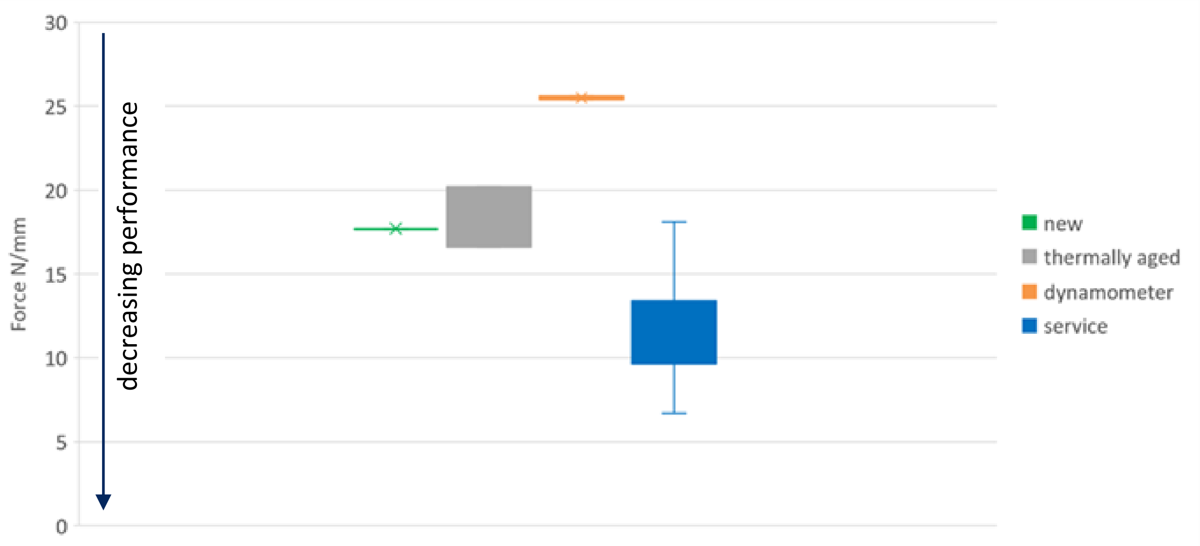

Figure 11: Interfacial peel force, belt 4 to tread (room temperature)

In some of the material property data for the thermally aged or thermally aged and dynamometer run tyres, the performance of the artificially aged tyres is worse than the new control tyre and closer to the performance of the service tyres. For these material properties, the degree of movement falls into the range of the two areas described above (either towards but not reaching or towards and overlapping with the tyres returned from service). However, having a range of effects means that the artificial ageing does not produce a consistent 'life' against which comparisons can be firmly made.

The aim of including the thermally aged or thermally aged and dynamometer run tyres was to provide a consistent baseline threshold. Together with the new tyre, this was anticipated to bracket a desired material property assessment and indicate potential limits. Based on the variable influence of the artificial ageing on the material properties, the resultant data from this project does not allow confirmation that artificially ageing tyres is a wholly suitable control method.

These control tyres have also not produced an extreme data threshold where safety may be compromised. It is not clear how the artificially aged tyre properties relate to a critical threshold for tyre disablement and some of the service return tyres show greater changes in property compared with the control tyres.

Therefore, the oven ageing procedure for commercial tyres would need to be refined before it could be reliably used as a benchmark. For this reason, we have decided not to include the artificially aged tyres in the remainder of this report. To fill the gap created from excluding the artificially aged tyres, we decided to add more service life tyres in a second phase of testing, and consequently the testing period was extended from the end of 2018 to Spring 2019.

8.2 Service tyres

8.2.1 Physical inspection

Cut sections of the service tyres were inspected for faults which may lead to structural integrity issues or features that may vary with age and service life. The inspections did not focus on physical dimensions (the size and shape) of the tyre or composite parts. These overall physical attributes may change with production revisions or from model to model but were not considered to be a priority with regard to ageing and tyre integrity.

The cut section inspections revealed a number of tyres with faults associated with the steel belt package. The faults observed were in areas where the adhesive bond had been lost between the steel cord and its coating compound, or where cracks were present in the rubber compound in the area around the cords. In addition, one tyre showed a detachment between the steel cords of belt 2 and their coating compound.

Of the 26 tyres returned from service, 19 contained these areas of interest. One tyre additionally contained a detachment between the steel cords of belt 2 and their coating compound. The study did not specifically examine whether corrosion was widespread, though corrosion was recorded when found.

All of the faults were found in the tyres returned from service, whereas there were none of note in any of the new or new/thermally aged tyres. The faults were not identified by the shearography inspections; therefore shearography may not be able to detect all of the internal anomalies that may be present in a tyre following service use. Evidence of this is provided by faults found in tyres when sectioned that had previously been accepted for testing including the completion of a shearography inspection.

8.2.2 Physical properties of rubber compounds

Tread

The hardness of the tread compound is shown in Figure 12. The new tyre is of the same make and model as the Model 1 service (used) tyres and is shown as an unfilled circle of the same colour. Model 2 and Model 3 tyres are shown in separate colours.

In common with many of the tyre properties, the hardness can be compared in more detail between examples of the same tyre model. Model 3 in Figure 12 appears to show a step change increase in hardness observed with tyres from 2009 and older. The hardness appears to plateau with tyres from 2009 and older. The two 2016 service tyres appear to be exceptions to the overall trend; this may indicate, based on these observations, that within the data set there is variability in chemical composition for different production years of the same tyre model, resulting in the different hardness values observed for these tyres.

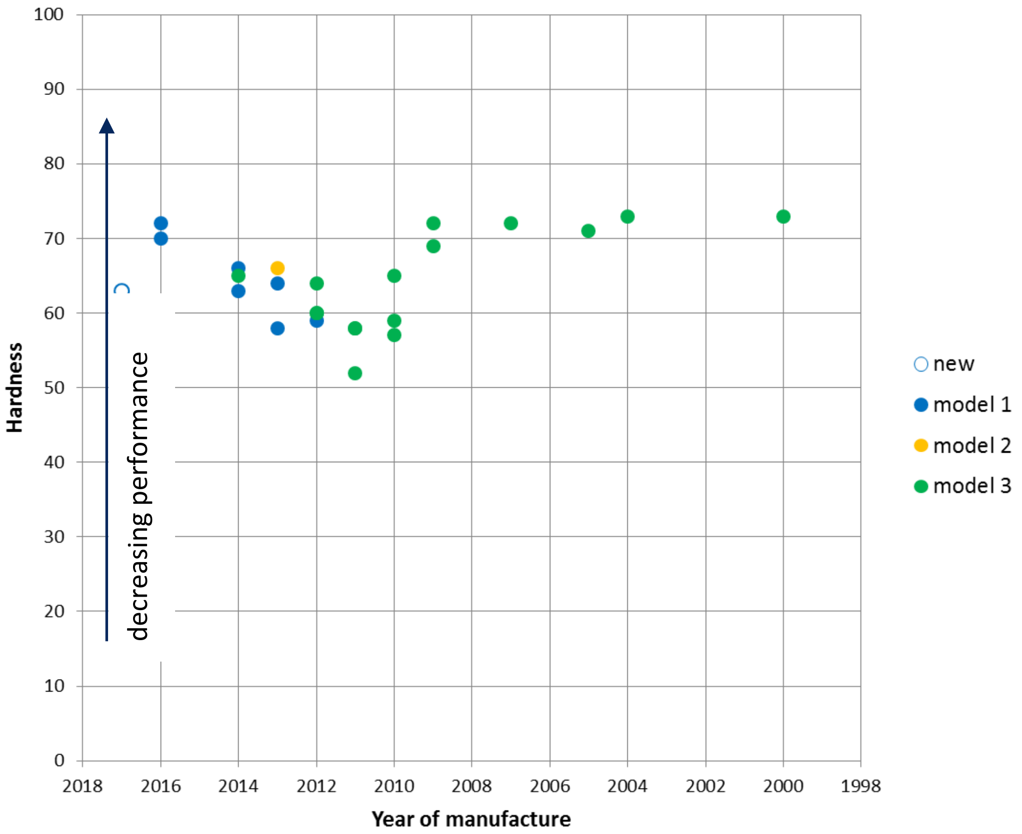

Figure 12: Tread compound hardness

Consideration was given as to whether tyres that had been subjected to regrooving in the sample of service tyres would show any difference in hardness. The regrooving originated from more service wear and thus the engagement of a section of tread deeper in the original tyre structure. The same data as shown in Figure 12 is reproduced in Figure 13, with regrooved and non-regrooved identified separately.

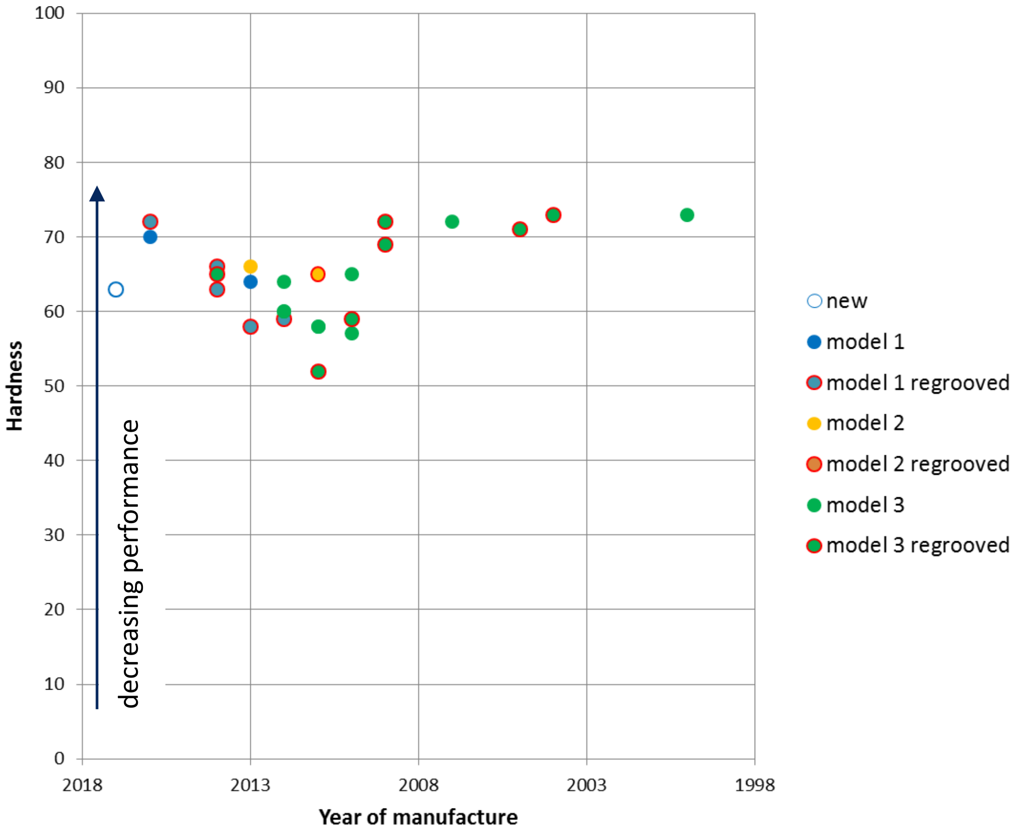

Figure 13: Tread Shore A hardness for service regrooved tyres

Data suggests that the hardness Shore A of regrooved tyres was not different to that of tyres that had not been regrooved. The moduli of the tread compounds at both 100% and 300% elongation do not show significant trends with time. This is shown in Smithers Rapra Chart 2 and Chart 3.

The tensile strength of the tread compound shows a reduction with age compared to a new tyre; however there was considerable scatter in the data, therefore a trend could not be established conclusively (Figure 14).

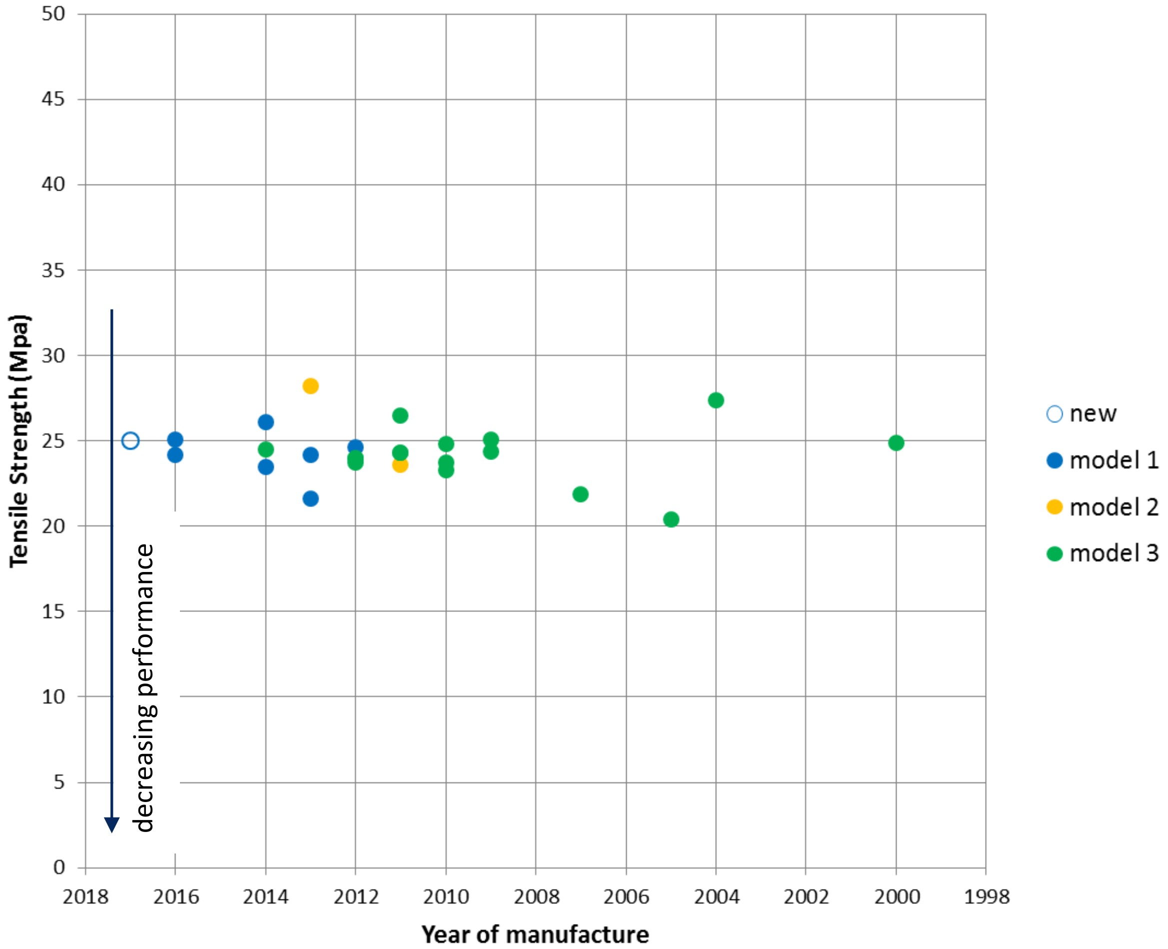

Figure 14: Tread compound tensile strength

Sidewall

The hardness of the sidewall compound appears to show an increase with time for Model 3 tyres. Similarly to the tread compound hardness, sidewall hardness seems to plateau with tyres 2009 and older (Figure 15).

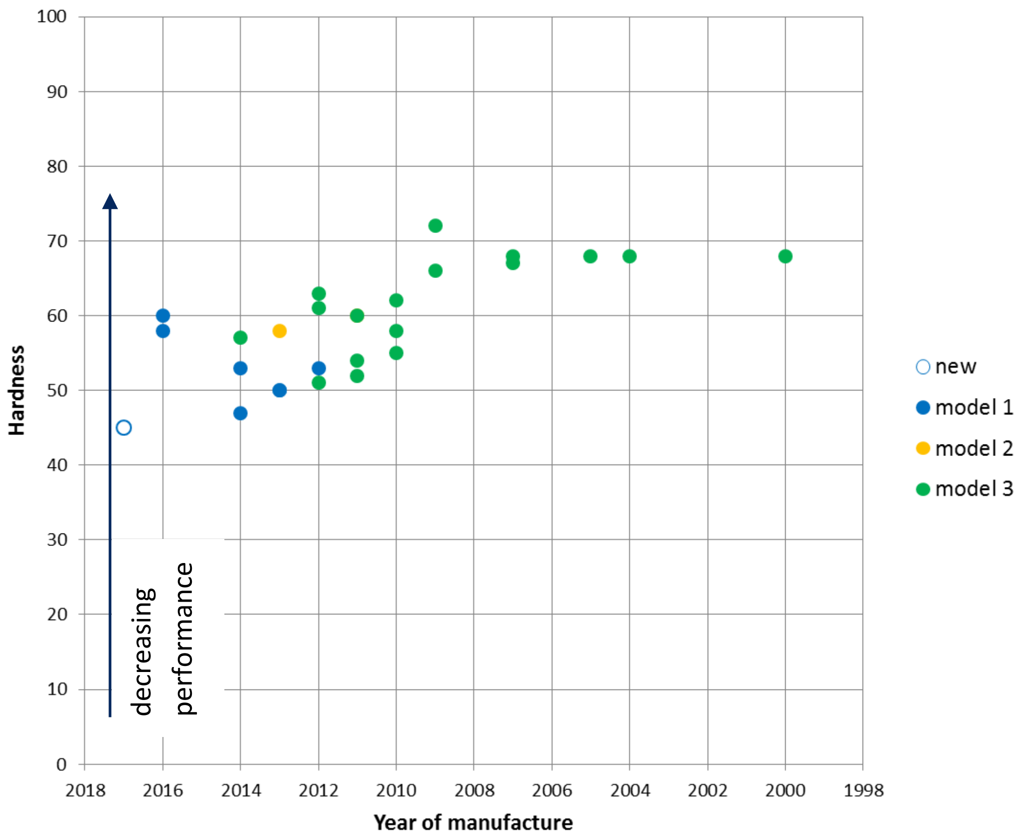

Figure 15: Sidewall compound hardness

The modulus of the sidewall compounds at both 100% and 300% elongation showed increases of stiffness with age. Data are available in the Smithers Rapra Tables 13 and 14. The ultimate elongation of the sidewall compound showed a reduction compared to the new tyre, given the moduli increase, the trend in elasticity was not unexpected.

Inner liner

The inner liner samples appear to show a general reduction in hardness with age and a number (18) of the service tyres had a modulus in excess of the new control tyre (Figure 17), thus a conclusion that there is always a reduction in elongation with age cannot be confirmed. Nevertheless, for Model 3 tyres, there appears to be a small reduction of inner liner hardness with increasing age, however this may be negligible given the variability in the hardness data (Figure 16).

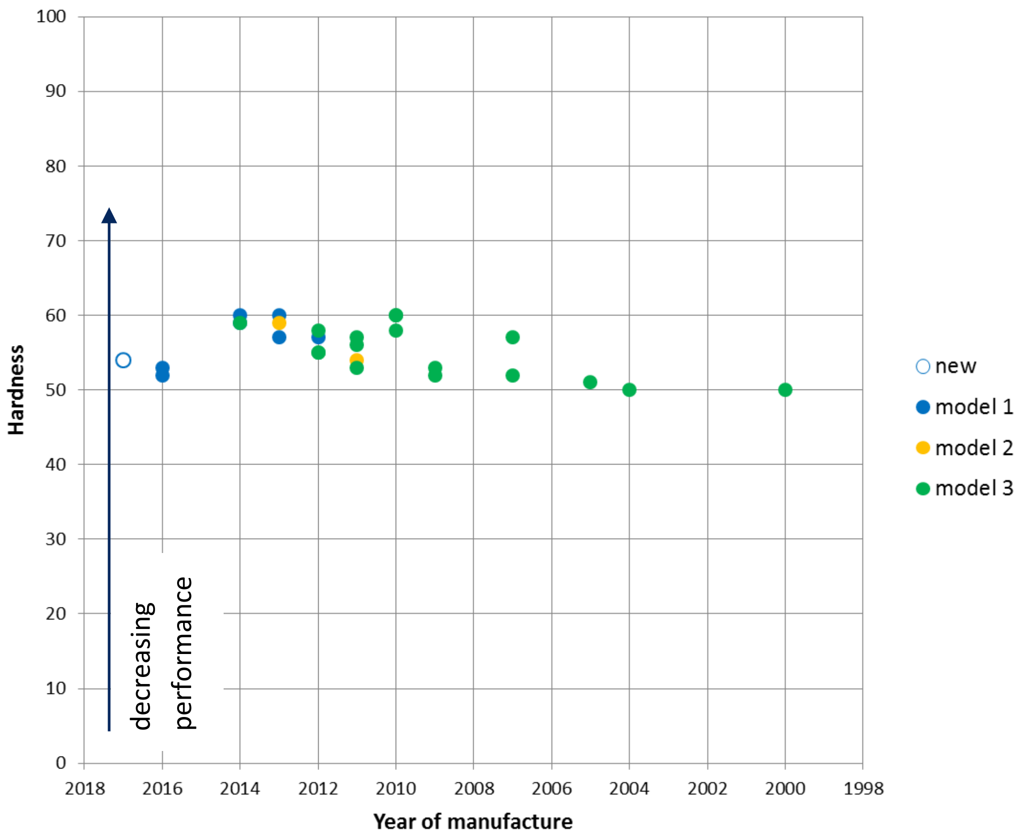

Figure 16: Inner liner hardness Shore A

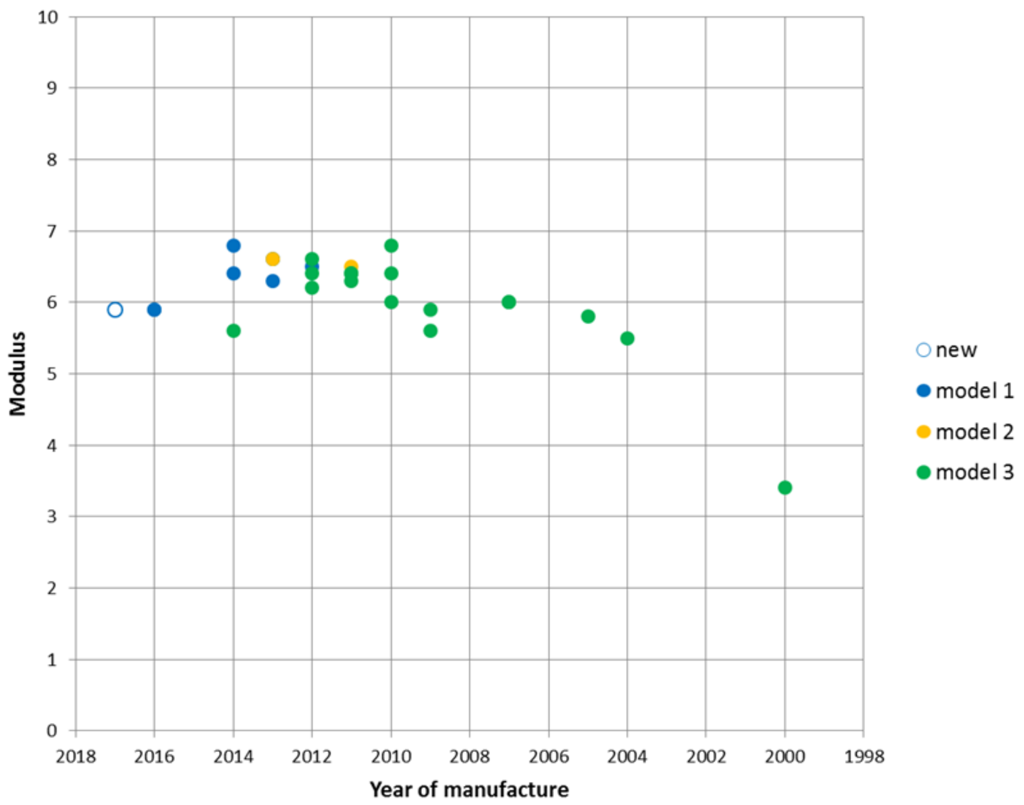

Figure 17: Inner liner modulus at 300% Extension

Shoulder wedge

In relation to shoulder wedge compound, trends were difficult to identify (without valid justification for removing apparent outliers). However, hardness showed a slight decrease with time, the moduli did not show a significant trend with age, likewise the ultimate elongation. The tensile strength of the shoulder wedge showed a slight reduction with increasing age.

Belt skim

The belt skim compound showed an increase in hardness with time (Figure 18), which seemed to be greatest during the first five years of life of the tyre when comparing the new and other Model 1 tyres. A marginal increase in hardness appears to continue beyond this early life. This trend can especially be seen when looking at the Model 3 data. (NB: a number of data points are overlaid so not all are visible, e.g. 'model 1' and 'model 3' series both contain a hardness result of 81 with a 2016 tyre.)

The belt skim modulus at 100% elongation showed evidence of increase in compound stiffness with age. Only the new control tyre achieved 200% elongation before fracture.

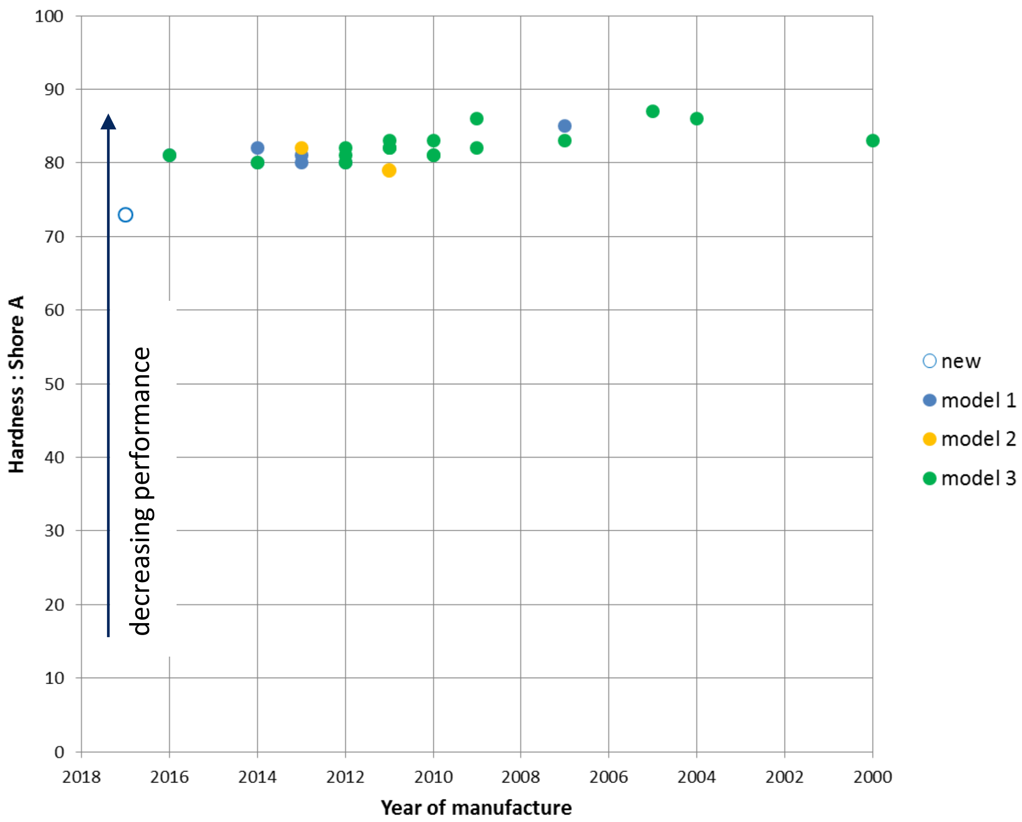

Figure 18: Belt skim Shore A hardness

Summary – Hardness and Tensile Strength

Changes in rubber hardness and tensile measurements are indicative of changes in the tyre properties, but the tyre is not primarily loaded in tension. The exception would be bulging of the tyre close to the contact patch. In general, the tyre would be expected to become stiffer over time due to oxidisation and to changes in the rubber cross-links that are established during the curing process. These changes are indicative of a reduced ability to resist deflection. This is not such a concern for tyre integrity (mainly for performance – grip etc.) except for extreme changes that could lead to cracking. Cracking could lead to corrosion, although this was not observed in any of the used tyres tested in this programme – the corrosion observed in Section 8.2.7 was due to penetration of the tread – but it should be noted that the tyre selection process may have biased this, because cracked tyres were rejected (see Table 6).

It should also be noted that tyres are designed with certain properties for the intended performance and handling, so there is no one 'correct' specification or range for these values that can be applied across all tyres. However, any change from the original values for a particular tyre design would indicate a change in operational performance (e.g. handling, traction and fuel consumption).

8.2.3 Residual ozone resistance

Tread and sidewall test samples were excised and exposed to ozone for 70 hours at 38°C and 50 parts per hundred million and subsequently examined up to a magnification of 7x for signs of cracking. No significant difference (age-related or otherwise) was found in any of the tested tyres, with all service tyres receiving a cracking rating of 'severe', i.e. having large cracks visible to the eye. These cracks also appeared in the thermally aged or thermally aged and dynamometer run tyres although the new tyre had no cracks in the sidewall compound when viewed at 7x magnification.

8.2.4 Interfacial peel force

A tyre is a composite item which is made up of a number of parts, with rubber compounds bonded to various reinforcing elements (see Figure 4). The adhesion between these components is a potential weakness in the overall structure, and separation of the constituent parts is a possible mode of failure of a tyre.

Belt 2 to belt 3

Figure 19 shows the interfacial peel force between belt 2 and belt 3; with no clear trend over time when looking at each tyre model separately; though there is a substantial drop in force observed in the early life in the (single) new tyre (of Model 1) to the service tyres of the same model.

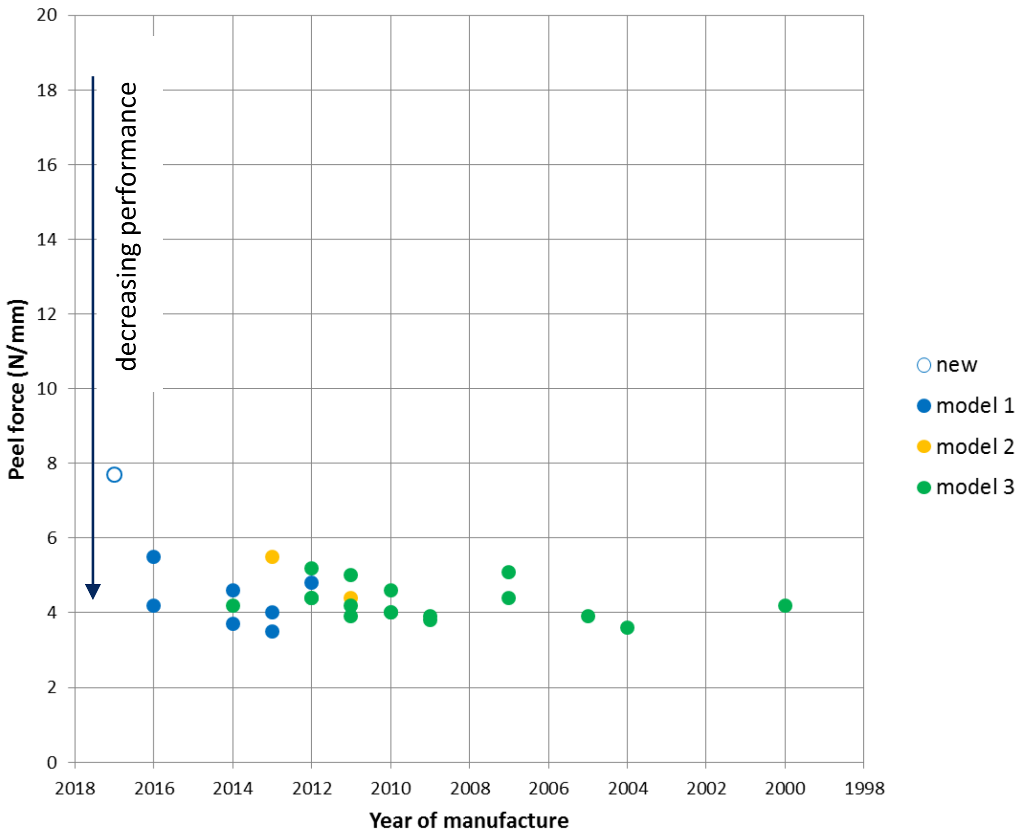

Figure 19: Interfacial peel force, belt 2 to belt 3

Belt 3 to belt 4

Peel force reduction appears in the first three to four years of tyre life. The data reveals a marked reduction in peel force within this age range, and for belt 2 to 3, belt 3 to 4 and between the casing and sidewall, when compared with a new tyre. However, following the initial drop there does not appear to be any further significant reduction over the remaining age range of the tested service tyres.

The interfacial peel force between belt 3 and belt 4 is shown in Figure 20. The data for Model 1 shows a rapid drop in peel force over the first three to four years of tyre life, especially when compared with a new tyre of the same model. The data for Model 3 shows no substantial change with age, noting that the scatter is very large in these results.

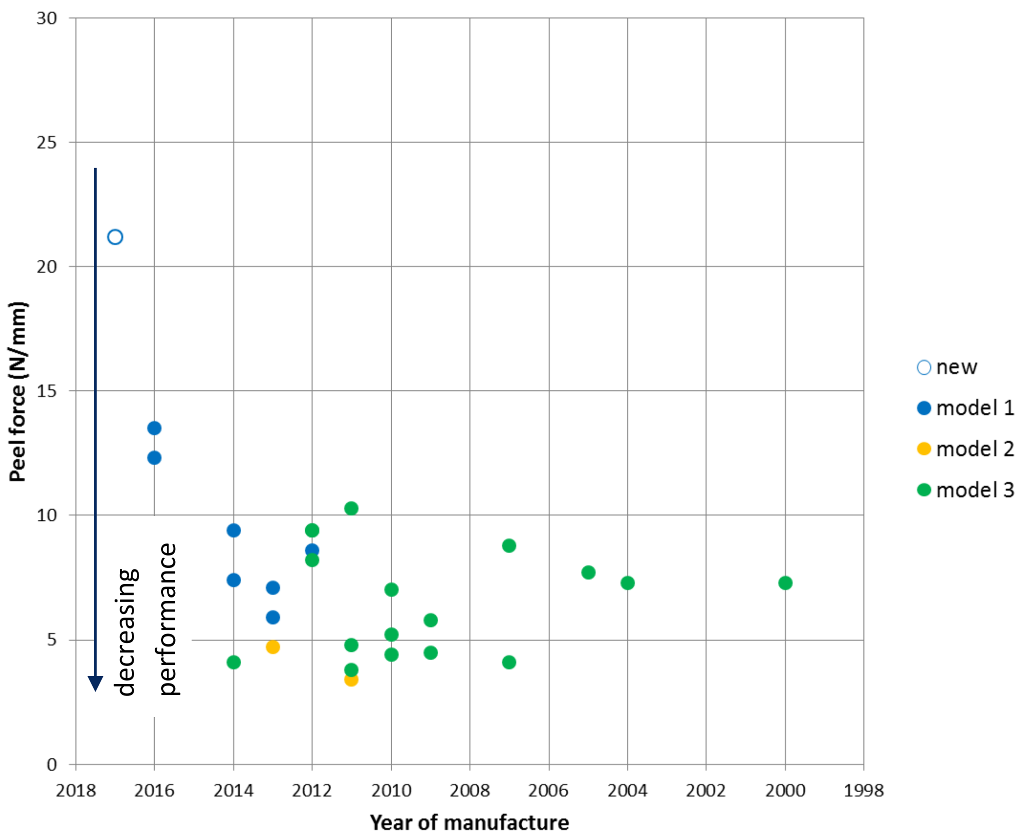

Figure 20: Interfacial peel force, belt 3 to belt 4

Casing to sidewall

The interfacial peel force between the casing and sidewall (Figure 21) exhibited a marked reduction when compared to the new tyre (Model 1); the majority of the reduction appears to occur in the first three to four years of a tyre’s life, although different tyre models may behave differently.

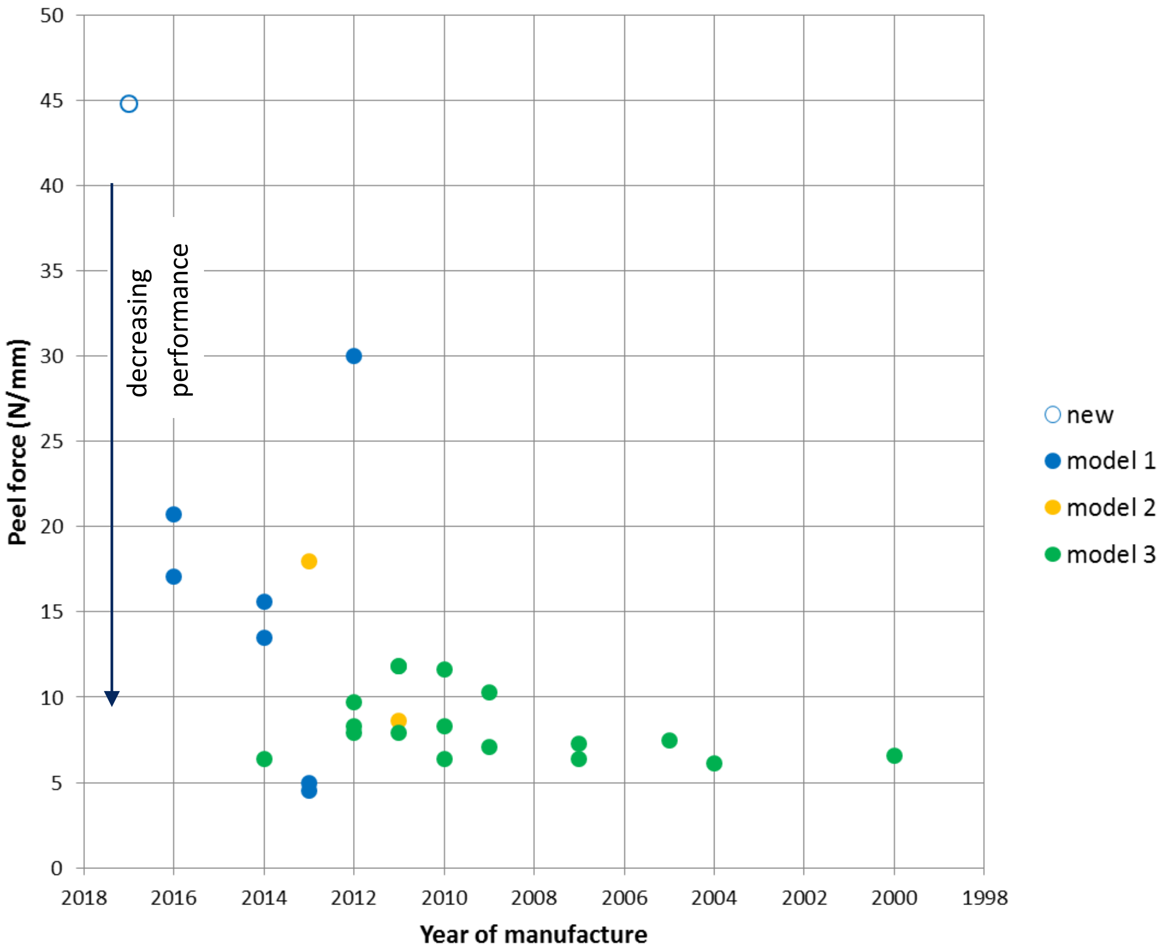

Figure 21: Interfacial peel force, casing to Sidewall

Belt 4 to tread

The interfacial peel force between belt 4 and the tread is shown in Figure 22. The data shows an apparent reduction in peel force between the belt 4 to tread interface, when compared to the new tyre. Used Model 3 tyres appear to have a higher peel force on average than Model 1 (possibly due to design differences), but there is no strong trend with age identifiable within the scatter.

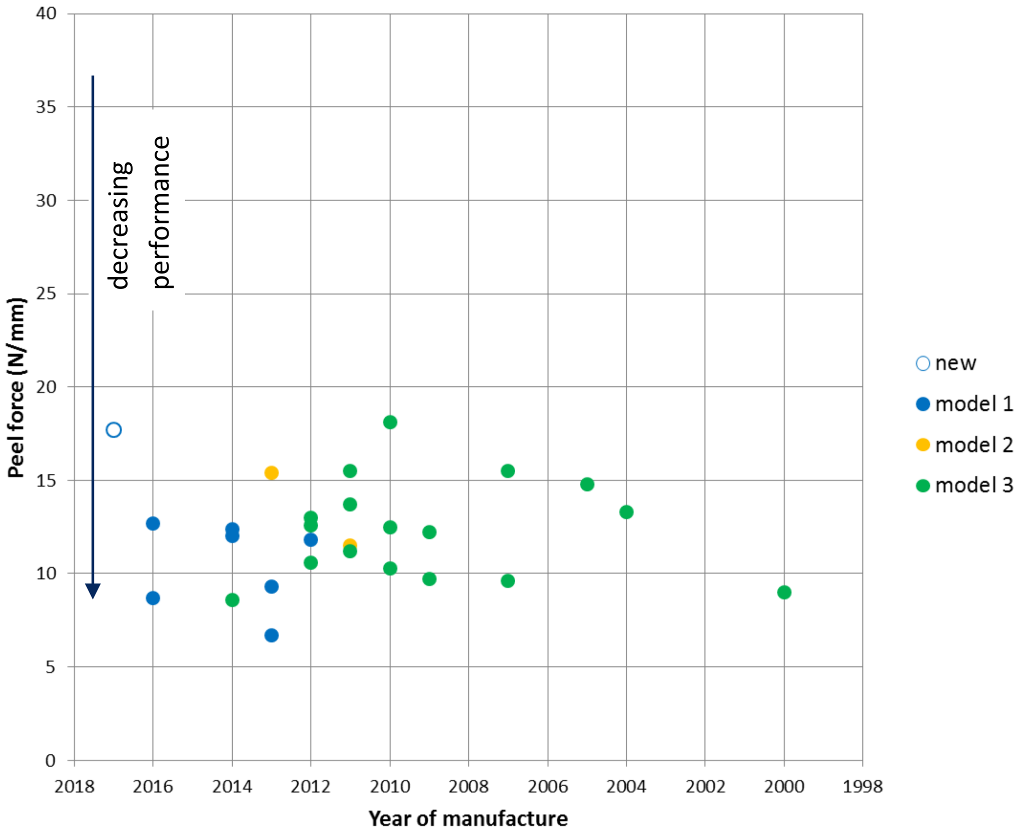

Figure 22: Interfacial peel force, belt 4 to tread

Summary

Peel strength is considered to be directly relevant to structural integrity. The peel strength represents the adhesion between the different layers used in the construction of a tyre, therefore lower or reduced peel strength may be a predictor of the likelihood of delamination of a tyre. The adhesion between layers of a tyre may be degraded by oxidisation of the rubber compounds, corrosion of the steel ply cords or other ageing effects. The tyre manufacturer may be expected to have a target peel strength for a particular tyre design, but this value is not publicly available.

The interfacial peel force results at the belt 3 to belt 4 interface and between the casing and sidewall may indicate changes in material properties within the first three to four years of tyre age. Beyond this time period the changes do not stop but continue at relatively flat or at a less marked rate. It is possible that any long-term trends are masked by the different tyre models.

Before opinion could be offered as to whether the initial data drop was a normal aspect of tyre life, further information is needed as to the behaviour expected by the tyre manufacturer. As already noted, design data may enable these observed changes to be compared with any critical limitations on peel force for each of the areas.

8.2.5 Physical properties of ply cords

The tyre ply cord tensile strengths were tested for all tyres, with results shown in Figure 23. No discernible trend was exhibited in these results.

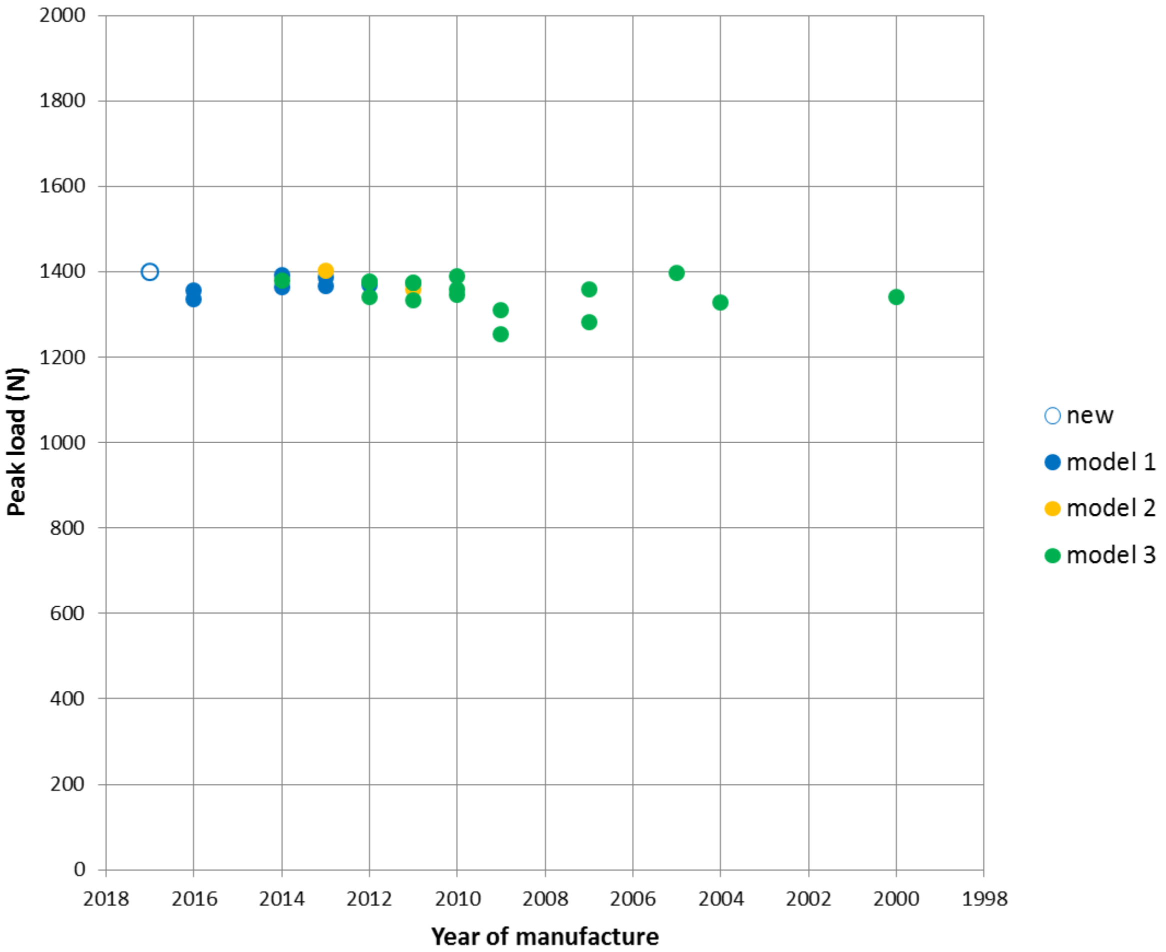

Figure 23: Ply cord tensile strength

8.2.6 Inner liner permeability

A number of authors whose work was surveyed for this research have quantified permeability and pressure loss and commented on the possibly undesirable effects of oxygen migration through a tyre, but none were found to have investigated the effect of age on permeability. Testing any direct effects of permeability on tyre integrity was outside the scope of this research.

No trend was identifiable in respect of permeability and tyre age or Model from the inner liner testing (see Figure 24) and the results showed a considerable scatter. Observations on the presence of corrosion in the tyres returned from service are provided in the following section.

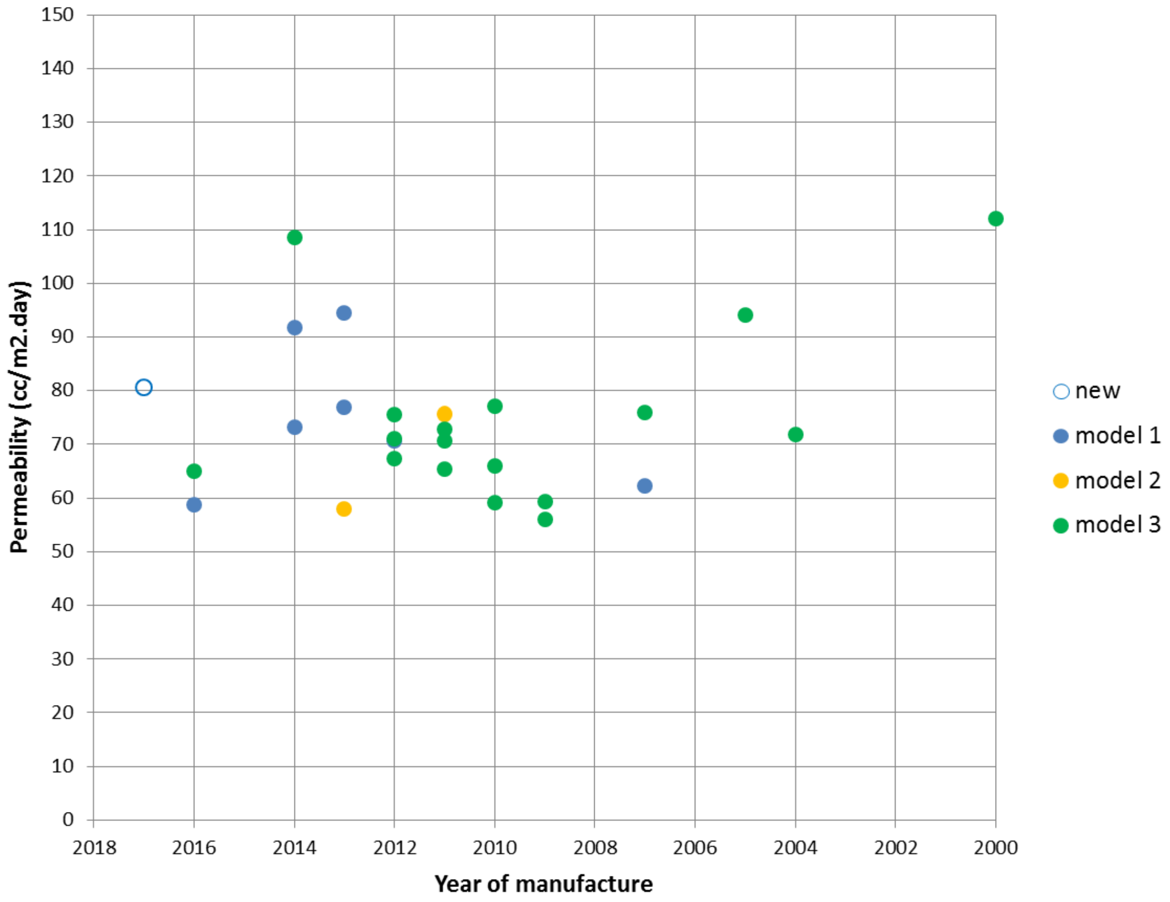

Figure 24: Liner permeability

8.2.7 Corrosion

Background to mechanism

Radial tyres are composite constructions of inner liner rubber, skim rubber, wedge rubber brass-coated steel belt cords and tread rubbers. For maximum long-term durability the brass-coated steel cords in radial tyres should have a high level of adhesion with the rubber to which they are bonded in the belt layers. The brass coating provides a degree of resistance to corrosion caused by water moisture ingress into the tyre from cuts and penetrations into the rubber and belts. The bonding between layers is controlled by the skim and wedge rubber, and this also is critical to the structural integrity of the tyre.

Corrosion

Corrosion, i.e. the rusting of the steel cords, can compromise the adhesion between the rubber and cords as well as, ultimately if severe, the steel cord strength itself.

Gardner and Queiser (2006) discuss cuts and punctures that are relatively small and which do not penetrate the tyre sufficiently to deflate the tyre. For such penetrations, they state, *"contact pressure between the tire and road can drive moisture and other contaminates further into the tread and belt structure - i.e. along the steel cords - causing corrosion and adhesion failure separation, ultimately failing in a manner such as tread/belt detachment"*.

If the liner remains intact, the majority of the moisture entering the tyre can only do so via cuts and damage in the tread region. Hence the uppermost belts are the first to be in contact with moisture, which can eventually permeate through to the other belt layers.

Oxygen permeation

Oxidative ageing of the skim and wedge rubber inside the tyre has been associated with a loss of elasticity and peel strength. These changes allow cracks to form inside the tyre at the edge of the steel belts, potentially resulting in delamination of the tyre, and these cracks grow more quickly in oxidised rubber (Baldwin and Bauer, 2008). However, as this research was conducted using light-duty tyres, findings may not necessarily carry over to the heavy duty tyres used in the current study.

As the tyre is pressurised when inflated, oxygen from the inflation gases can become dissolved in the rubber compounds of the tyre and then migrate through the structure of the carcass (Sivarao *et al.*, 2015).

As an example of the oxygen migration mechanism, Baldwin and Bauer refer in their review of 'Rubber Oxidation and Tire Aging' in the context of passenger car and light truck steel-ply radial tyres. The paper discusses that because of the higher oxygen pressure (of mounted tyres) being on the inside of tyres, most of the oxidation that occurs in the belt skim rubber is due to oxygen permeating through the inner liner from the inside cavity.

Whilst inner liner compounds are formulated, through the use of halogenated butyl rubber, to improve retention and minimise air permeation, the rate of permeation depends on the compound properties and thickness of the liner.

Of the described effects – that of the moisture likely arriving from an external perforation and that from the oxygen permeated from the ready supply of highly pressured inside gases – both are important when considering the mechanism by which steel belt corrosion may occur (see test results on inner liner permeability at 8.2.6). As noted above, research on light-duty tyres may not necessarily be applicable to heavy duty tyres.

Observed corrosion

During sectioning and peel adhesion testing it was revealed that a number of the tyre samples exhibited corrosion of the steel cords, as can be seen by way of example in Tyre 44 (a 12-year old tyre) belt 3, shown in Figure 25.

Figure 25: Tyre 44 belt 3 corrosion present

It is possible that the mechanisms described above provide the moisture and oxygen required for corrosion of the steel belts to take place. Possibly the combined effect of moisture ingress from penetrations into the tread area, together with the oxygen migration of the higher pressure inflation gases (relative to atmospheric pressure), permeation through the inner liner, into the tyre carcass, can result in the corrosion noted. However, other mechanisms may exist that provide moisture and oxygen to the belts, such as the introduction of oxygen from the atmosphere outside the tyre. The testing of service tyres carried out here has not explored which mechanisms dominate.

Of the 26 tyres returned from service, 16 exhibited corrosion of one or more of the steel belts, with the corrosion being most prevalent (but not exclusively) in belt 4, the uppermost belt in the tyre's structure. This is likely because the corrosion was observed during the peel force tests and each test (at a single belt layer) was performed with a sample cut from a different region of the tyre. With oxygen being available throughout the carcass of the tyre, the belt affected by corrosion would be expected to depend on the availability of moisture. Cuts or penetrations provide the means for moisture ingress to reach a belt in the tyre. Therefore, the individual belt affected is dependent on the depth of penetrations and shallower penetrations are generally more prevalent than deeper. It is also possible that the moisture has travelled along cords (known as 'wicking') and caused corrosion in belts at the lower levels, without penetrations having taken place directly above the corrosion.

Table 15 shows the observed corrosion by belt layer for all tyres for which corrosion was observed.

No tyres had corrosion observed at belt 1, one tyre had observed corrosion at belt 2, eight at belt 3 and 10 at belt 4. Seven of the tyres had corrosion at belt 4, but not at deeper layers. Interestingly, four tyres had corrosion observed at belt 3 and one at belt 2, with no corrosion observed at higher belt levels.

Table 15: Observed corrosion by belt layer

	Belt 1	Belt 2	Belt 3	Belt 4
Tyre 6	0	0	1	0
Tyre 7	0	1	0	0
Tyre 8	0	0	0	1
Tyre 14	0	0	0	1
Tyre 15	0	0	0	1
Tyre 16	0	0	0	1
Tyre 20	0	0	0	1
Tyre 22	0	0	0	1
Tyre 30	0	0	1	1
Tyre 35	0	0	1	0
Tyre 37	0	0	1	0
Tyre 39	0	0	0	1
Tyre 42	0	0	1	0
Tyre 43	0	0	1	0
Tyre 44	0	0	1	1
Tyre 47	0	0	1	1
Total	***0***	***1***	***8***	***10***

Although a small sample, it is clear from this data that corrosion was far more prevalent in the outer belts of the tyre than the inner belts, which supports the hypothesis that this corrosion is due to penetrations through the tread of the tyre and into the outer layers that were not deep enough to penetrate the lower layers or to puncture the tyre. The correlation between corrosion and tyre age, and between corrosion and the mechanical properties of the tyre, are evaluated in the following sections.

Effect of corrosion on peel force

The peel force between belt 4 and the tread is shown in Figure 26, with identification of those tyres observed as exhibiting corrosion.

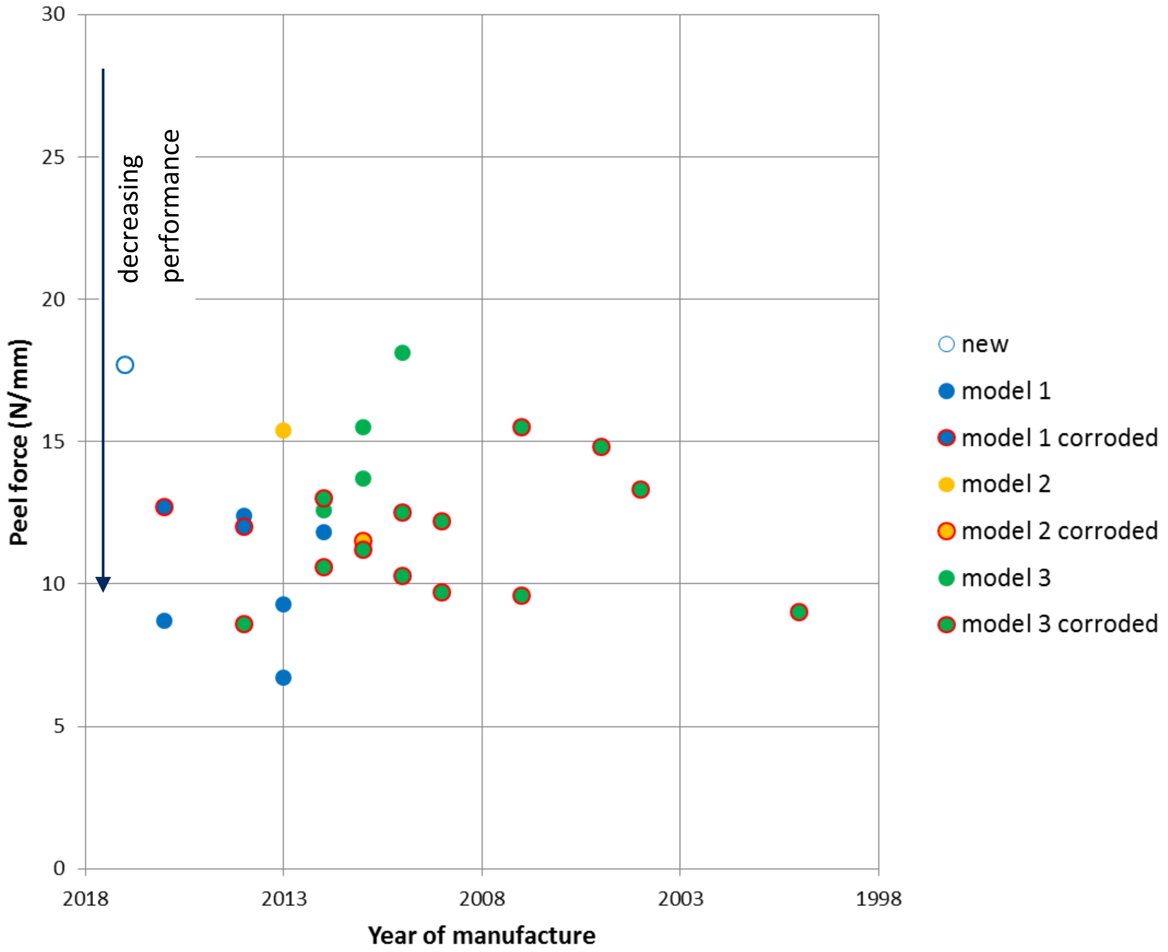

Figure 26: Peel force belt 4 to tread: with identification of those tyres observed with corrosion

The new control tyre understandably did not show any signs of corrosion; tyres in the first seven years of life showed a reasonably equal spread of those with or without corrosion, whereas **all** of the inspected tyres eight years or older displayed evidence of corrosion (Figure 26).

The presence of this corrosion would be expected to adversely affect the bond between the steel cords and the adhesive rubber compound with which they are coated. This is important to consider as loss of integrity at belt 4 can be associated with separation of the tread and deflation of the tyre. However, no trend was identified for a difference in peel force between those tyres in our sample with observed corrosion and those tyres without.

When considering the interfacial peel force between belt 3 to 4 the level of force is generally lower from that in belt 4 to the tread, though somewhat higher on the new tyre. Again with belt 3 to 4, there is no trend for tyres with corrosion observed to have a lower peel force than those without observed corrosion (Figure 27).

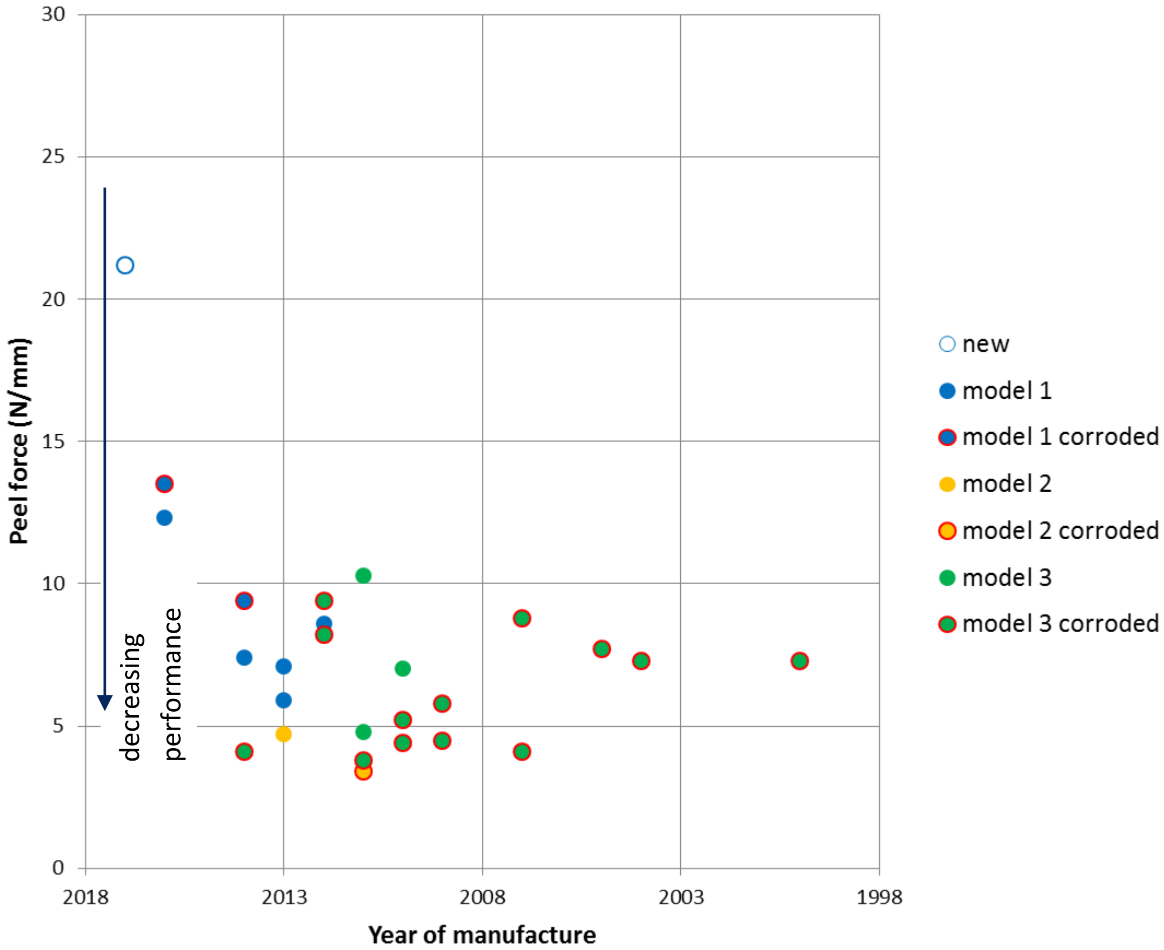

Figure 27: Interfacial peel force belt 3 to 4, with identification of those tyres observed to have corrosion

Effect of corrosion on ply cord strength

When considering the ply cord peak load data, the service tyres with or without corrosion are identified in Figure 28. Lower tensile strength would be worse for the strength of the tyre; corrosion will affect this and may contribute to additional fatigue damage over time, but no substantial difference in tensile strength can be observed between the corroded and non-corroded plies in Figure 28. Corrosion was not heavy enough to affect the strength of the cords themselves.

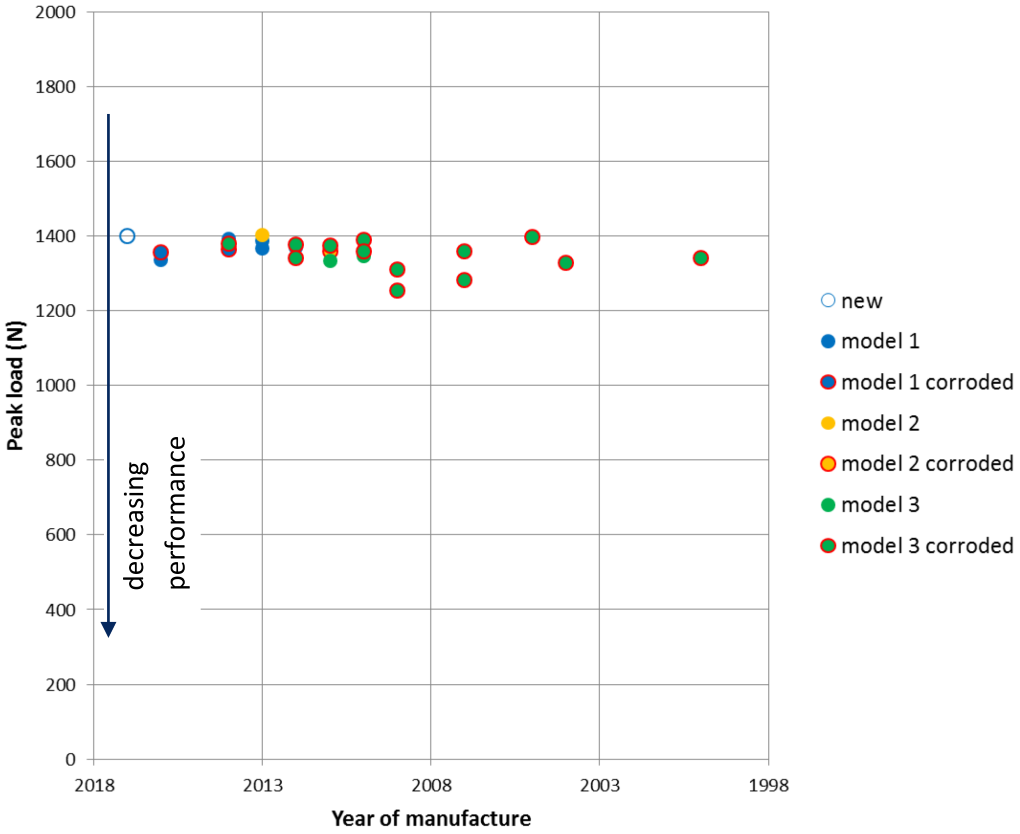

Figure 28: Ply cord peak load, with identification of those tyres observed to have corrosion

Further exploration of the observed corrosion was not carried out by Smithers Rapra and additional examinations would be required to quantify the areas of the tyre displaying such properties.

Summary

Sixteen of the 26 service tyres tested in this study showed corrosion of the steel cords, with corrosion more prevalent in the outer layers than the inner layers, which supports the hypothesis that this corrosion is due to penetrations through the tread of the tyre and into the outer layers that were not deep enough to penetrate the lower layers or to puncture the tyre.

Corrosion is considered to be relevant to the structural integrity of the tyre, although no obvious effect on peel strength or ply strength was observed in this test series. In this test series all tyres eight years old or older showed corrosion.

8.3 Comment on statistical validity

Given the limited number of tyres involved in this research compared to the number in use in the UK, statistically valid conclusions may not be made without an increased sample size; however, the study does provide data to suggest that some of the physical properties of a tyre may be affected by the service length and given the scatter observed, by the type of service seen by the individual tyre.

The in-service conditions such as under-inflation (to any degree), overloading and the heat history of each tyre during its lifetime were unknown, thus it was not possible to establish if the observed changes were a result of only service use, age alone, or a combination of both.

In the absence of data from the original tyre manufacturers as to critical limits designed into and specified for each of the tyres' inspected properties, comparison of the observed changes with any safety limit is not currently possible.

9 Conclusions

The key aim of this project was to develop an understanding of whether the material properties of commercial vehicle tyres evolve due to the passage of time to such an extent that the integrity of the tyre, and therefore its safety, is compromised.

Little relevant information was available, regarding the effects of ageing on commercial tyres, from the literature review; which revealed the majority of previously published testing in relation to ageing effects had been conducted on light goods and passenger car tyres, not heavy commercial vehicle, bus and truck radial tyres.

The tyres chosen for testing were from one manufacturer and originating from in-service use within the UK vehicle fleet. In accordance with the project specification the tyres were sized 295/80 R22.5, of first life (not re-treaded) and aged between 3 and 19 years.

Following acquisition of the first life tyres, each was inspected and the carcass evaluated to ensure that each tyre fell within the scope of the study and did not harbour pre-existing defects.

Thirty-one tyres were subjected to laboratory testing including new and new thermally/dynamically aged tyres intended as reference control points. A suite of assessments, measurements and laboratory tests were undertaken by Smithers Rapra Laboratories to assess the material properties and structural integrity of the selected tyres.

The data generated has provided indications as to trends in the observed changes in key physical properties of the tyre materials selected for inspection, although the number of tyres tested was not sufficient to provide statistically valid conclusions.

The testing provided some data to suggest that the physical properties of the tyre are affected by the length of time that the tyre is in service; for instance, reductions in interfacial peel forces at several interfaces within the tyre were noted, as well as ply cord peak breaking force, hardness of the belt skim compound and sidewall hardness. It was noted that the majority of the changes appear to occur in the first three to four years of the inspected service life. Beyond this time period the changes do not stop but continue at relatively flat or at a less marked rate. It is possible that any long-term trends are masked by the different tyre models returned from service. Tyres of a single model were not available over the full age range of the tyres tested, so three models had to be included to cover the desired range for the study. The consequence of this is a limitation on the comparisons which can be made between the new (control) tyre and the oldest tyres returned from service, which were a different model.

Interfacial peel forces are critical in preventing separation of the rubber compound from the steel belts within the tyre. However, whilst Smithers Rapra has knowledge of general limitations expected for peel testing, this research project did not have access to original manufacture design data to indicate the precise critical limitations on peel force, at each interface, relative to the structural integrity of the type of tyre being studied. The views of the tyre manufacturer were sought regarding the rate of change in the tyre properties during the first two to four years of use. They confirmed that this, together with the “plateau” over the longer term, was not unexpected. They were not able to comment on the peel test results as it is not a test they carry out themselves. They confirmed that the test conditions or parameters, the condition of the tyres examined, and their maintenance and use history would impact on the test results. Due to these variables they were not able to provide further comment on the results.

Examination of the peel adhesion test samples revealed that a number of the samples exhibited corrosion of the steel cords themselves. Of the 26 tyres returned from service, 16 exhibited corrosion of one or more of the steel belts, with the corrosion being most prevalent in belt 4, the uppermost belt in the tyre's structure. This evidence supports the hypothesis that this corrosion is due to penetrations through the tread of the tyre and into the outer layers that were not deep enough to penetrate the lower layers or to puncture the tyre, although on the data available does not definitively prove the relationship. The presence of this corrosion would be expected to adversely affect the bond between the steel cords and the adhesive rubber compound with which they are coated, although no obvious effect on peel strength or ply strength was observed in this test series. In this test series all tyres eight years old or older showed corrosion, which was present on around 60% of younger tyres when aggregating the peel test results

It was noted that with each of the physical properties studied there was some scatter in the data obtained from tyres returned from service. This most probably results from variation in the operating conditions experienced by each of the sample tyres, and the heat history of each of the tyres. Conditions that can deleteriously affect component properties are overloading, under or over-inflation, heat history from mechanical drag or any combination thereof.

As details of the service conditions experienced by each of the returned tyres were unknown, it was not possible to clearly determine whether the apparent changes observed resulted solely from chronological tyre age, service life use or a combination of these two factors.

Stakeholder engagements undertaken highlighted limitations in the service life data retrievable from tyre management companies and the fleet operators of the vehicles. It appears that once a tyre has become worn any data in relation to original fitment or removal dates, the driven mileage and/or chronological age of the tyre were not generally available.

Data were supplied from commercial tyre remanufacturers, based on their experience across the industry, of the prevalence of defects in tyres subject to the remanufacturing process, at all stages in that process.

Engagement with the remanufacturers has shown that reasons for rejection from the retreading process may be defined by a combination of the tyre brand, model, size and the factory or period of manufacture; these data may be incomplete as the inspection process would cease as soon as a tyre was rejected. With rejection, age (date of manufacture) data would generally not be recorded because it is no longer of use to the commercial process. There are a number of barriers and commercial sensitivities limiting the information that the remanufacturers are able to provide; however, the remanufacturers assume a conversion rate of about 52% with most rejections occurring as a part of the initial visual inspection, where screening removes tyres designed for a single life, without a corresponding mould available, with a stretched casing, over an age limit (seven to ten years depending on the remanufacturer) and with safety-related defects. It should be noted that exclusion from the retreading process cannot be interpreted as a judgement of a tyre's safety performance alone.

Members of the British Tyre Manufacturers Association (BTMA) have varying positions regarding the maximum age of casing they will accept for retreading, some members may have seven or eight years as a maximum but none more than 10 years; the date of manufacture being determined from the regulated tyre marking code on the tyre sidewall.

Nevertheless, some members of the industry (Continental/Uniroyal/Michelin) have published recommendations on the maximum age of a tyre in use mainly for commercial reasons, as do the BTMA in relation to retreading age limits.

Limitations

Given the limited number of tyres involved in this research compared to the number in use in the UK, statistically valid conclusions cannot be made without an increased sample size. However, the study does provide data to suggest that some of the physical properties of a tyre are affected by the service length, and given the scatter observed, by the type of physical service seen by the individual tyre.

The majority of the changes observed in the test program occurred in the first three to four years of service life; however, further data would be needed to compare those changes with the critical limits for each of the properties, as designed and specified, by the original tyre manufacturer. After this time, the data demonstrated smaller changes or no change discernible through the scatter and different tyre models.

The in-service conditions such as under-inflation (to any degree), overloading and the heat history of each tyre during its lifetime were unknown, thus it was not possible to establish whether the observed changes were a result of only service use, age alone, or a combination of both.

As identified in the limitations above, to improve statistical significance of the project and its findings the following recommendations are made:

- Testing of a substantially larger sample size would achieve a more representative database of physical properties
- Obtaining tyres for test which all originate from the same manufacturing facility, and which have the same design specification in order to reduce observed scatter
- Obtaining data to enable an understanding of the critical limits relevant to each tyre component's physical properties and in particular interfacial peel forces as specified by the tyre's manufacturer
- Conducting a controlled fleet service study in order to understand the impact of tyre service on tyres of the same manufacturer/age/construction. This could be achieved by placement of control tyres into a fleet and running a comprehensive fleet management process to track the service life of the individual tyres before removal and laboratory testing.

10 Observations in relation to tyre service life

1. A final cut-off age could be implemented where first life tyres should be removed from service, or at least used on non-steering axles and used as one of a pair.
   - This falls in line with the existing guidance issued by the DfT.
   - From discussions with the remanufacturers, a maximum first life service age of 10 years would be consistent with the industry approach.
   - There is advice, from those who place a figure on chronological age (Continental, Uniroyal and Michelin), that tyres 10 years or older should be fitted only on drive or tag/trailer axles.
   - As demonstrated, some of the material properties of commercial vehicle tyres vary with age, particularly in early years. However, the project has not identified any fundamental change or a threshold in material properties that would provide evidence either supporting or contradicting a final cut off age approach. Such a limit would be expected to capture not only material property changes, but also suboptimal in-service use, risks from localised damage and defects and other common reasons for rejection from remanufacture.
2. An earlier limit could be implemented to supplement the existing value in having tyres inspected during the Periodic Technical Inspection. For instance, tyres over the age of ‘X’ years (where ‘X’ is selected based on the bullet points below and associated evidence) could be listed as a Periodic Technical Inspection advisory item.
   - From existing guidance, published by commercial tyre manufacturers, there is advice that tyres which are in use for five years or more from their date of manufacture should continue to be inspected by a tyre specialist at least annually. A tyre dealer has been proposed in this context as the ‘tyre specialist’; however, further stakeholder engagement would be required to determine the expertise and training required beyond that for standard PTI inspectors.
   - Some members of the remanufacture industry have a maximum age limit of seven or eight years for carcasses entering the remanufacturing process. The remanufacturing industry has been clear that this limit is associated with the plentiful supply of carcasses and the opportunity to keep rejection rates low.
   - Of the 26 tyres returned from service and tested within this project, 16 exhibited corrosion of one or more of the steel belts, and all tyres eight years old or older showed corrosion.
   - The corrosion was most prevalent in belt 4, the uppermost belt in the tyre’s structure. This supports the hypothesis that this corrosion is due to penetrations through the tread of the tyre and into the outer layers. Though not established by this research, close inspection may be able to identify some penetrations.
   - Some component properties of a tyre, for example the interfacial adhesions, clearly evolve over time, with changes being observed from a new tyre to early-years service tyres. For each tyre, continued evolution depends upon the service and environmental conditions to which the tyre is subjected throughout its life.

Service related evolution varies widely so that accurately predicting in advance the serviceable life of any specific tyre is not thought possible.

- The testing results generated for this project show changes in some material properties within the first three to four years of tyre age; beyond this the changes do not stop but continue at a flat or low rate.
- Additional insight from tyre manufacturers would be needed to relate material property changes to a safety critical limit for risk of disablement.

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Tyre Ageing

The aim of this study was to develop an understanding of ageing effects on the material properties of commercial vehicle tyres and whether their structural integrity and therefore safety are compromised.

A review of published literature showed that most previous testing into ageing effects had been conducted on light goods and passenger car tyres, so the availability of relevant data on those used on heavy vehicles was limited.

Limitations were also found in service life data from tyre management companies and fleet operators. Fitment or removal dates, driven mileage and other service data were not generally available.

Thirty-one tyres were subjected to laboratory tests in order to assess their properties and structural integrity. Three models of tyre from one manufacturer were used, sourced from service use within the United Kingdom, and aged between 3 and 19 years. The sample contained 5 new tyres of the same make.

Test data indicated that some physical properties of the tyres had been affected by their length of time in service. The majority of the changes appeared to occur in the first three to four years of life, beyond which changes continued but at lower rates. Effects may have been masked somewhat by the use of different tyre models, and by differences in operating conditions.

Of the 26 tyres returned from service, 16 exhibited corrosion of their steel reinforcement cords; this was most prevalent in the outermost layers of the tyres. Corrosion was found in all tyres aged eight years or more. Although no effect on structural strength was measured, the small size of the sample allowed only for limited interpretation of this data.

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THE EFFECT OF AGEING ON TYRE MATERIAL PROPERTIES (DFT REFERENCE: P4102035)

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CONTENTS PAGE

GLOSSARY & NOTES

The following is a glossary of the terminology employed in this report, with each term defined within the context of use in this document:

Term	Definition
Bead	That edge of a tyre that sits on the wheel rim. This area of the tyre consists of a hoop of high tensile steel bead wire coated with rubber compound, and various supporting layers.
Belts/Breaker	The rubber coated layers of reinforcing cords positioned between the tyre's body plies and tread layer.
Brake Drag	Brake drag occurs when the vehicle's brake pads or shoes do not release completely after the brake pedal is released. This causes heat generation through frictional forces.
BSW	Black Sidewall, indicating that the sidewall compound is black in colour (as opposed to white) and contains carbon black reinforcing filler.
Carcass/Casing	The steel tyre cord layers of the tyre that supports the load applied in service, and which absorbs shock during driving.
Chunking	Removal of portions of the tread rubber by cutting or tearing.
Compound	A blend of rubber polymer(s), fillers, additives and curatives used to form a tyre, and to impart the required performance attributes.
Cord sockets	Areas around a tyre cord where the adhesive bond between the steel tyre cord and the rubber coating has been lost.
Crown	The centre portion of the tread area of the tyre.
Cut section	An incision made through the structure of a tyre in order to reveal its internal components.
DOT	A marking applied to one sidewall only. The marking contains information about the tyre, including basic characteristics, capacities and construction. It also displays the U.S. Department of Transportation (DOT) Tyre Identification Number used for safety standard certification and in case of a tyre recall.
Dynamometer	A laboratory device sometimes called a rolling road is a device upon which a tyre can be run at a chosen speed, with an applied load.
Hardness	A measure of the resistance of a rubber compound to indentation.
Heel	Part of the tyre bead design on the outside of the tyre.
Innerliner	A layer of rubber compound applied to the internal surface of a tyre casing in order to enable the tyre to retain inflation gases.
Inside perimeter	A bead to bead tyre dimension taken on the internal surface of the tyre.
Modulus	A measure of the stiffness of a rubber compound or tyre cord.
Outside perimeter	A bead to bead tyre dimension taken on the external surface of the tyre.

Ozone	A colourless unstable toxic gas with a pungent odour and powerful oxidising properties, consisting of three oxygen atoms chemically bonded together. When ozone impinges on an unprotected diene based rubber polymer, it causes a chemical reaction called ozonolysis resulting in cracking of the rubber compound.
Permeability	The state or quality of being permeable. In the context of this report this term is used to refer to the inner liner compound and its ability to retain the tyre's inflation gases
Ply/Body Ply	A tyre component comprising steel tyre cords coated with rubber compound to promote adhesion, which forms an integral structural component of the tyre. In a radial tyre the ply cords run radially from bead to bead.
Radial	A particular type of vehicle tyre where the ply cords run from bead to bead, and are positioned at 90° to the direction of travel.
Regrooving	The process of carving additional grooves in the tread rubber of a tyre in order to create additional tread depth.
Rubber Above Ply	The thickness of the rubber coating layer applied to the ply cords.
Serial Side	A unique number displayed on the sidewall of a tyre which identify production batches of tyres.
Shoulder	The portion of the tread located at each extremity of the tread area of the tyre.
Shoulder wedge	Rubber wedge shaped inserts positioned internally within the tyre structure in the shoulder area, at the belt edges. These components are utilised in order to ensure a smooth belt profile and to separate the body plies from the belt edges.
Sidewall	The vertically positioned side of a tyre consisting of number of component layers including rubber compounds and ply cords.
Skid depth	The depth of the tyre's tread pattern, sometimes called 'tread depth'.
Steel Tyre Cord	A cord reinforcing material used in the tyre, consisting of individual high tensile steel filaments twisted together to form a cord. Usually brass coated for the purposes of peel force to rubber.
Stencil	An identification mark applied to one sidewall of the tyre.
TBR	Truck and Bus Radial tyre.
Tensile Strength	A measure of the maximum tensile stress that can be applied to a rubber compound or a tyre cord before it breaks.
Toe	Part of the tyre bead design on the inside of the tyre.
Tread	The rubber portion of the tyre intended for contact with the road when driving.
Ultimate Elongation	The percentage increase in length that occurs before a rubber compound or tyre breaks under tension.

Note on tyre belt numbering: In this report the steel belts of each tyre are referred to by numbers from 1 to 4. In the context of this report belt 1 is that which is positioned closest to the tyre innerliner, belt 4 is that closest to the tread.

THE EFFECT OF AGEING ON TYRE MATERIAL PROPERTIES (DFT REFERENCE: P4102035)

1. INTRODUCTION

TRL has commissioned Smithers Rapra to support them in a tyre ageing study they are conducting on behalf of the United Kingdom Department for Transport (DfT). The tyre test programme has been designed to meet TRL's work package scope (DfT reference P4102035).

The aim of this study is to provide data in order to develop an understanding of whether the material properties of a certain type of vehicle tyre evolves as a result of the passage of time. The tyre size identified by TRL for the testing is 295/80R22.5. This particular Truck & Bus Radial (TBR) tyre size was selected as it has been established in UK vehicle fleets for many years. The tyre samples themselves were obtained by TRL. Test tyre selections were limited to first-life (TBR) tyres, 3 to 19 years in age, with new tyres utilised as comparative test samples. All test tyre samples were obtained in the UK.

In order to establish an understanding of the tyre material property changes that can occur with the passage of time, Smithers Rapra conducted a broad range of assessments and tests. The purpose of these tests was to quantify the material property retention of aged tyres. These tests were conducted on various key components of the tyres.

The proposed scope of work was developed with TRL in order to provide objective scientific data on the following:

- Influence of time (chronological age) on the physical properties and performance of the key components of the tyre carcass that are critical to mechanical integrity.
- Any changes in tyre innerliner permeability over time.
- The tracking of component material physical property changes that could influence the performance of the tyre in service over time.

As details of the service conditions experienced by each of the returned used tyres are unknown, it is not possible to determine whether the apparent changes observed result from tyre age, service or a combination of these two factors. Service conditions can include circumstances that can deleteriously affect tyre component properties:

- Over loading
- Under inflation
- Heat history (For example as a result of issues such as 'brake drag.')
- Any combination of the aforementioned

1.1 Tyre Samples

The following are the details of the 295/80R22.5 Load Range H medium radial truck tyres initially received from TRL and selected for the proposed programme of testing and analysis: (Table A)

Status	Assigned Tyre No.	Size	DOM	Tyre Model
New (2017) control	1	295/80R22.5	4117	1
New (2017) Thermally Aged Control	2	295/80R22.5	4117	1
New (2017) Thermally Aged Control	3	295/80R22.5	4117	1
New (2017) Thermally Aged + Dynamometer	4	295/80R22.5	4417	1
New (2017) Thermally Aged + Dynamometer	5	295/80R22.5	4417	1
2011	6	295/80R22.5	0911	2
2012	7	295/80R22.5	2312	3
2011	8	295/80R22.5	2511	3
2013	9	295/80R22.5	2313	2
2011	10	295/80R22.5	2911	3
2013	11	295/80R22.5	3113	1
2012	12	295/80R22.5	4212	1
2011	13	295/80R22.5	2711	3
2012	14	295/80R22.5	1812	3
2010	15	295/80R22.5	2710	3
2014	16	295/80R22.5	2514	3
2013	17	295/80R22.5	2313	2
2012	18	295/80R22.5	4012	3
2014	19	295/80R22.5	2414	1
2010	20	295/80R22.5	3610	3
2010	21	295/80R22.5	0910	3
2014	22	295/80R22.5	2114	1
2012	23	295/80R22.5	3312	3
2012	24	295/80R22.5	0312	3
2012	25	295/80R22.5	0712	3
2013	26	295/80R22.5	3113	1

Table A: Test tyre details.

The examination and selection of these tyres took place on 16th March 2018, and was conducted at Smithers Rapra's Shawbury UK facility by Mr G.S Crutchley, Lead Consultant, Smithers Rapra and Mr P. Balderstone, Vehicle Examination Consultant, TRL. The entire sample set of tyres from Tyre 1 to Tyre 26 were given the Smithers Rapra reference SR14032 for traceability.

Three tyres (Tyres 9, 23 and 25) were found to meet the criteria for testing but were not used due to the agreed quota being met with the other tyres. A further tyre (Tyre 24) was deemed not suitable for the study due to the presence of a penetration. All four of the above tyres were retained by Smithers Rapra.

Subsequent to the initial programme of work being undertaken, a further series of tyres was obtained in order to provide a wider range of tyre dates of manufacture, and therefore to yield further data via an additional programme of testing. The tyres obtained are shown in Table B below.

Please note: The numbers Tyre 27 to Tyre 29 were not allocated in this study.

Status	Assigned Tyre No.	Size	DOM	Tyre Model
2000	30	295/80R22.5	5000	3
2002	31	295/80R22.5	1302	3
1997	32	295/80R22.5	157	4
2007	33	295/80R22.5	3307	3
2007	34	295/80R22.5	3507	3
2009	35	295/80R22.5	1409	3
2005	36	295/80R22.5	2205	2
2004	37	295/80R22.5	4704	3
2007	38	295/80R22.5	1307	2
2009	39	295/80R22.5	0309	3
2008	40	295/80R22.5	4108	3
2015	41	295/80R22.5	4515	2
2016	42	295/80R22.5	2516	1
2007	43	295/80R22.5	1607	3
2007	44	295/80R22.5	2407	3
2004	45	295/80R22.5	2304	2
2016	46	295/80R22.5	0116	1
2005	47	295/80R22.5	2205	3

Table B: Additional tyres obtained for use in the study.

The examination of Tyres 30 to 45 took place on 8th November 2018, and was conducted at Smithers Rapra's Shawbury facility by Mr G.S Crutchley, Lead Consultant, Smithers Rapra and Mr P. Balderstone, Vehicle Examination Consultant, TRL. Tyre 46 was delivered at a later date and examined at Smithers Rapra's Shawbury facility by Mr G.S Crutchley and Mr P. Balderstone on 13th November 2018. Tyre 47 was examined at Smithers Rapra's Shawbury facility by Mr G.S Crutchley on 19th December 2019.

Two tyres (Tyres 38 & 41) were found to meet the criteria for testing but were not used. In addition to these, seven tyres (Tyres 31, 32, 33, 34, 36, 40 & 45) were rejected as they did not meet the criteria for selection for testing. Therefore, a total of nine tyres were submitted for testing.

The entire sample set of tyres from Tyre 30 to Tyre 47 were given the Smithers Rapra reference SR14154 for traceability.

2. TESTING AND ANALYSIS

2.1 Test Programme

The test methods utilised in this study are a combination of recognised international testing standards and Smithers Rapra's proprietary in-house test methods. The accelerated thermal ageing protocol has been developed from work undertaken on tyre ageing studies for the USA government, and therefore the test conditions employed are not specific for any particular geographic region.

The agreed scope of work is summarised in Table 1 below:

Test Program.	**Tested tyres**	**Test Location**
Initial non-destructive tyre examination, selection and photography.	31	Smithers Rapra, UK
8 Weeks thermal ageing at 65°C using an oxygen enriched inflation gas mixture.	4 – Tyres 2, 3, 4 & 5.	Smithers Rapra, USA
Tyre data collection.	31	Smithers Rapra, UK & USA
Shearography.	31	Smithers Rapra, USA
Dynamometer test.	2 – Tyres 4 & 5.	Smithers Rapra, USA
Sample excising.	31	Smithers Rapra, USA
Cut section measurements/examinations of 2 sections per tyre.	31	Smithers Rapra, USA

Physical properties of 5 areas/components of the tyre.	31	Smithers Rapra, USA
Residual ozone resistance tread and sidewall.	31	Smithers Rapra, USA
Peel force tests 5 tyre interfaces at room temperature and 2 at elevated temperature.	31	Smithers Rapra, USA
Physical properties of ply cords.	31	Smithers Rapra, USA
Innerliner air permeability.	31	Smithers Rapra, UK
Data analysis.	31	Smithers Rapra, UK & USA
Reporting.	31	Smithers Rapra, UK

Table 1: Scope of work.

The purpose of each test is summarised in Table 2 below:

Test:
Tyre Data Collection Sidewall data from each of the test tyres was collected and recorded for reference.
Non-destructive Examination The condition of all tyres was recorded prior to testing. This examination recorded the general condition of each tyre, and any damage observed. Any important features were recorded photographically using high resolution digital images. Evidence of significant under-inflation or repairs were recorded, if observed.
8 Weeks Oven Aging, Oxygen Enriched Atmosphere. Four new unused tyres were thermally aged, with inflation gasses replaced at regular intervals. This controlled thermal ageing process provides a set of control data (in addition to that obtained from the new tyre samples). This data is intended to provide information which is valuable in determining the importance of differences observed between the physical properties of the new tyre controls, and those tyres returned from service.
Dynamometer Tyres 4 and 5 were also subjected to the same thermal ageing regime, but after ageing were subjected to dynamometer tyre excising (in general accordance with FMVSS 119) for 47hrs at 225r/m prior to further testing being undertaken. This additional test was conducted in order to determine the effect of dynamic inputs on the aged properties of the tyre's materials.
Shearography Each of the tyres was subjected to shearography. This non-destructive test was used for comparison of the tyres, and to identify the presence of any internal damage not visible externally.

Sample Excising
Test samples appropriate for each of the proposed tests were extracted from the components of each of the test tyres.
Cut Section Measurements/Examinations Cut sections were prepared from each of the tyres, and dimensional measurements recorded in order to indicate any important changes associated with tyre age.
Physical Properties Of Five (5) Rubber Compound Areas Of The Tyre Components from 5 rubber compound areas of each tyre were subjected to physical property determination. These included tread, sidewall and innerliner compounds and two further compounds selected from the working steel belts. The specific tests included tensile properties (strength, modulus and elongation) and hardness.
Residual Ozone Resistance Tread and Sidewall Compounds The resistance of the tread and sidewall compounds to attack by atmospheric ozone, and changes in performance due to ageing was assessed.
Interfacial Peel Force The interfacial peel force levels at key material interfaces within each tyre were measured, to allow new, thermally aged, thermally/dynamically aged and service returned tyres to be compared directly. A total of five (5) interfacial peel force tests were conducted at room temperature, and two (2) interfaces tested under elevated temperature test conditions.
Physical Properties of Ply Cords The key physical properties of each tyre's steel ply cords were determined for comparison.
Innerliner Permeability Samples of the innerliner compound (air retention) layer of each tyre were subjected test in order to determine whether there were any changes due to ageing.

Table 2: Test purposes.

3. TEST METHODOLOGY

3.1 Initial Non-destructive Tyre Examination, Selection and Photography.

In order to facilitate the proposed programme of testing, Smithers Rapra received a total of 49 tyres from TRL. These consisted of 5 new tyres and 44 used tyres returned from service which had been pre-selected by TRL as potential candidate test samples.

As stated in Section 1.1, the used tyre selections were made at Smithers Rapra's Shawbury facility by Mr G.S Crutchley, Lead Consultant, Smithers Rapra and Mr P Balderstone, Vehicle Examination Consultant, TRL. In order to make the selections, the used tyres were subjected to a detailed visual examination, with their general condition and any physical damage being recorded photographically using high resolution digital images. Each used tyre was specifically examined to determine if it exhibited evidence of significant physical damage, under-inflation, penetrations or repairs. Any tyres that were observed to exhibit evidence of this nature were rejected from the study. Once the required number of test tyre selections were made, the remaining used tyres were not examined, but were retained by Smithers Rapra.

From the full set of used tyres received, a total of 26 were selected for testing in order to provide a total of 31 tyres for test, including the new and thermally/dynamically aged tyres used as controls. The condition of all of the selected tyres was then categorised prior to testing commencing.

The observations made and a selection of the digital images recorded during this initial examination are included in Appendix 1 of this report.

3.2 Tyre Analysis

The following are the recognised test methods relating to the programme of analysis described in Table 2:

Rubber Compound Tensile Properties: (Tensile Strength, Modulus, Elongation): ASTM D412.

Rubber Compound Hardness: ASTM D2240.

Residual Ozone Resistance: ASTM D1149. (Please note that this test method specifically relates to unaged rubber compound and not tyres. Therefore, the tests described in this report were conducted in general accordance with the standard, but the results should be considered comparative only.)

Interfacial Peel Force Tests: ASTM D413 (elevated temperature peel force samples were heated at 100°C for 1hr prior to testing.)

Ply Cord Tensile Properties: In general accordance with ASTM D2969. (However, the steel tyre cords were coated with rubber as they had been extracted from the test tyres prior to testing.)

Dynamometer Test: In accordance with FMVSS 119.

Each of the selected test tyres were subjected to the following testing:

- Shearography.
- Cut section measurements.
- Cut section examinations.
- Tensile and hardness properties.
- Residual ozone resistance.
- Room temperature interfacial peel force.
- Elevated temperature interfacial peel force.
- Physical properties of ply cords.

Note: Tyres 2, and 3 (Table A, Tyre Assigned No.) were subjected to thermal ageing in an oven for 56 days at 65°C. Prior to the heat ageing programme commencing, these tyres were inflated with an oxygen enriched air inflation (50/50 oxygen/nitrogen mix) gas mixture.

Tyres 4 and 5 were also subjected to the same thermal ageing regime, but after ageing were subjected to dynamometer tyre excising (in general accordance with FMVSS 119) for 47hrs at 225r/m prior to further testing being undertaken. This additional test was conducted in order to demonstrate the effect of dynamic inputs on the aged properties of the tyre's materials.

Innerliner Permeability (Oxygen Gas Transmission Rate): The liner permeability test was conducted in accordance with ASTM F1927-14, using Oxtran 2/21 test apparatus with computer control. This test measures the oxygen gas transmission rate through the liner samples. Test conditions were 23 ± 2°C, 50 ± 5% Relative Humidity (RH).

4. RESULTS – EXAMINATION, SHEAROGRAPHY & SECTIONING

It should be noted that the number of tyres chosen for the study is small relative to the total number of tyres of this size in use in the UK vehicle fleet. In addition, it has been noted that with each of the physical properties studied there was significant scatter in the data obtained from tyres returned from service. This prevents the correlation of a particular physical property with tyre age. This scatter most probably results from variation in the operating conditions experienced by each of the sample tyres, and the heat history of each of the tyres. Accurate correlations are not possible since no details of the service history of the returned tyres was available. In addition, as noted in Section 4.3 there are also tyre design differences present in the sample set which may affect the results.

4.1 Initial Non-Destructive Tyre Examination.

The results of the examination of each of the test tyres are presented in Appendix 1 of this report.

A total of 49 tyres were sourced by TRL for this study. These included five new/unused tyres selected as control tyre samples, and 44 tyres returned from service. The tyres were given an initial examination in order to record their general condition as received, and to make test tyre selections.

From the 44 tyres returned from service, five tyres (Tyres 24, 33, 36, 40 and 45) were rejected due to the presence of penetrations. Tyre 31 was rejected as it exhibited heat damage to the sidewall. Tyre 32 was rejected as it exhibited hydrocarbon oil damage and liner cracks. Tyre 34 was rejected as it had a load and speed index that was different to the other tyres in the study.

From the remaining tyres from service the number required for testing were selected at random, therefore tyres 9, 23, 25, 38 and 41 were not submitted, but were retained by Smithers Rapra.

The examination showed that of the total of 26 tyres returned from service and selected for the study,17 tyres (65%) had been subjected to regrooving.

With regards to the examination of the tyres returned from service, a range of damage types were observed and recorded. Remaining tread depths were in the range 0.71 to 9.45 mm, therefore all tyres showed signs of tread wear. The majority of the tyres showed cuts to the tread, and a number of the tyres showed evidence of tread chunking. The image shown below is of the tread region of Tyre 6, showing the type of tread damage typically observed in this study.

Image 1: Tyre 6 - tread damage. Note that this tyre has been regrooved.

The examination of the liner of each tyre confirmed that none of the tyres exhibited any obvious evidence of significant under-inflation. However, the possibility that any particular tyre has been run underinflated at some point during its service life cannot be entirely discounted.

Additionally, it should be noted that the examination was not able to establish the heat history of each of the tyres returned from service. This service history related factor remains unknown, but it should be noted that variations in heat history affect the results of the physical property tests and the validity of any conclusions. However, it is not possible to quantify this effect through the findings of this study.

4.2 Shearography

Each of the test tyres was subjected to a non-destructive examination using the technique of shearography. During the testing process, the tyre is subjected to a low pressure differential inside a vacuum chamber. This induces deformations in the tyre carcass and causes any internal detachments to become evident. Laser holography is then used to detect and view the detachments.

The shearography technique can be used in the tyre retreading industry in order to inspect and select tyre casings prior to retreading. It is useful for identifying internal detachments which cannot be seen externally, and therefore which may otherwise remain undetected.

The results of the shearography test are presented in Appendix 2 of this report, and the results are summarised in Tables 3 and 4 below:

As stated above, all of the test tyres were examined using the technique of shearography, in order to investigate whether any of the tyres contained internal detachments or other features of interest. The results are reported in Tables 3 and 4 of Section 4.2 of this report.

Of these tyres a total of eleven (11) did show such features in the sidewall, these were tyres 2, 5, 6, 8, 15, 18, 20, 26, 44, 46 and 47. It should be noted that tyre 2 does contain small anomalies in the mid/upper sidewall on the serial code side. This tyre was a new tyre.

Tyre 5 also showed anomalies, this was one of two tyres that were thermally aged and subjected to dynamometer test. It is not possible to conclude whether these were present in the new tyre, or if they developed as a result of a dynamometer test.

The other dynamometer tyre, which was tyre 4, did not show any such anomalies.

A total of nine (9) tyres showed features in the tread area, these being tyres 6, 20, 30, 35, 37, 39, 42, 44 and 47.

Status	Assigned Tire No.	DOM	Sidewall Anomalies?	Serial Sidewall Anomaly Description(s)	Sidewall Anomalies?	Opposite Sidewall Anomaly Description(s)	Tread Area Anomalies?	Tread Area Anomaly Description(s)
New Unaged	1	4117	no	NA	no	NA	no	NA
New Oven-Aged	2	4117	yes	Small anomolies present at 0° in mid/upper sidewall	no	NA	no	NA
New Oven-Aged	3	4117	no	NA	no	NA	no	NA
Dynamometer	4	4417	no	NA	no	NA	no	NA
Dynamometer	5	4417	yes	upper/mid sidewall (Scan #1 Sector #1 and #9)	yes	One (1) moderate size localized anomoly at 130° (Scan #3 Sector #4) upper sidewall	no	NA
2011	6	911	no	NA	yes	One (1) moderate size localized anomaly at 160° (Scan #3 Sector #5) upper sidewall	yes	or near belt edges (Scan 2 Sectors #1/#2, #5, #6, #7)
2012	7	2312	no	NA	no	NA	no	NA
2011	8	2511	yes	turn-up/chafer location (Scan 1 all sectors)	no	NA	no	NA
2011	10	2911	no	NA	no	NA	no	NA
2013	11	3113	no	NA	no	NA	no	NA
2012	12	4212	no	NA	no	NA	no	NA
2011	13	2711	no	NA	no	NA	no	NA
2012	14	1812	no	NA	no	NA	no	NA
2010	15	2710	no	NA	yes	#3 Sector #1) upper sidewall Intermittent circumferential line of small	no	NA
2014	16	2514	no	NA	no	NA	no	NA
2013	17	2313	no	NA	no	NA	no	NA
2012	18	4012	yes	One (1) small localized anomaly at 0° (Scan #1 Sector #1) upper sidewall	no	NA	no	NA
2014	19	2414	no	NA	no	NA	no	NA
2010	20	3610	yes	One (1) damage-area anomaly at 220-230° (Scan #1 Sector #7) upper sidewall	yes	Three (3) adjacent minor, localized anomalies at 110° (Scan #3 Sector #4) upper sidewall. Circumferential line of bead heel area anomalies (Scan #3 Sectors #3-8)	yes	One (1) small localized anomaly at 20° (Scan 2 Sector #1/#2)
2010	21	910	no	NA	no	NA	no	NA
2014	22	2114	no	NA	no	NA	no	NA
2013	26	3113	no	NA	yes	One (1) small localized anomaly at 100° (Scan #3 Sector #4) lower/mid sidewall	no	NA

Table 3: Shearography results summary.

Production Year	Assigned Tire No.	DOT	Sidewall Anomalies?	Serial Sidewall Anomaly Description(s)	Sidewall Anomalies?	Opposite Sidewall Anomaly Description(s)	Tread Area Anomalies?	Tread Area Anomaly Description(s)
2000	30	5000	no	NA	no	NA	yes	Moderate anomalies at or near belt edges at 40° (Scan 2 Sector 2), 210° (Scan 2 Sector 6), and 260°-280° (Scan 2 Sector 8),
2009	35	1409	no	NA	no	NA	yes	(1) at 50° (Scan 2 Sector 2), two (2) at 90° (Scan 2 Sector 3); one (1) at 180° (Scan 2 Sector 5); multiple
2004	37	4704	no	NA	no	NA	yes	Two (2) minor localized anomalies at or near belt edges: one (1) at 75° (Scan 2 Sector 3); one (1) at 115° (Scan 2 Sector 4)
2009	39	309	no	NA	no	NA	yes	Minor localized anomalies at or near belt edges: one (1) at 0° (Scan 2 Sector 1), one (1) at 115° (Scan 2 Sector 4), one (1) at 160° (Scan2 Sector 5), one (1) at 245° (Scan 2 Sector 7) and one (1) at 285° (Scan 2 Sector 8).
2016	42	2516	no	NA	no	NA	yes	Minor localized anomaly at or near belt edges: one (1) at 110° (Scan 2 Sector 4)
2007	43	1607	no	NA	no	NA	no	NA
2007	44	2407	no	NA	yes	One (1) small localized anomaly in upper sidewall at 10° (Scan 3 Sector 1); one (1) moderate circumferential anomaly in upper sidewall 85° to 100° (Scan 3 Sector 3).	yes	Small localized anomalies at or near belt edges: one (1) at 20° (Scan 2 Sector 2); one (1) at 60° (Scan 2 Sector 2); one (1) at 120° (Scan 2 Sector 4); one (1) at 340° (Scan 2 Sector 9)
2016	46	116	yes	Minor upper sidewall anomalies at 0° (Scan1 Sector 1), 50° (Scan 1 Sector 20), 260° (Scan 1 Sector 8), and 310° (Scan 1	no	NA	no	NA
2005	47	2205	no	NA	yes	One (1) minor localized anomaly in upper sidewall at 70° (Scan 3 Sector 3); one (1) moderate circumferential anomaly in upper	yes	Small localized anomalies at or near belt edges: one (1) at 20° (Scan 2 Sector 2); and one (1) at 110° (Scan 2 Sector 4)

Table 4: Shearography results summary (cont.)

4.3 Cut Section Measurements

All tyres were subjected to sectioning and the subsequent recording of key component dimensions. Two sections were cut from each tyre 180° apart, tyre component measurements made, and the average result recorded. Tables 5 to 8 below summarise the results obtained.

The purpose of making cut section measurements was to determine whether in any of the tyres there are any structural or design related factors present which might affect the analysis results in respect of tyre ageing. Evidence of tread abrasion was observed, which can be attributed to tyre age and service. However, all of the other differences observed were related to the design of the tyres. The following comments are appropriate.

Belt 4 dimensions – Differences were observed in the dimensions of this particular belt. These differences could affect the way in which the tyres perform relative to each other, and could therefore have an impact on the way in which they individually aged in service. In addition, it was noted that there was variation amongst the DOT codes of the sample tyres, this may indicate differences in tyre manufacturing plant or tyre design.

Belt 1 – Some of the sample tyres have split belts, whilst others have continuous width belts. This represents a difference in tyre design, and as indicated above it could affect the way in which individual tyres perform relative to each other.

Outside Perimeter – The differences observed in these measurements are related to abrasion of the tread compound during service.

Tread/Crown Thicknesses – Again the differences observed are related to abrasion of the tread compound during service.

BSW (Sidewall) Gauge – There were differences noted in sidewall gauge. During the initial visual examination, it was noted that none of the tyres appeared to show significant sidewall abrasion. Therefore, it is concluded that the differences observed are likely to result from differences in tyre design and not tyre service.

General comments – The differences noted in the cut section measurements indicate that there is some variation in design/specification in the sample set of tyres analysed. Examination of the DOT codes for each of the tyres shows that there are a total of six (6) different manufacturing plant codes present in the sample set. Hence this information confirms the conclusion from the cut section measurements, that within the sample set there are a number of tyre design/specification variations. These could affect the way in which the individual tyres aged in service, and therefore would likewise have an effect on the tyre material physical properties measured.

It should also be noted that whilst some differences in components/component dimensions have been noted, it is also possible that there may be differences in the rubber compounds in the tyre. Such differences may be related to formulation or processing of the rubber compounds, and these could also affect the way in which the tyres age in service.

Status	TRL-Assigned Tyre No.	Outside Perimeter Heel to Heel	Inside Perimeter Toe To Toe	Toe to Heel	Non-Skid Depth	Belt 1 Split SS	Belt 1 Split NS	Belt 1 Combined width	Belt 2 Width	Belt 3 Width	Belt 4 width	Bead Construction
New Unaged	1	714	686	32.2	16.1	65	62	180	219	196	96	5 Turns 8 Wires
New Oven-Aged	2	728	680	33.92	15.51	62	64	179	217	197	96	5 Turns 8 Wires
New Oven-Aged	3	730	682	33.14	15.48	62	64	179	218	197	97	5 Turns 8 Wires
Dynamometer	4	727	685	33.32	15.52	67	63	178	221	199	97	5 Turns 8 Wires
Dynamometer	5	724	684	33.22	15.54	64	63	179	221	199	96	5 Turns 8 Wires
2011	6	687	692	27.7	4.6	56	56	175	211	188	95	5 Turns 8 Wires
2012	7	688	684	32.4	4.7	57	55	177	210	189	95	5 Turns 8 Wires
2011	8	704	685	32.3	5.5	N/A-No Split	N/A-No Split	183	214	188	96	5 Turns 8 Wires
2011	10	701	687	32.8	5.3	N/A-No Split	N/A-No Split	129	217	189	96	5 Turns 8 Wires
2013	11	711	684	33	3.4	59	60	179	217	198	97	5 Turns 8 Wires
2012	12	695	687	31.9	8.3	56	60	178	221	196	95	5 Turns 8 Wires
2011	13	702	689	32	7	N/A-No Split	N/A-No Split	185	215	188	95	5 Turns 8 Wires
2012	14	704	686	32.1	6.5	60	60	180	210	189	94	5 Turns 8 Wires
2010	15	704	692	32.8	6.1	57	58	179	212	189	95	5 Turns 8 Wires
2014	16	701	689	34.7	5.5	N/A-No Split	N/A-No Split	179	212	189	154	5 Turns 8 Wires
2013	17	680	691	31.2	3.1	59	60	179	214	192	97	5 Turns 8 Wires
2012	18	702	685	32.5	3.8	59	58	179	213	191	157	5 Turns 8 Wires
2014	19	716	687	33.9	4.6	61	54	176	219	197	95	5 Turns 8 Wires
2010	20	701	687	32.5	6.8	N/A-No Split	N/A-No Split	182	212	189	95	5 Turns 8 Wires
2010	21	704	689	33.5	7.9	62	59	177	212	189	94	5 Turns 8 Wires
2014	22	721	681	32.1	5	58	56	188	222	199	95	5 Turns 8 Wires
2013	26	703	683	31.9	4.8	58	58	175	215	196	95	5 Turns 8 Wires

Table 5: Cut section measurements (all measurements are in mm).

Status	TRL-Assigned Tyre No.	Outside Perimeter Heel to Heel	Inside Perimeter Toe To Toe	Toe to Heel	Non-Skid Depth	Belt 1 Split SS	Belt 1 Split NS	Belt 1 Combined width	Belt 2 Width	Belt 3 Width	Belt 4 width	Bead Construction
2000	30	709	683	33.66	5.65	63	56	178	212	186	155	6 Turns 8 Wires
2009	35	701	689	32.02	5.86	56	63	179	210	188	99	5 Turns 8 Wires
2004	37	697	688	33.77	7.99	63	71	187	211	193	98	6 Turns 8 Wires
2009	39	694	685	32.96	4.68	66	63	185	211	186	97	6 Turns 8 Wires
2016	42	706	683	32.08	7.69	64	65	178	218	198	95	5 Turns 8 Wires
2007	43	709	684	33.57	8.26	60	58	181	209	189	97	6 Turns 8 Wires
2007	44	699	688	33.97	3.77	64	63	183	212	188	98	6 Turns 8 Wires
2016	46	704	685	34.23	3.05	65	65	185	221	197	95	5 Turns 8 Wires
2005	47	706	681	33.73	5.59	56	56	177	207	193	156	6 Turns 8 Wires

Table 6: Cut section measurements cont. (all measurements are in mm).

Status	TRL-Assigned Tyre No.	Innerliner Gauge	Gum Under Ply Gauge	Body Ply Gauge	Rubber Above Ply	Belt/ Breaker Gauge	Tread Thickness	Total Crown Thickness	Total Shoulder Thickness	Shoulder Tread Rubber Thickness	BSW Gauge
New Unaged	1	2	1.5	1	2.5	7.4	20.7	35	44.5	26.5	10
New Oven-Aged	2	2.3	1.6	1	2.8	7.3	20.3	35	44.1	26.5	9.8
New Oven-Aged	3	2	1.6	1.1	2.6	7.9	20	35.1	43.8	26.3	9.8
Dynamometer	4	2	1.8	1	2.4	7.6	20.5	35.1	42.4	26.1	8.6
Dynamometer	5	2	1.9	0.6	2.6	7.3	20.7	35.1	42.9	26.2	8.6
2011	6	2.1	1.5	0.9	2.7	7.6	6.6	21.2	25.8	10.1	8
2012	7	2.7	1.5	0.8	2.2	8.6	11	26.7	31.3	17.5	8.6
2011	8	2.6	1.6	0.9	1.1	10	9.2	25.3	35.6	20.4	8.5
2011	10	2.9	1.5	0.9	1.6	10.3	9	26	33	18.1	8
2013	11	2	1.6	0.8	2.7	8.1	7.8	22.9	31.6	16.1	8.7
2012	12	1.8	1.4	0.9	2.1	8.5	6.6	21.2	32.4	17.5	9
2011	13	2.3	1.1	0.7	1.4	10.1	12.9	28.3	31	17.7	8.1
2012	14	2.3	1.2	1	2.1	9	10.9	26.4	35.2	20.3	8.3
2010	15	2	1.5	0.7	2.4	8.4	11.1	26	34.3	20.1	8.2
2014	16	2	1.9	1	1	9.2	6.8	21.9	35.2	20.4	9.1
2013	17	2	1.5	1.1	2.6	7.5	6.6	21.2	25.4	9	8.2
2012	18	2	1.7	1.1	2	8	10.8	25.4	32.2	17.8	9.5
2014	19	2.2	1	0.9	2.4	8.9	4.4	19.7	39.8	23.7	9.5
2010	20	2.1	1.4	1.2	0.9	9.6	8.4	14.7	31.6	17.6	7.9
2010	21	2	1.3	1.2	2.2	9.3	12	27.9	36.9	22.9	8
2014	22	2.1	1.7	0.8	2.7	8.1	6.1	21.3	38.6	21.6	9
2013	26	2.1	1.6	0.9	2.3	8.5	5.1	20.4	37	20.7	8.8

Table 7: Cut section measurements cont. (all measurements are in mm).

Production Year	TRL-Assigned Tyre No.	Innerliner Gauge	Gum Under Ply Gauge	Body Ply Gauge	Rubber Above Ply	Belt/ Breaker Gauge	Tread Thickness	Total Crown Thickness	Total Shoulder Thickness	Shoulder Tread Rubber Thickness	BSW Gauge
2000	30	2.1	1.9	1.1	2.6	8.2	10.0	25.7	35.6	21.6	8.4
2009	35	2.1	1.9	1.0	2.3	8.3	8.2	23.7	31.0	17.0	6.1
2004	37	2.0	1.6	1.0	2.2	7.8	7.1	22.2	34.6	19.4	8.1
2009	39	2.7	1.6	1.0	2.5	8.2	5.0	20.9	28.2	14.1	6.7
2016	42	2.0	1.8	0.8	2.6	7.6	8.3	23.0	31.9	17.3	8.9
2007	43	2.1	1.5	0.8	2.8	8.0	14.6	29.7	35.4	19.9	7.7
2007	44	2.0	1.3	0.9	2.4	8.5	6.1	21.0	28.5	15.2	8.0
2016	46	2.1	1.5	1.1	2.7	8.0	8.6	23.8	30.7	16.0	9.0
2005	47	2.0	1.6	0.7	2.2	7.8	8.6	22.9	37.3	20.1	9.5

Table 8: Cut section measurements cont. (all measurements are in mm).

4.4 Cut Section Examinations

Subsequent to the removal of sections from each of the tyres, the visible steel belt package of each tyre was examined. All important features were recorded, with the results being presented in Tables 9 and 10 below.

Examination of the sections removed from the tyres showed that a total of nineteen (19) tyres had anomalies associated with the steel belt package. All of the anomalies were found in the tyres returned from service, there were no anomalies of note in any of the new or new/thermally aged tyres. The anomalies observed are recorded in Tables 9 and 10.

As stated, of the twenty-six (26) tyres returned from service, a total of nineteen (19) tyres showed anomalies of interest. These were tyres 6, 8, 10, 12, 13, 14, 15, 18, 19, 21, 30, 35, 37, 39, 42, 43, 44, 46 and 47. The anomalies observed were in the main 'cord sockets', where the adhesive bond has been lost between the steel tyre cord in the affected area and its coating compound, or cracks in the rubber compound in the area around the cords. In addition, Tyre 6 showed a detachment between the steel cords of belt #2 and their coating compound.

Additionally, tyres 10, 12, 13, 14, 19, 21 showed anomalies when the cut sections were examined, however, these anomalies were not visible when the same tyres were examined using shearography. Therefore, it is apparent that the shearography technique may not be able to detect all of the internal anomalies that may be present in a tyre following service.

Status	Assigned Tyre No.	0° Relative to Serial Side DOT		180° Relative to Serial Side DOT	
		Stencil Side	Opposite Stencil Side	Stencil Side	Opposite Stencil Side
New	1	ok	ok	ok	ok
New Aged	2	ok	ok	ok	ok
New Aged	3	ok	ok	ok	ok
Dynamometer	4	ok	ok	ok	ok
Dynamometer	5	ok	ok	ok	ok
2011	6	ok	ok	0.63" detachment upper gum off #2 belt	ok
2012	7	ok	ok	ok	ok
2011	8	ok	ok	#3 belt most socketed, #2 belt 6 cords w/ cracks	ok
2011	10	#2 belt 2 cord sockets	ok	ok	ok
2013	11	ok	ok	ok	ok
2012	12	#3 belt 3 cord sockets	ok	ok	ok
2011	13	#2 belt 3 cord sockets	ok	ok	ok
2012	14	#3 belt 1 cord socket	ok	ok	ok
2010	15	ok	ok	#2 belt 2 cord sockets	ok
2014	16	ok	ok	ok	ok
2013	17	ok	ok	ok	ok
2012	18	ok	ok	#2 & #3 belts 2 cord sockets	ok
2014	19	ok	#3 belt 2 cord sockets	ok	ok
2010	20	ok	ok	ok	ok
2010	21	#3 belt 5 cord sockets	ok	ok	ok
2014	22	ok	ok	ok	ok
2013	26	ok	ok	ok	ok

Table 9: Cut section examination results.

Production Year	Assigned Tyre Number	0° Relative to Serial Side DOT		180° Relative to Serial Side DOT	
		Stencil Side	Opposite Stencil Side	Stencil Side	Opposite Stencil Side
2000	30	#3 belt 13 socketed cords and 2 cracks at cords #2 belt 10 socketed cords and 7 cracks at cords	#3 belt 1 crack at cord #2 belt most cords socketed	#3 belt 1 crack at cord #2 belt 13 socketed cords	#3 belt 2 cracks at cord #2 belt 14 socketed cords
2009	35	#2 belt 5 cracks at cords	#2 belt 5 cracks at cords	#2 belt 1 crack at cord	#2 belt 3 cracks at cords
2004	37	#3 belt 2 socketed cords and 3 cracks at cords #2 belt 12 socketed cords	#3 belt 4 cord cracks #2 belt 5 socketed cords and 1 crack at cord	#2 belt 8 socketed cords	#2 belt 10 cords socketed
2009	39	#3 belt 7 cracks at cords #2 belt 1 crack at cord	#3 belt 6 cracks at cords #2 belt 4 cracks at cords	#3 belt with 11 cracks at cord	#3 belt 9 cracks at cords #2 belt 1 crack at cord
2016	42	ok	ok	ok	ok
2007	43	#3 belt 11 cracks at cords	#3 belt 6 cords with cracks	#2 belt 1 crack at cord	#2 belt 3 cracks at cord
2007	44	#3 belt 2 socketed cords #2 belt 5 socketed cords	#3 belt 2 socketed cords and 6 cracks at cords #2 belt 20 cords socketed and 1 crack at cord	#2 belt 5 socketed cords and 1 crack at cord	#3 belt 14 socketed cords and 2 cracks at cords #2 belt 2 cracks at cord
2016	46	#3 belt 4 socketed cords	#2 belt 1 crack at cord	ok	ok
2005	47	#3 belt with 3 cracks at cords #2 belt with 4 cracks at cords	#3 belt with 1 crack at cord (to #2 belt) #2 belt 1 socketed cord and 2 cracks at cord	#2 belt 5 cracks at cords	ok

Table 10: Cut section examination results.

5. RESULTS - TYRE MATERIAL PHYSICAL PROPERTIES

In order to provide data on key materials within the structure of the tyres under study, the physical properties of key components were determined.

5.1 Tread Compound Tensile and Hardness Properties

Tables 11 and 12 below summarise the data obtained as a result of the analysis of the tread compound of each of the sample tyres.

Status	Assigned Tyre No.	Hardness Shore A	Modulus at 100% extension (MPa)	Modulus at 300% extension (MPa)	Tensile Strength (MPa)	Ultimate Elongation (%)
New	1	63	3.0	15.0	25.0	461
New Oven-Aged	2	72	4.3	19.8	26.6	404
New Oven-Aged	3	73	3.9	18.6	24.3	360
Dynamometer	4	70	4.2	19.9	24.0	364
Dynamometer	5	73	4.4	20.3	25.8	386
2011	6	65	4.7	20.6	23.6	343
2012	7	60	4.3	20.9	24.0	341
2011	8	52	4.6	21.0	24.3	341
2011	10	58	4.1	19.2	26.5	407
2013	11	64	4.7	20.2	24.2	362
2012	12	59	4.7	21.0	24.6	356
2011	13	58	4.2	20.2	24.3	350
2012	14	64	4.0	20.3	24.0	347
2010	15	57	4.1	19.4	24.8	377
2014	16	65	3.3	18.4	24.5	394
2013	17	66	4.3	18.4	28.2	455
2012	18	60	4.5	20.1	23.7	352
2014	19	63	4.1	18.6	23.5	370
2010	20	59	4.2	19.5	23.3	351
2010	21	65	4.4	20.4	23.7	337
2014	22	66	5.2	22.2	26.1	349
2013	26	58	4.8	19.9	21.6	326

Table 11: Tread compound physical property data.

Production Year	TRL-Assigned Tyre No.	Hardness Shore A	M100 (MPa)	M300 (MPa)	Tensile Strength (MPa)	Ultimate Elongation (%)
2000	30	73	4.9	19.9	24.9	376
2009	35	72	4.5	20.5	25.1	356
2004	37	73	3.5	20.0	27.4	387
2009	39	69	4.2	19.3	24.4	384
2016	42	72	3.9	17.1	24.2	408
2007	43	72	4.7	21.3	21.9	306
2007	44*	-	-	-	-	-
2016	46	70	4.7	20.3	25.1	351
2005	47	71	3.8	19.6	20.4	316

Table 12: Tread compound physical property data (cont.)

*Suitable test specimens were unable to be obtained due to tread damage.

This data is also summarised graphically in the charts 1 to 5 presented below:

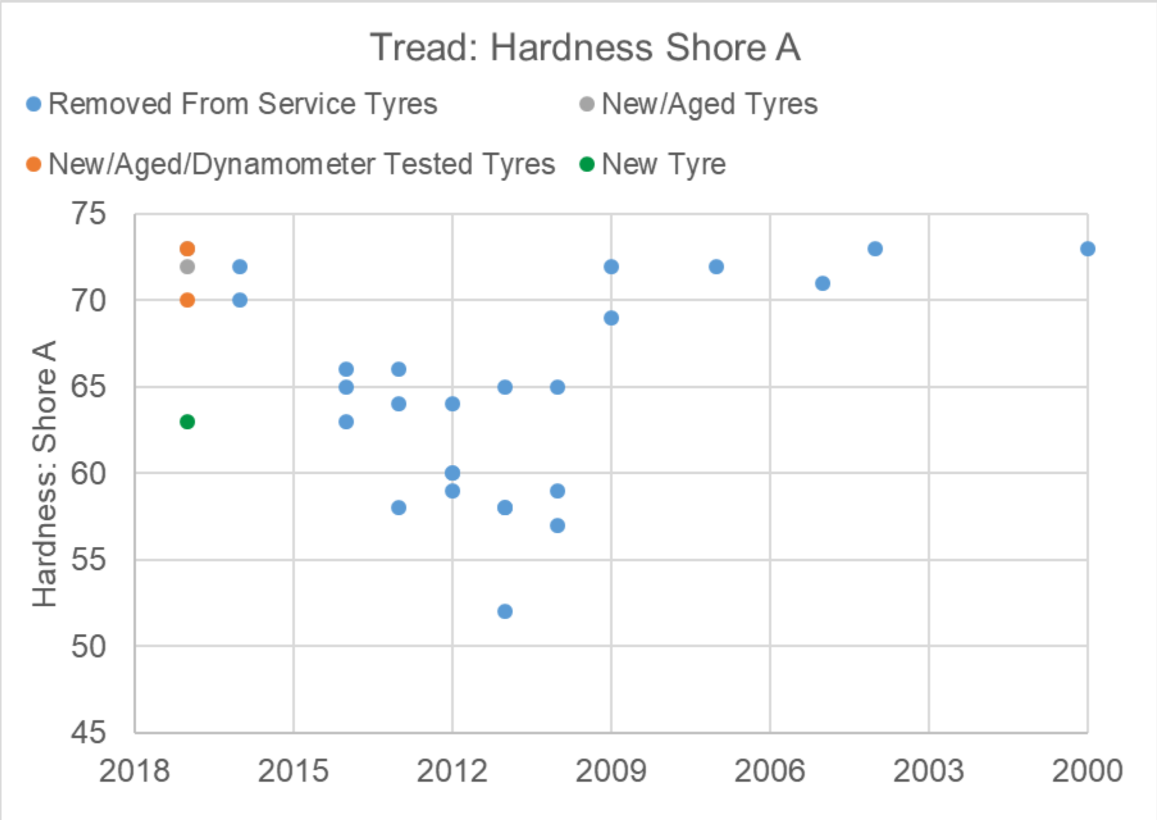


Chart 1: Tread compound hardness.

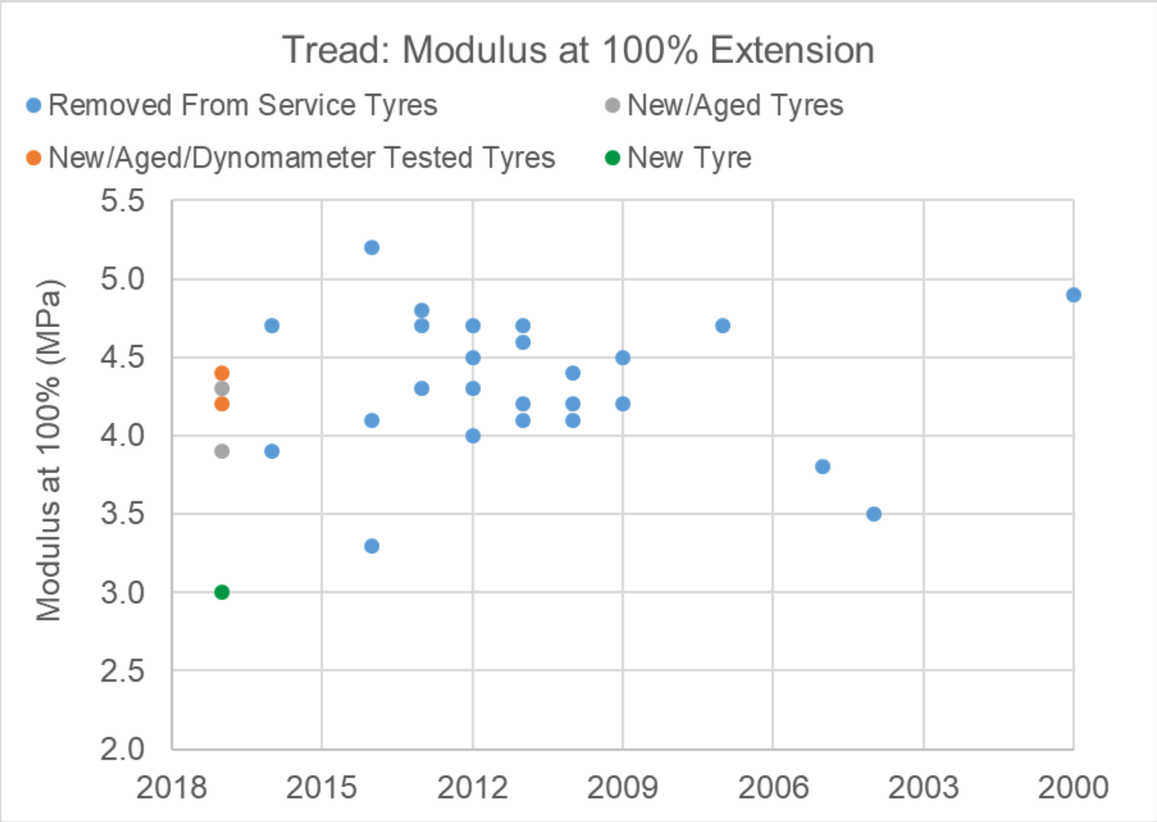


Chart 2: Tread compound modulus at 100% extension.

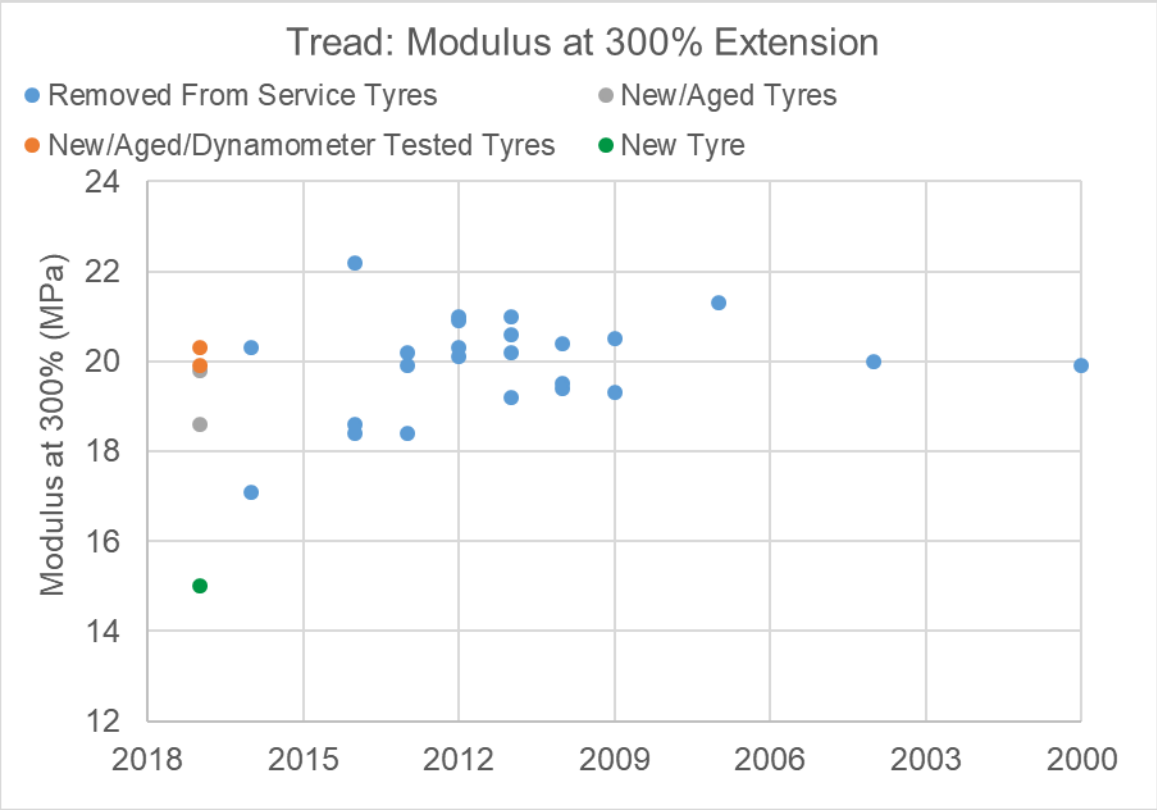


Chart 3: Tread compound modulus at 300% extension.

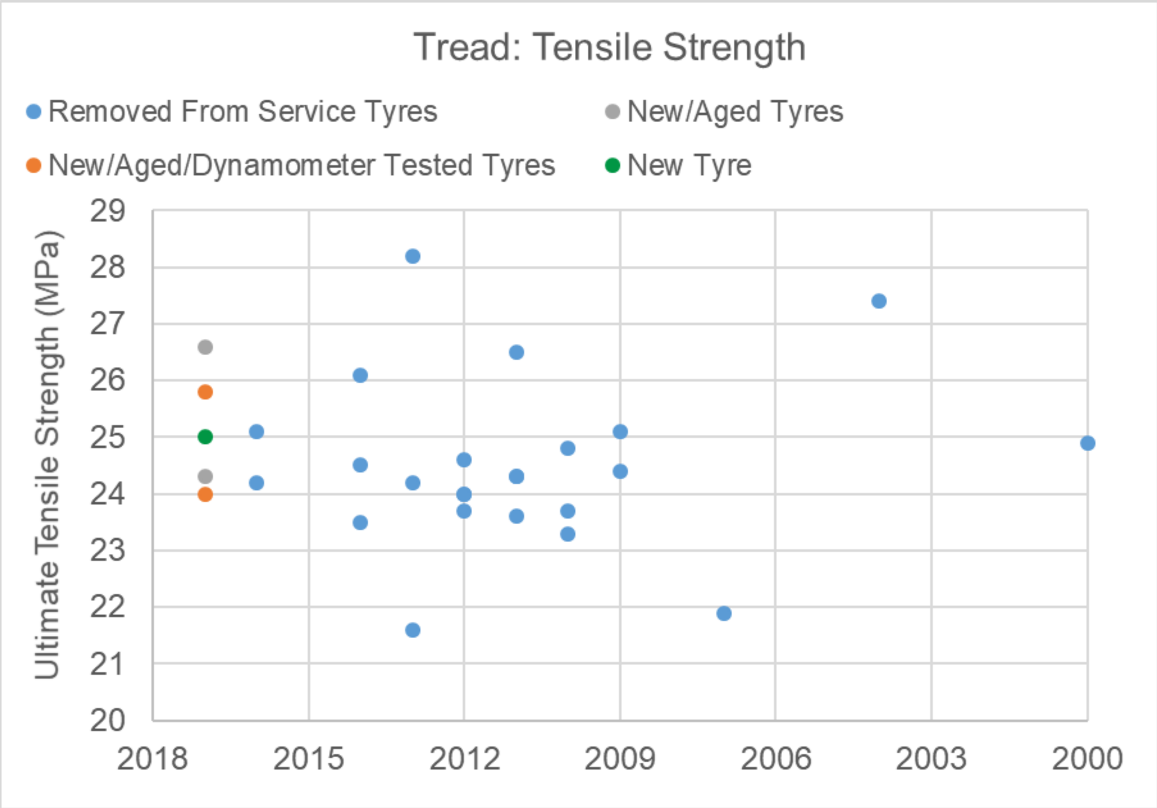


Chart 4: Tread compound tensile strength.

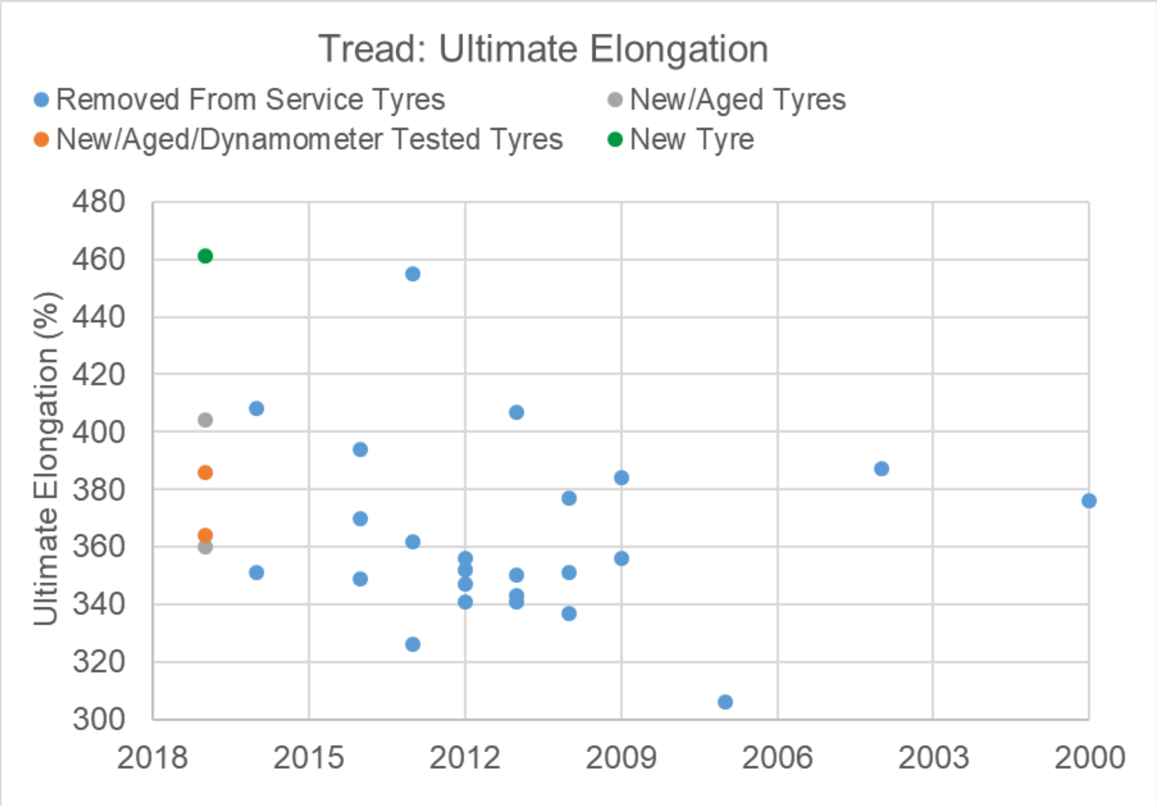


Chart 5: Tread compound ultimate elongation

5.2 Sidewall Compound Tensile and Hardness Properties

Tables 13 and 14 below summarise the data obtained as a result of the analysis of the sidewall compound of each of the sample tyres.

Status	Assigned Tyre No.	Hardness Shore A	Modulus at 100% extension (MPa)	Modulus at 300% extension (MPa)	Tensile Strength (MPa)	Ultimate Elongation (%)
New	1	45	1.5	5.9	22.2	649
New Oven-Aged	2	66	2.4	9.9	20.4	490
New Oven-Aged	3	64	2.3	9.9	17.1	449
Dynamometer	4	63	2.3	9.5	18.4	459
Dynamometer	5	64	2.4	9.8	16.4	445
2011	6	60	3.3	13.6	17.9	396
2012	7	61	3.2	12.8	17.3	383
2011	8	52	3.3	13.0	17.1	387
2011	10	60	3.2	12.5	19.7	444
2013	11	50	2.4	9.7	22.5	517
2012	12	53	2.0	8.1	22.1	572
2011	13	54	2.8	11.0	19.9	470
2012	14	51	3.5	13.0	18.5	393
2010	15	55	3.1	12.5	17.3	405
2014	16	57	2.9	12.2	20.1	449
2013	17	58	2.7	11.3	21.3	492
2012	18	63	3.0	11.4	19.4	443
2014	19	53	2.1	8.1	23.0	579
2010	20	62	3.4	13.7	19.1	385
2010	21	58	3.4	13.5	19.0	413
2014	22	47	1.9	7.6	22.1	558
2013	26	50	2.3	9.2	21.0	529

Table 13: Sidewall compound physical property data.

Production Year	TRL-Assigned Tyre No.	Hardness Shore A	M100 (MPa)	M300 (MPa)	Tensile Strength (MPa)	Ultimate Elongation (%)
2000	30	68	3.8	14.2	19.2	392
2009	35	72	3.2	12.7	18.2	402
2004	37	68	3.8	14.5	18.7	389
2009	39	66	3.3	13.3	19.9	415
2016	42	58	2.0	7.3	23.6	620
2007	43	67	4.0	15.0	16.5	330
2007	44	68	3.4	14.0	17.4	352
2016	46	60	2.0	7.8	20.1	533
2005	47	68	3.4	13.3	17.0	380

Table 14: Sidewall compound physical property data (cont.)

This data is also summarised graphically in the charts 6 to 10 presented below:

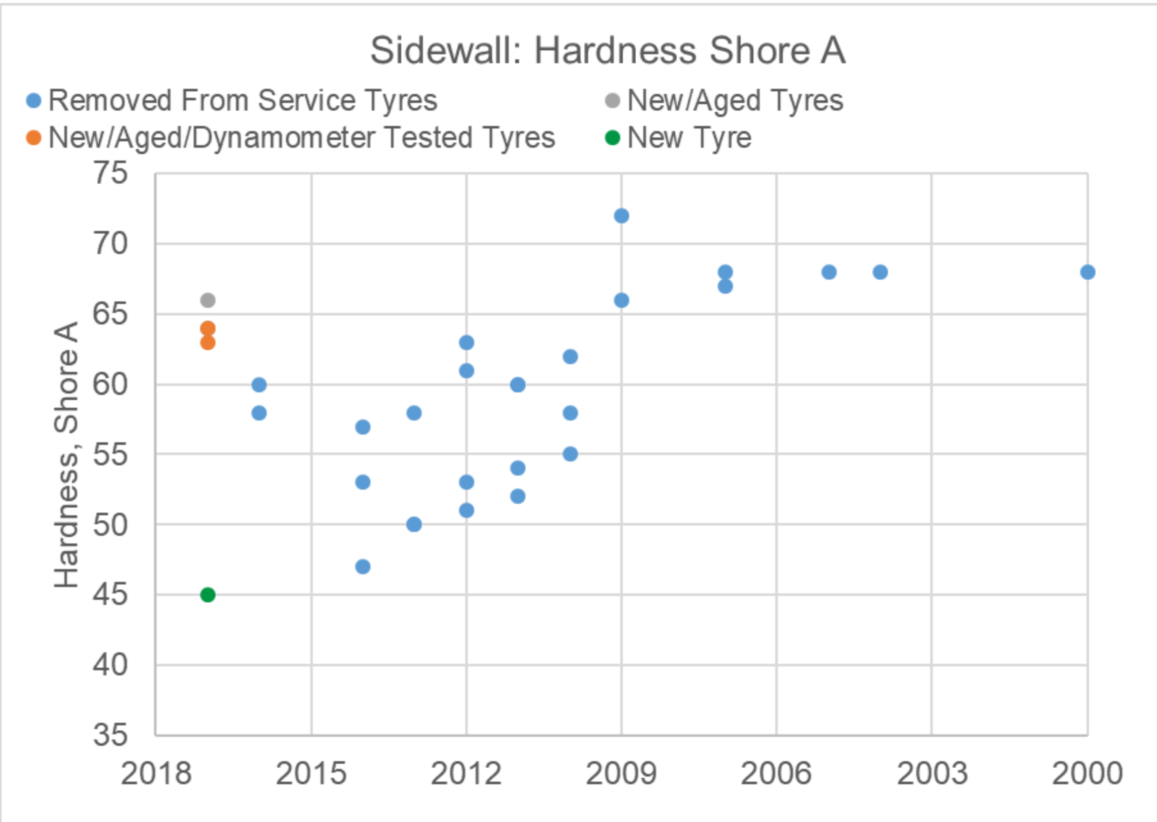


Chart 6: Sidewall compound hardness.

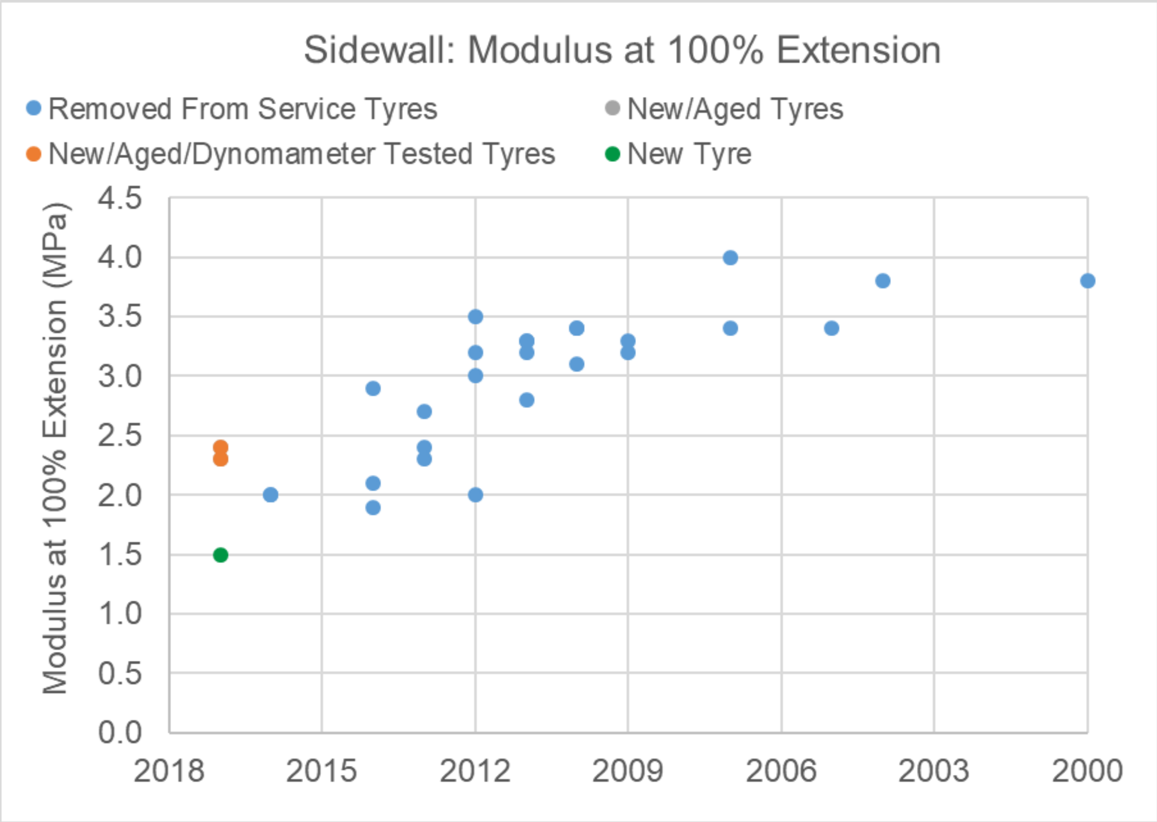


Chart 7: Sidewall compound modulus at 100% extension.

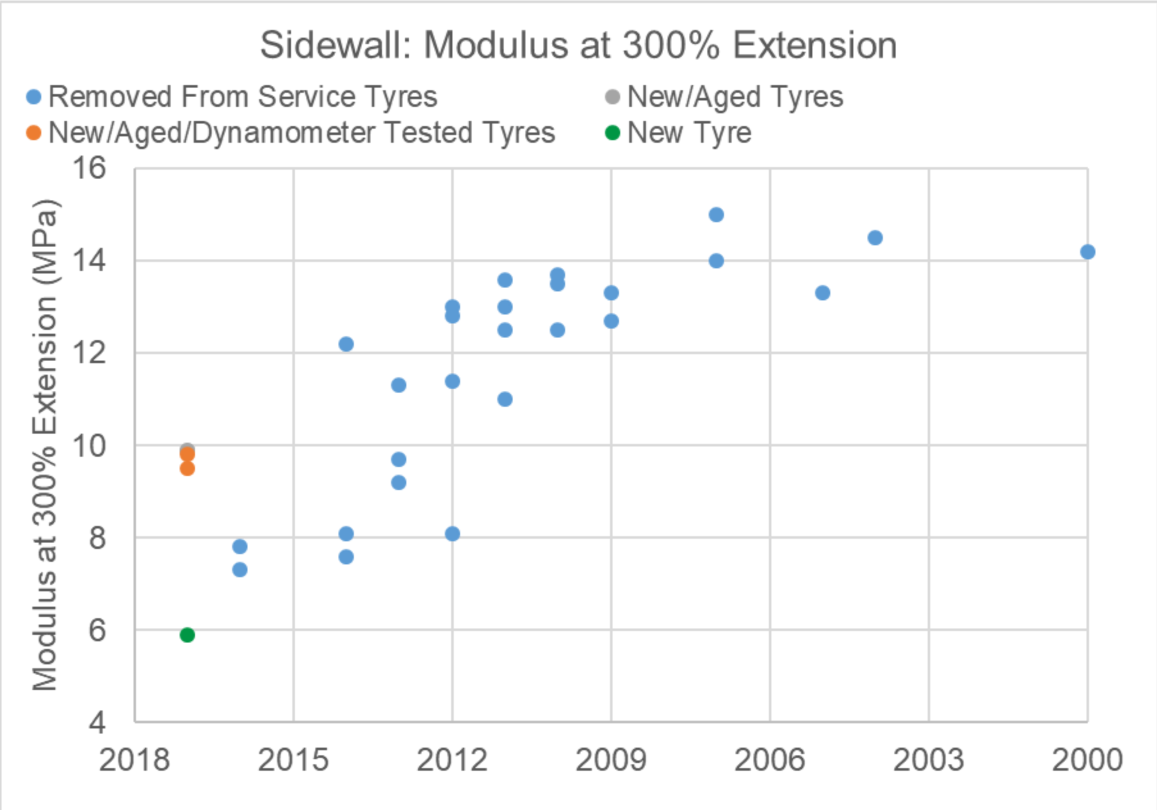


Chart 8: Sidewall compound modulus at 300% extension.

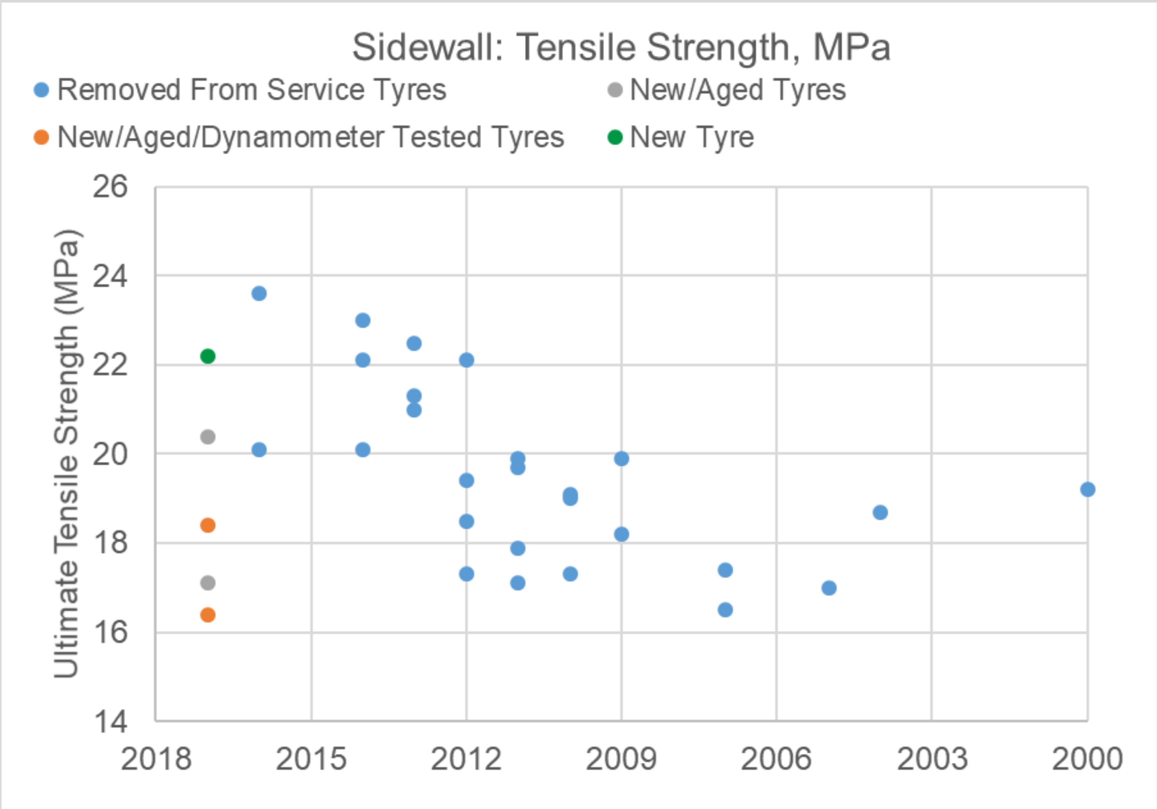


Chart 9: Sidewall compound ultimate tensile strength.

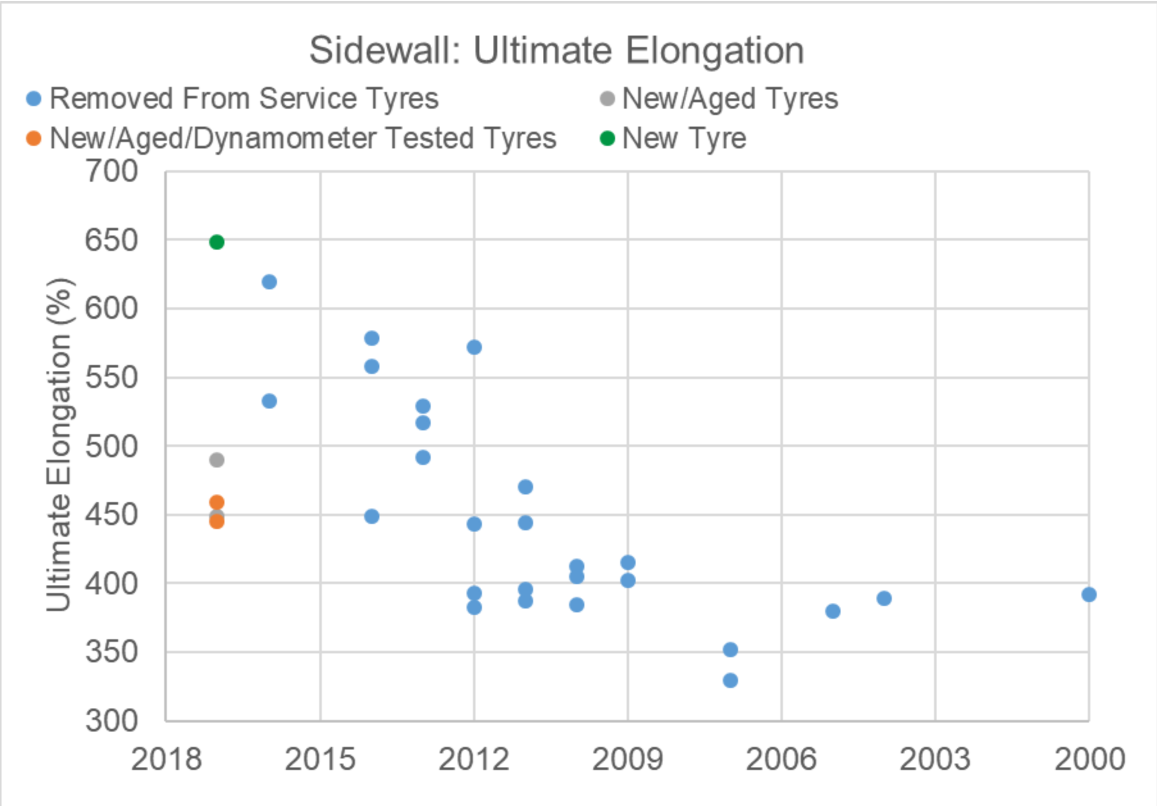


Chart 10: Sidewall compound ultimate elongation.

5.3 Innerliner Compound Tensile and Hardness Properties

Tables 15 and 16 below summarises the data obtained as a result of the analysis of the innerliner compound of each of the sample tyres.

Status	Assigned Tyre No.	Hardness Shore A	Modulus at 100% extension (MPa)	Modulus at 300% extension (MPa)	Tensile Strength (MPa)	Ultimate Elongation (%)
New	1	54	1.4	5.9	11.1	552
New Oven-Aged	2	58	1.5	5.8	8.5	449
New Oven-Aged	3	58	1.5	5.7	6.9	447
Dynamometer	4	57	1.4	5.0	7.8	501
Dynamometer	5	58	1.4	5.3	8.3	489
2011	6	54	1.6	6.5	10.5	501
2012	7	55	1.5	6.2	10.4	517
2011	8	53	1.6	6.3	10.4	537
2011	10	56	1.5	6.4	11.5	545
2013	11	57	1.6	6.6	10.6	514
2012	12	57	1.6	6.5	10.0	459
2011	13	57	1.5	6.4	10.5	491
2012	14	55	1.6	6.4	9.2	437
2010	15	58	1.6	6.8	10.4	458
2014	16	59	1.5	5.6	9.8	561
2013	17	59	1.6	6.6	11.7	551
2012	18	58	1.6	6.6	10.6	477
2014	19	59	1.7	6.8	11.6	546
2010	20	60	1.6	6.4	9.9	475
2010	21	60	1.5	6.0	10.4	536
2014	22	60	1.5	6.4	10.5	534
2013	26	60	1.6	6.3	9.2	443

Table 15: Innerliner compound physical property data.

Production Year	TRL-Assigned Tyre No.	Hardness Shore A	M100 (MPa)	M300 (MPa)	Tensile Strength (MPa)	Ultimate Elongation (%)
2000	30	50	1.0	3.4	7.1	580
2009	35	53	1.4	5.9	10.6	532
2004	37	50	1.4	5.5	10.7	551
2009	39	52	1.4	5.6	11.1	569
2016	42	53	1.5	5.9	9.4	488
2007	43	52	1.5	6.0	9.3	496
2007	44	57	1.6	6.0	9.0	451
2016	46	52	1.5	5.9	10.0	522
2005	47	51	1.4	5.8	9.3	454

Table 16: Innerliner compound physical property data (cont.)

This data is also summarised graphically in the charts 11 to 15 presented below:

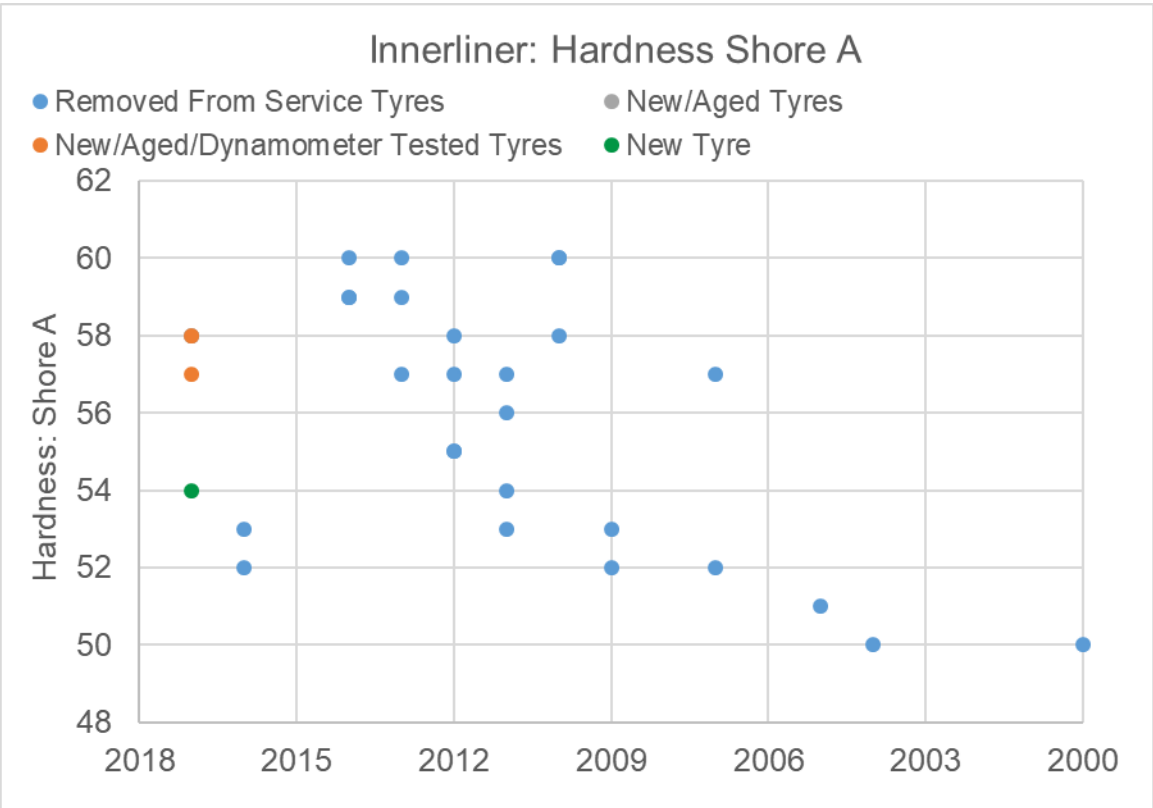


Chart 11: Innerliner hardness.

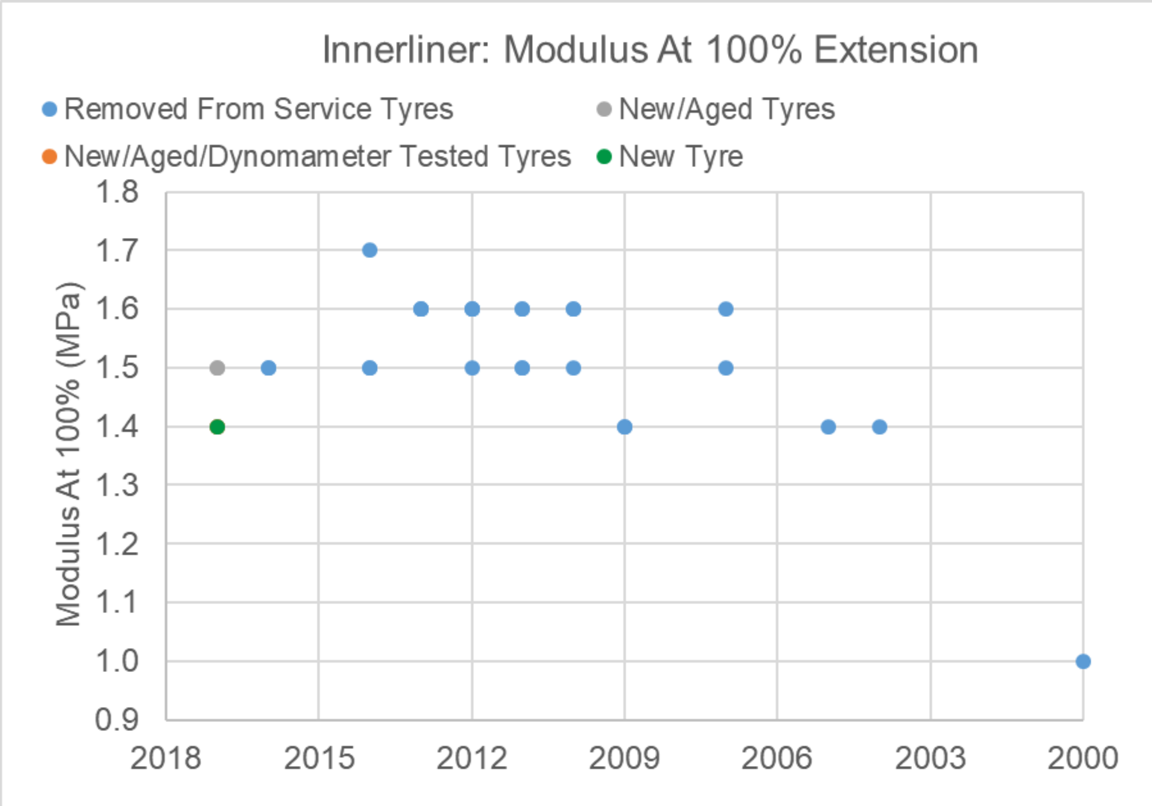


Chart 12: Innerliner modulus at 100% extension.

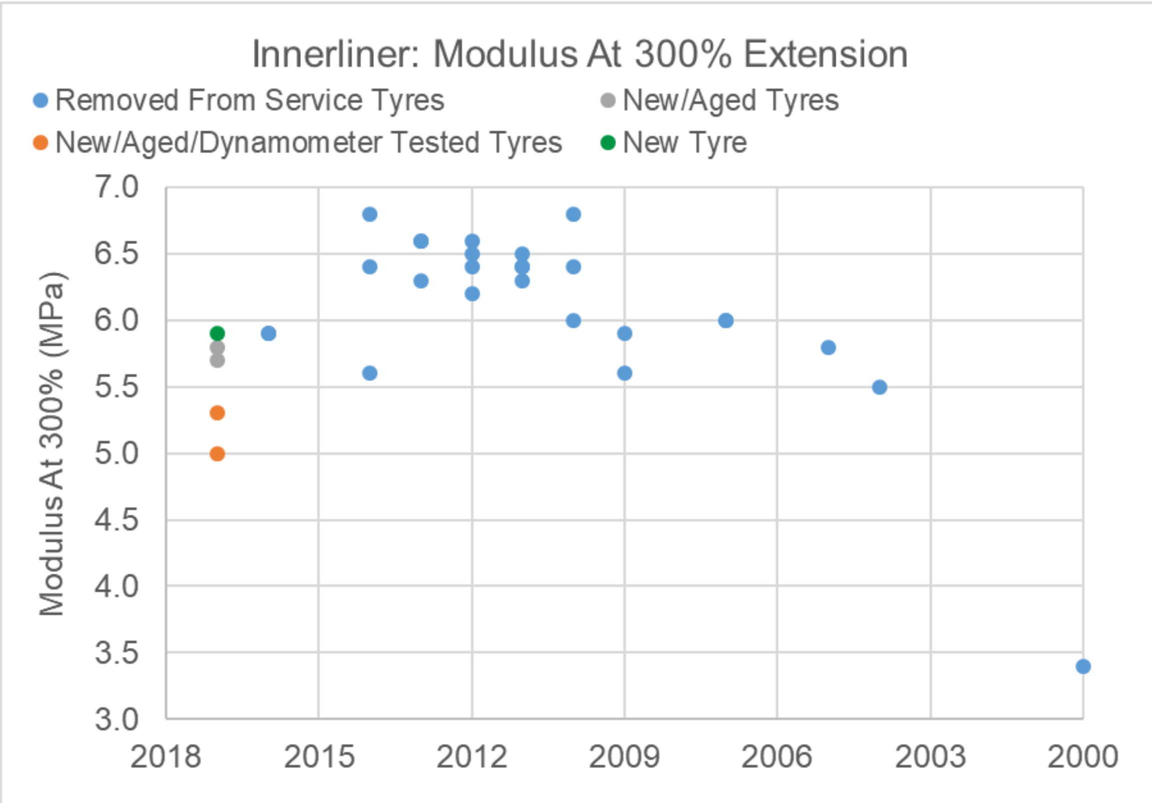


Chart 13: Innerliner modulus at 300% extension.

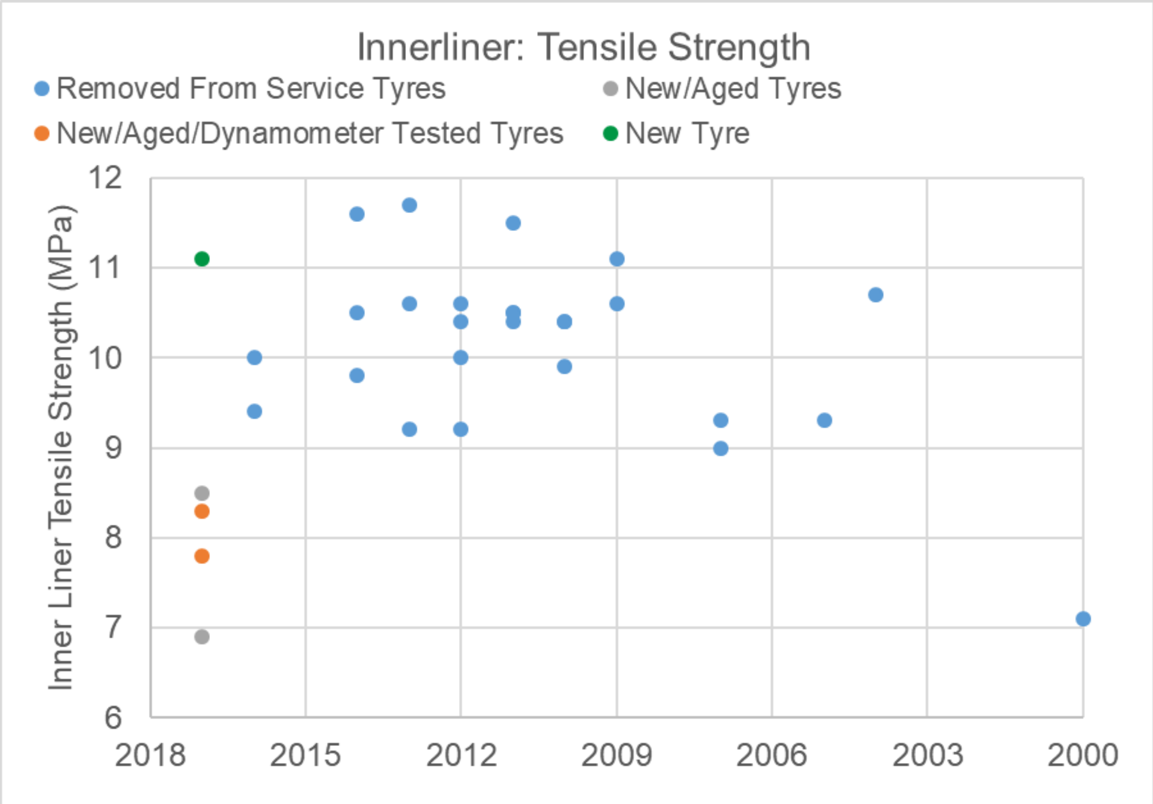


Chart 14: Innerliner tensile strength

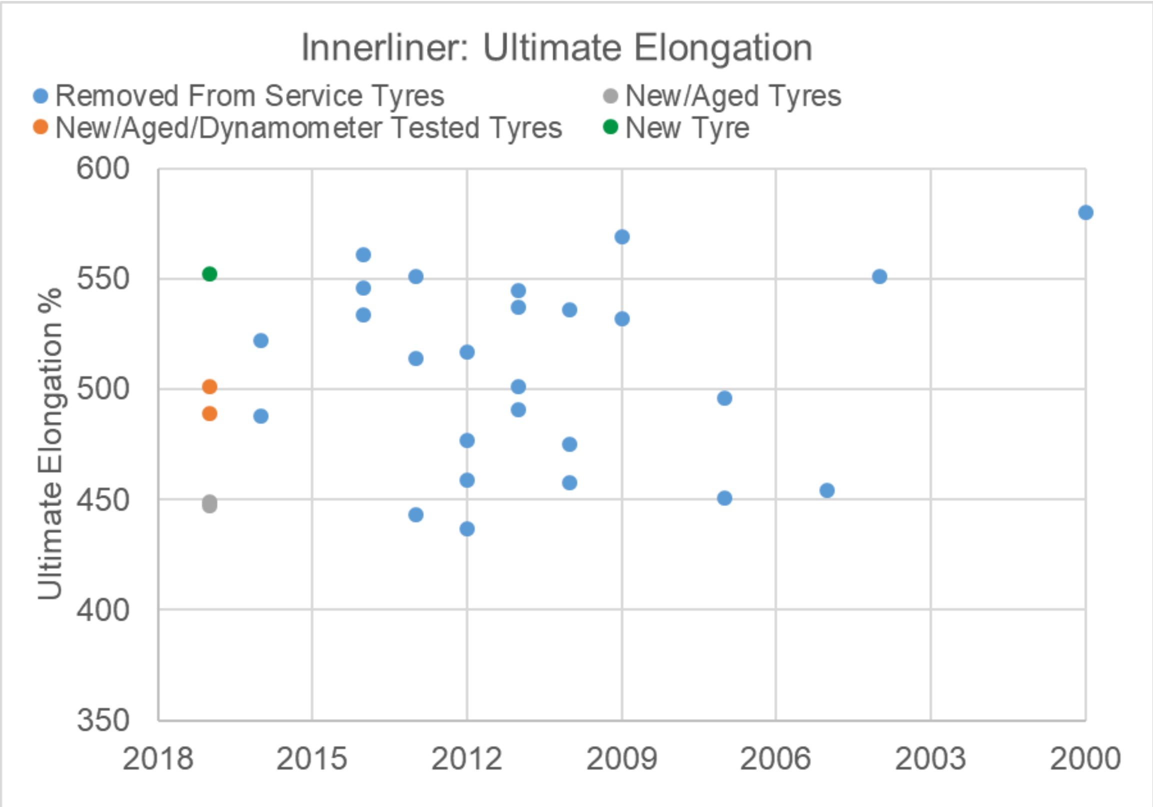


Chart 15: Innerliner ultimate elongation

5.4 Shoulder Wedge Compound Tensile and Hardness Properties

Tables 17 and 18 below summarise the data obtained as a result of the analysis of the shoulder wedge compound of each of the sample tyres.

Status	Assigned Tyre No.	Hardness Shore A	Modulus at 100% extension (MPa)	Modulus at 300% extension (MPa)	Tensile Strength (MPa)	Ultimate Elongation (%)
New	1	60	2.3	13.3	29.2	475
New Oven-Aged	2	67	3.0	17.2	29.3	441
New Oven-Aged	3	68	3.3	18.5	26.4	390
Dynamometer	4	64	2.8	16.1	20.8	342
Dynamometer	5	64	3.2	18.2	22.3	354
2011	6	61	2.6	15.0	25.9	429
2012	7	66	3.8	20.2	26.9	381
2011	8	66	3.2	17.7	24.1	386
2011	10	64	2.6	14.8	28.5	462
2013	11	67	4.1	-	20.1	299
2012	12	64	3.1	18.1	26.5	380
2011	13	65	3.9	20.8	23.8	331
2012	14	64	3.1	17.7	27.0	392
2010	15	65	3.0	16.8	27.3	418
2014	16	64	3.1	17.2	24.4	406
2013	17	62	2.4	13.3	26.8	473
2012	18	66	3.4	18.1	24.5	374
2014	19	67	3.4	17.6	22.7	357
2010	20	67	3.6	19.1	25.5	368
2010	21	66	3.8	19.9	24.7	348
2014	22	67	4.2	21.6	19.5	288
2013	26	67	4.9	-	16.8	234

Table 17: Shoulder wedge compound physical property data.

Production Year	TRL-Assigned Tyre No.	Hardness Shore A	M100 (MPa)	M300 (MPa)	Tensile Strength (MPa)	Ultimate Elongation (%)
2000	30	68	4.1	20.4	20.9	311
2004	37	62	2.7	15.2	28.6	441
2005	47	56	3.3		7.3	181
2007	43*	-	-	-	-	-
2007	44	60	3.1	18.4	19.9	316
2009	35	63	3.3	18.0	23.1	353
2009	39	62	3.5	18.8	26.3	377
2016	42	63	3.3	18.1	22.6	349
2016	46	61	3.9	-	17.7	268

Table 18: Shoulder wedge compound physical property data (cont.)

*Suitable test specimens were unable to be obtained.

This data is also summarised graphically in the charts 16 to 20 presented below:

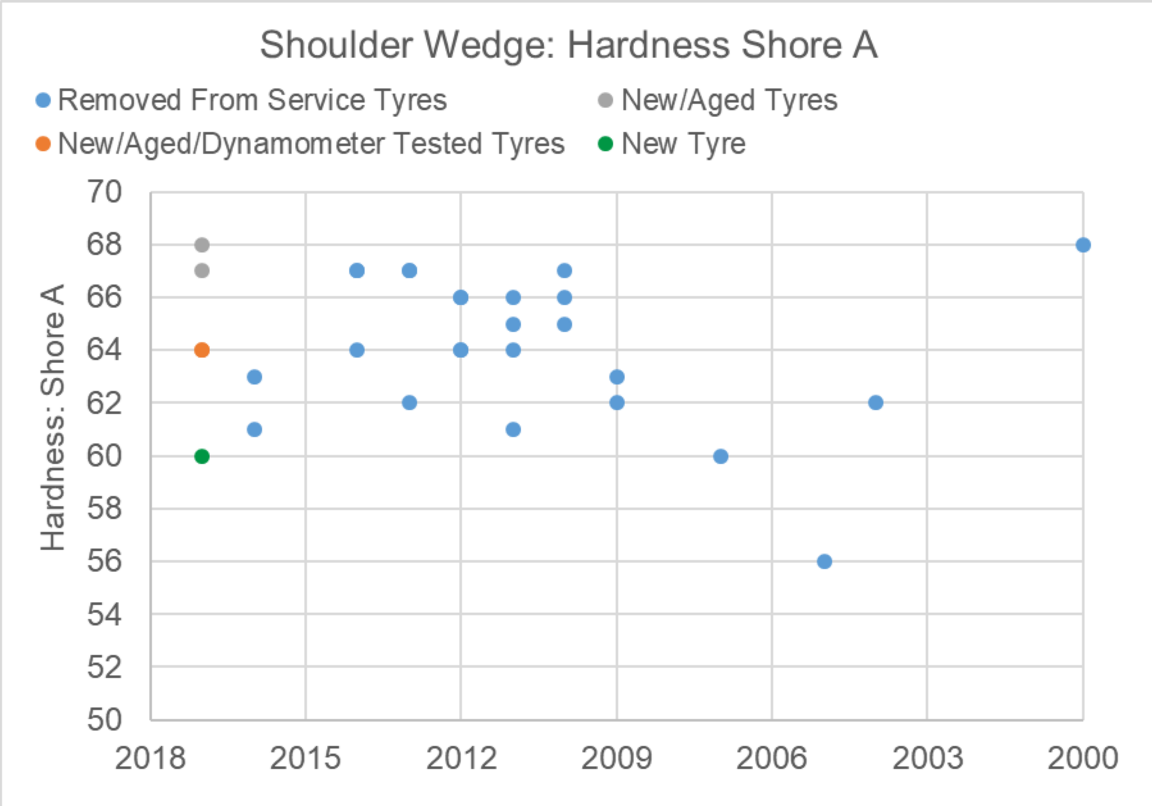


Chart 16: Shoulder wedge compound hardness.

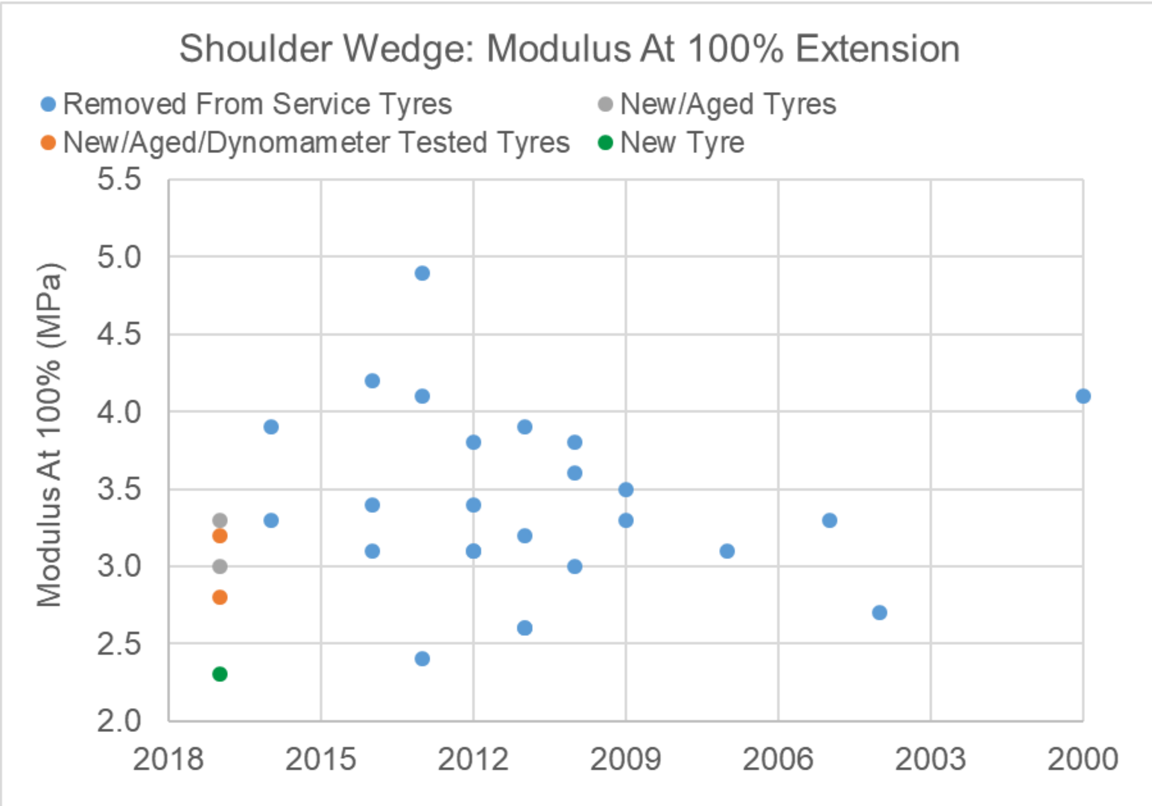


Chart 17: Shoulder wedge modulus at 100% extension.

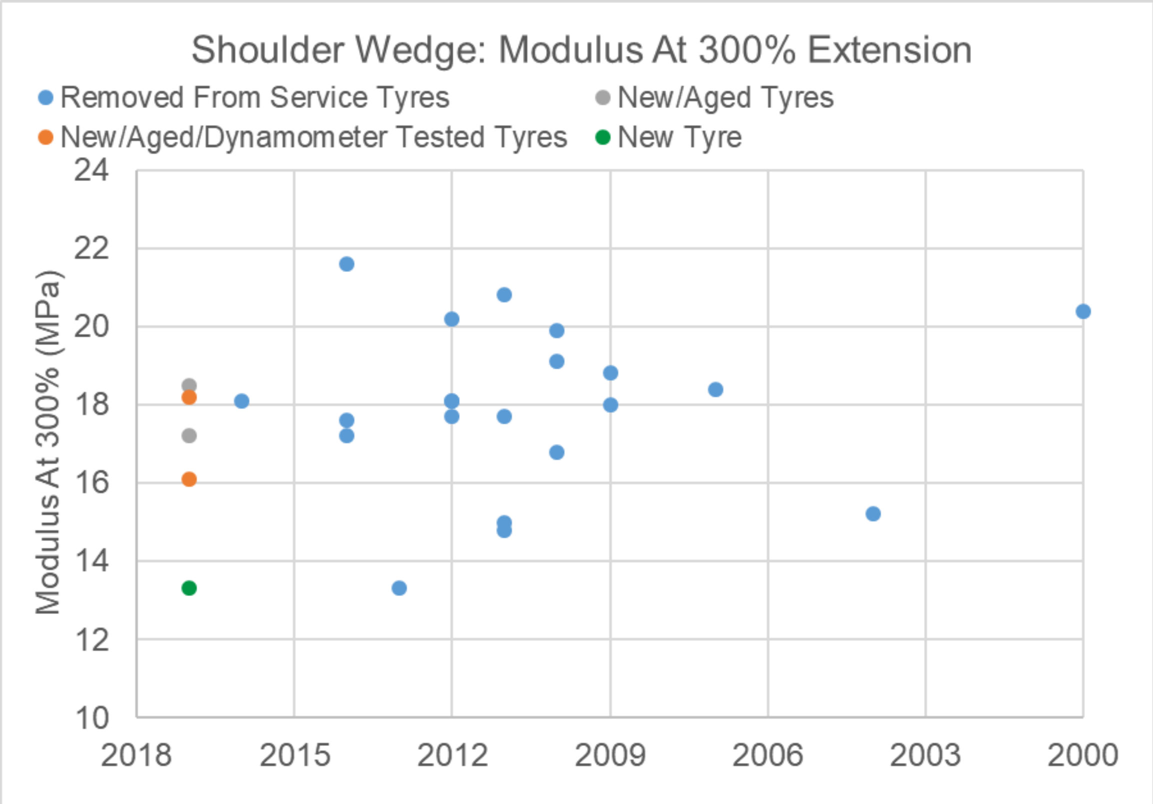


Chart 18: Shoulder wedge modulus at 300% extension.

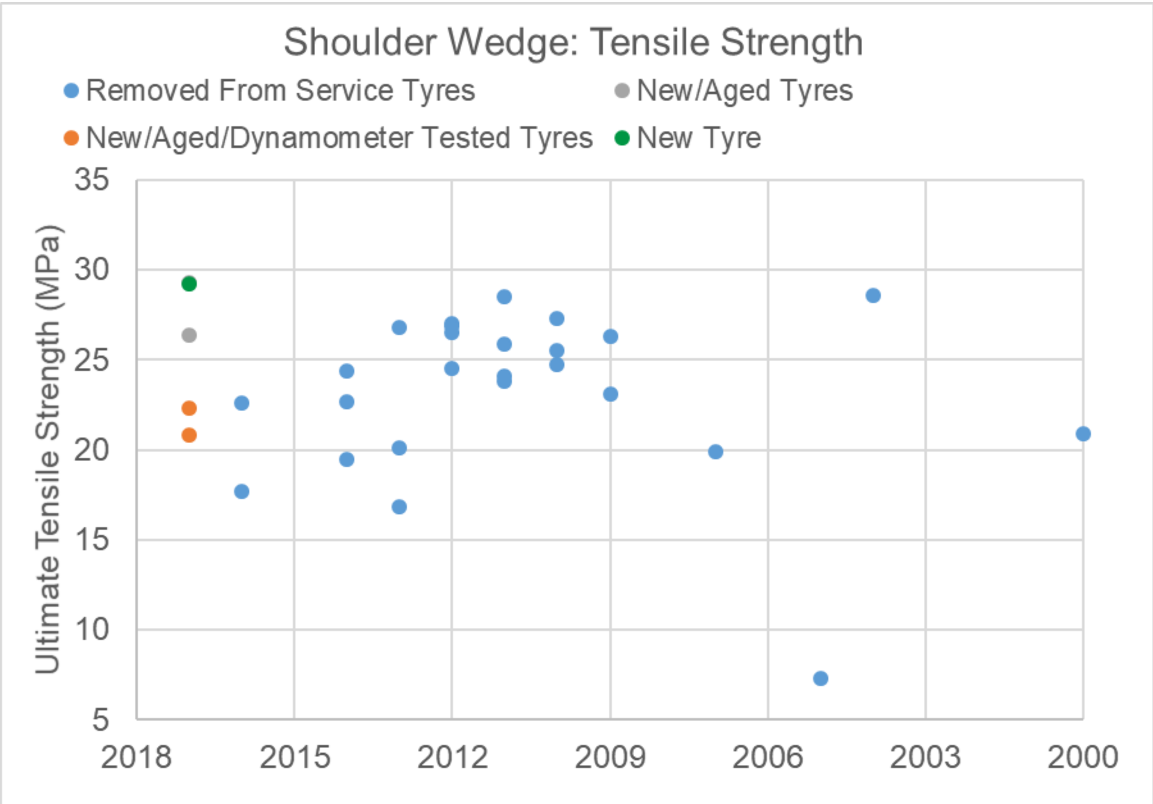


Chart 19: Shoulder wedge ultimate tensile strength.

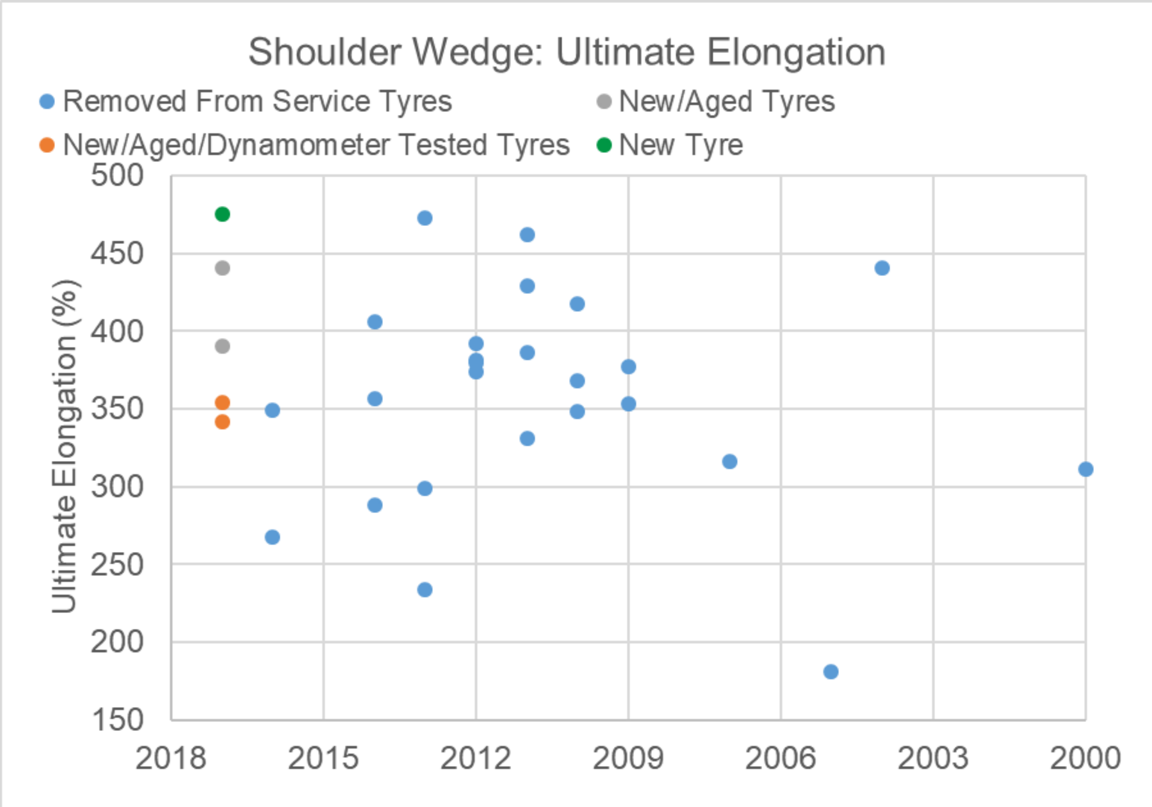


Chart 20: Shoulder wedge ultimate elongation.

5.5 Belt Skim Compound Tensile and Hardness Properties

Tables 19 and 20 below summarise the data obtained as a result of the analysis of the belt skim compound of each of the sample tyres.

Status	Assigned Tyre No.	Hardness Shore A	Modulus at 100% extension (MPa)	Modulus at 200% extension (MPa)	Tensile Strength (MPa)	Ultimate Elongation (%)
New	1	73	5.7	12.8	16.9	270
New Oven-Aged	2	77	6.3	-	13.3	194
New Oven-Aged	3	76	6.1	-	11.5	160
Dynamometer	4	77	6.1	-	12.7	181
Dynamometer	5	78	5.8	-	13.5	199
2011	6	79	8.7	-	9.8	100
2012	7	82	8.4	-	12.5	147
2011	8	83	-	-	9.3	96
2011	10	82	9.1	-	13.0	144
2013	11	81	7.8	-	12.7	157
2012	12	80	6.1	-	12.4	189
2011	13	82	8.8	-	10.3	118
2012	14	81	9.8	-	9.7	112
2010	15	81	-	-	7.8	90
2014	16	80	7.5	-	11.8	149
2013	17	82	7.1	-	10.1	149
2012	18	80	8.2	-	8.6	110
2014	19	82	6.7	-	11.5	143
2010	20	83	-	-	8.9	94
2010	21	81	-	-	7.5	86
2014	22	80	7.4	-	15.5	199
2013	26	80	8.4	-	11.7	143

Table 19: Belt skim compound physical property data.

Production Year	TRL-Assigned Tire No.	Durometer Hardness*	M100 (MPa)	M200 (MPa)	Tensile Strength (MPa)	Ultimate Elongation (%)
2000	30	83	13.1	-	14.4	110
2004	37	86	13.3	-	17.3	135
2005	47	87	-	-	11.8	88
2007	44	83	-	-	11.1	80
2007	43	85	11.6	-	16.5	146
2009	35	86	-	-	13.3	102
2009	39	82	12.6	-	14.1	117
2016	46	81	9.0	-	12.6	128
2016	42	81	9.3	-	14.9	156

Table 20: Belt skim compound physical property data (cont.)

Note: All belt skim compound hardness measurements were made using a ‘Rex Gauge’ brand hardness tester. Each test was made between the edges of belts 2 and 3.

This data is also summarised graphically in the charts 21 to 25 presented below:

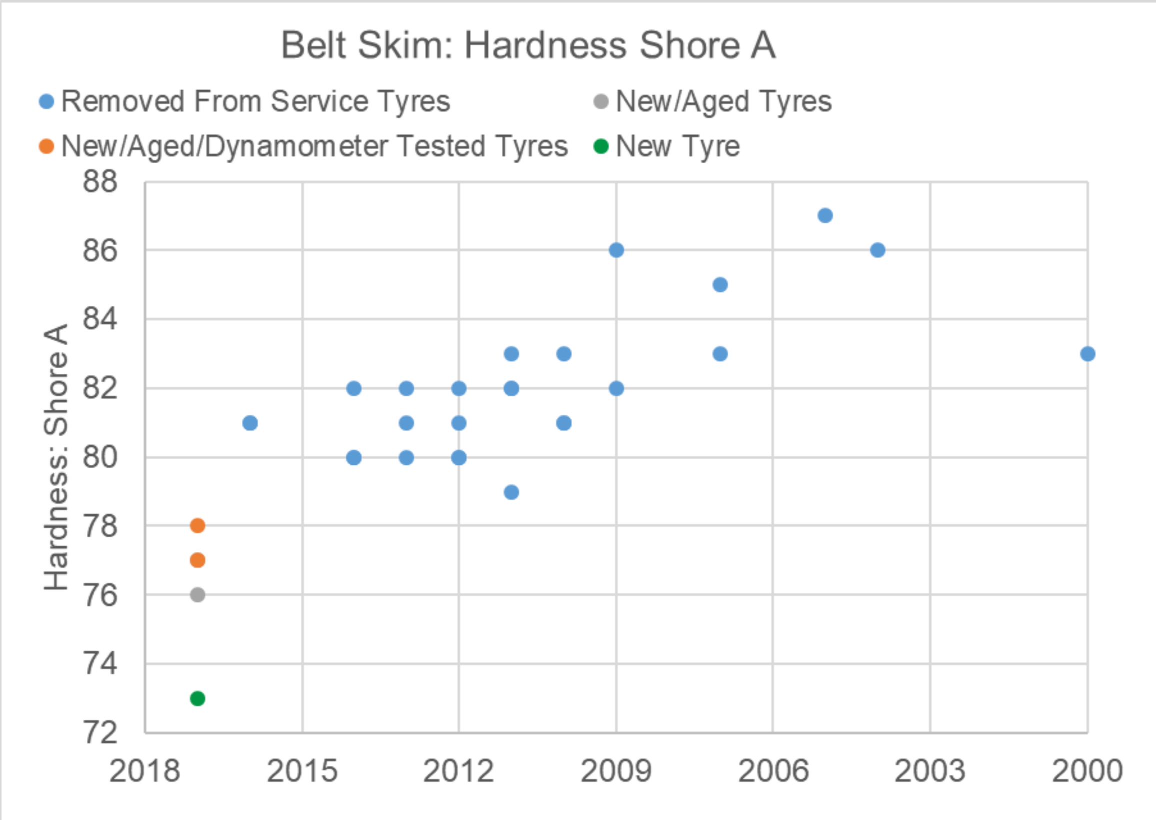


Chart 21: Belt skim hardness.

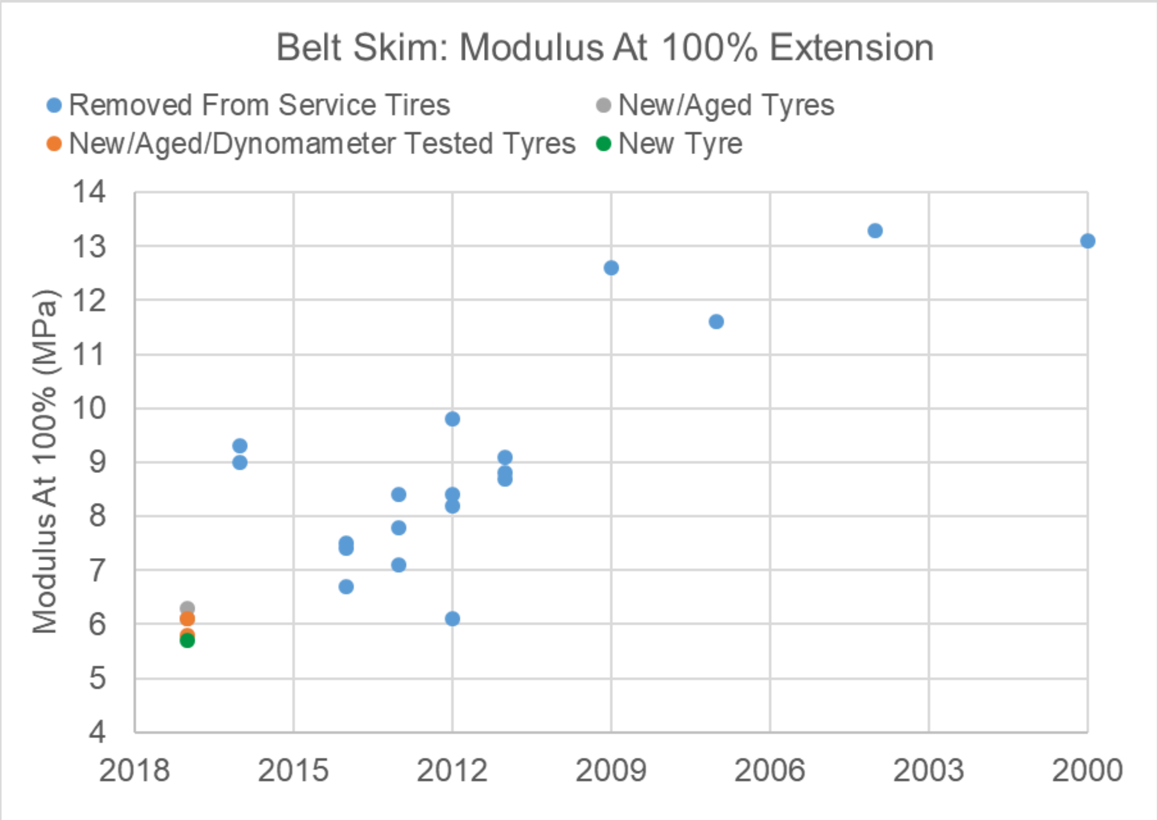


Chart 22: Belt skim modulus at 100% extension.

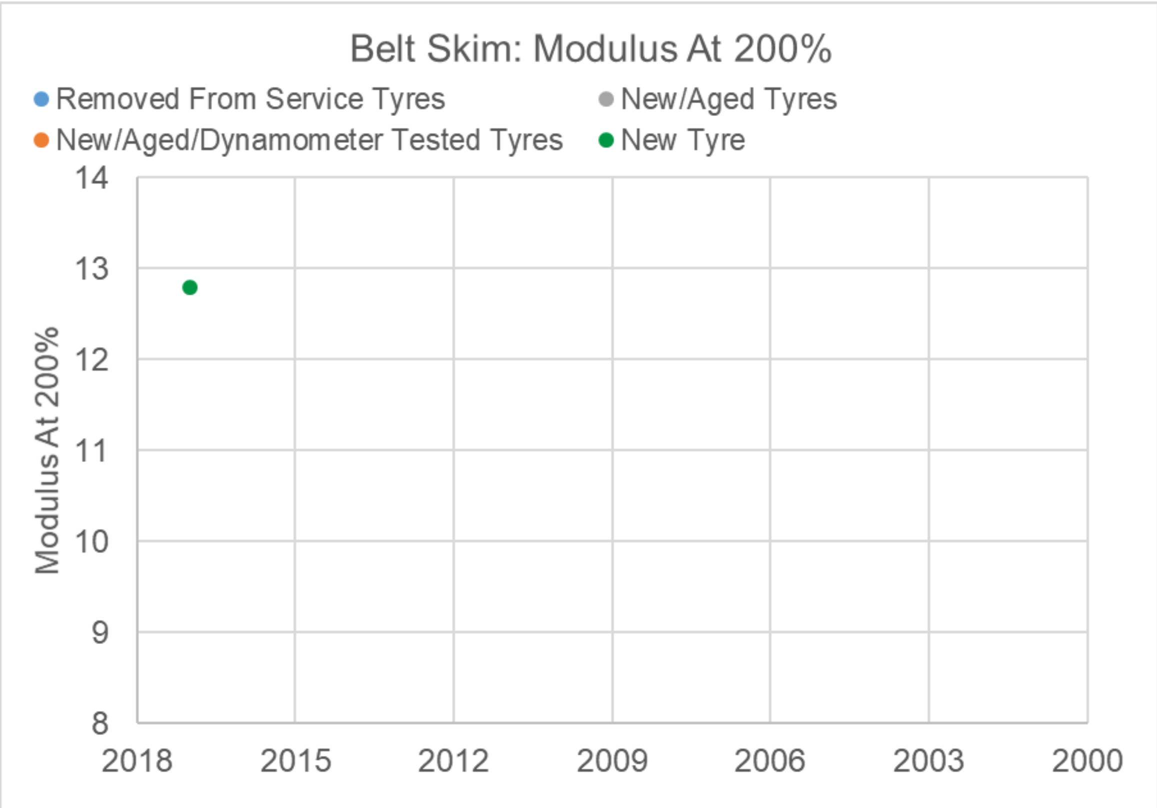


Chart 23: Belt skim modulus at 200% extension. (Note: All samples except the new tyre fractured at elongations less than 200%.)

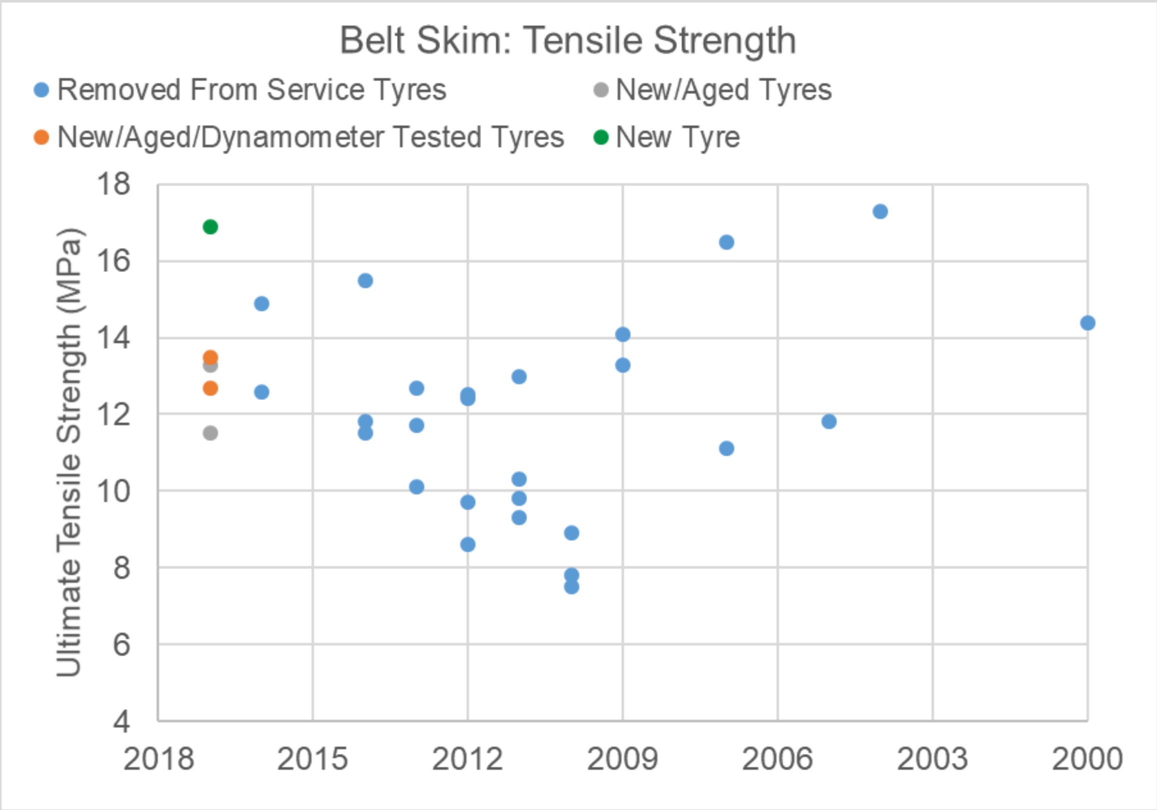


Chart 24: Belt skim ultimate tensile strength.

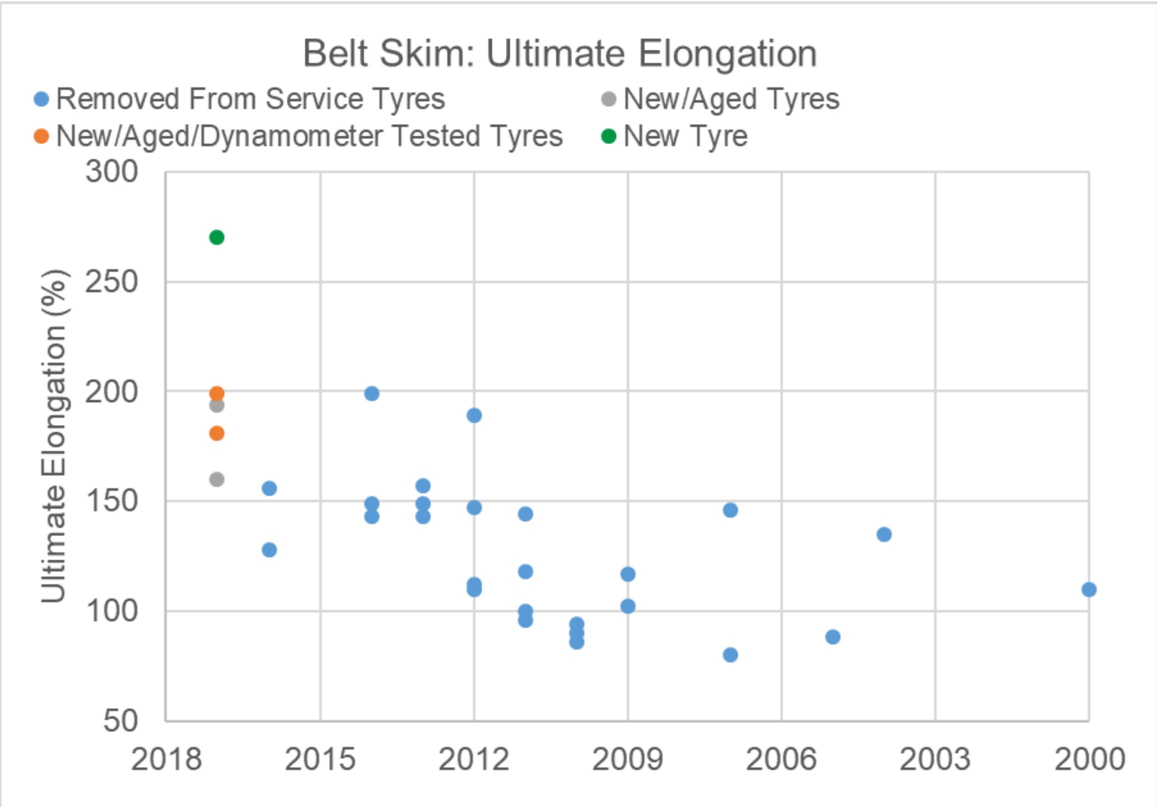


Chart 25: Belt skim ultimate elongation.

5.6 Residual Ozone Resistance

Tables 21 and 22 below summarise the data obtained as a result of the residual ozone resistance testing of the tread and sidewall compounds from each tyre. Test samples of each compound excised from the sample tyres was exposed to ozone (70hrs at 38°C and 50pphm). Subsequently each tested sample was examined for signs of cracking, with the level of cracking observed being assigned a subjective rating.

Please note that this test method specifically relates to unaged rubber compound and not tyres. Therefore, the tests described in this report were conducted in general accordance with the standard, but the results should be considered comparative only.

Ratings:
0 – no cracks at 7x magnification
1 – small cracks at 7x magnification
2 – small cracks visible to naked eye
3 – medium to large cracks visible to naked eye

Status	TRL-Assigned Tyre No.	Tread Compound Rating	Sidewall Compound Rating
New	1	3	0
New Oven-Aged	2	2	3
New Oven-Aged	3	3	3
Dynamometer	4	3	3
Dynamometer	5	3	3
2011	6	3	3
2012	7	3	3
2011	8	3	3
2011	10	3	3
2013	11	3	3
2012	12	3	3
2011	13	3	3
2012	14	3	3
2010	15	3	3
2014	16	3	3
2013	17	3	3
2012	18	3	3
2014	19	3	3
2010	20	3	3
2010	21	3	3
2014	22	3	3
2013	26	3	3

Table 21: Residual ozone test results.

Production Year	TRL-Assigned Tire No.	Tread Rating	Sidewall Rating
2000	30	3	3
2009	35	3	3
2004	37	3	3
2009	39	3	3
2016	42	3	3
2007	43	3	3
2007	44	3	3
2016	46	3	3
2005	47	3	3

Table 22: Residual ozone test results (cont.)

5.7 Interfacial Peel Force Tests – Room Temperature

Samples at key interfaces within each sample tyre were extracted, and subjected to peel force testing. Tables 23 and 24 below summarise the data obtained.

Status	Assigned Tyre No.	Belt 4 to Tread (N/mm)	Belt 2 to Belt 3 (Working Belts) (N/mm)	Belt 3 to Belt 4 (N/mm)	Casing to Sidewall (N/mm)	Casing to Innerliner (N/mm)
New	1	17.7	7.7	21.2	44.8	9.7
New Oven-Aged	2	16.6	5.5	13.9	11.5	3.5
New Oven-Aged	3	20.2	5.5	12.7	10.4	3.1
Dynamometer	4	25.4	5.6	17.9	5.8	4.2
Dynamometer	5	25.6	5.5	16.9	6.7	4.0
2011	6	11.5	4.4	3.4	8.6	3.5
2012	7	13.0	4.4	8.2	9.7	3.5
2011	8	11.2	4.2	3.8	7.9	3.8
2011	10	13.7	3.9	4.8	11.8	6.9
2013	11	9.3	4.0	7.1	5.0	3.4
2012	12	11.8	4.8	8.6	30.0	5.8
2011	13	15.5	5.0	10.3	11.8	4.2
2012	14	10.6	4.4	9.4	7.9	4.4
2010	15	12.5	4.0	5.2	8.3	4.5
2014	16	8.6	4.2	4.1	6.4	5.9
2013	17	15.4	5.5	4.7	18.0	10.5
2012	18	12.6	5.2	9.4	8.3	4.0
2014	19	12.4	3.7	7.4	13.5	5.1
2010	20	10.3	4.6	4.4	6.4	4.0
2010	21	18.1	4.0	7.0	11.6	4.9
2014	22	12.0	4.6	9.4	15.6	6.7
2013	26	6.7	3.5	5.9	4.5	3.1

Table 23: Room temperature interfacial peel force test results.

Production Year	TRL-Assigned Tire No.	Belt 4 to Tread (N/mm)	Belt 2 to Belt 3 (Working Belts) (N/mm)	Belt 3 to Belt 4 (N/mm)	Casing to Sidewall (N/mm)	Casing to Innerliner (N/mm)
2000	30	9.0	4.2	7.3	6.6	4.1
2009	35	12.2	3.8	5.8	7.1	8.1
2004	37	13.3	3.6	7.3	6.1	4.6
2009	39	9.7	3.9	4.5	10.3	5.0
2016	42	12.7	4.2	13.5	20.7	4.5
2007	43	15.5	5.1	8.8	6.4	3.4
2007	44	9.6	4.4	4.1	7.3	3.8
2016	46	8.7	5.5	12.3	17.1	4.6
2005	47	14.8	3.9	7.7	7.5	9.1

Table 24: Room temperature interfacial peel force test results.

This data is also summarised graphically in the charts 26 to 30 presented below:

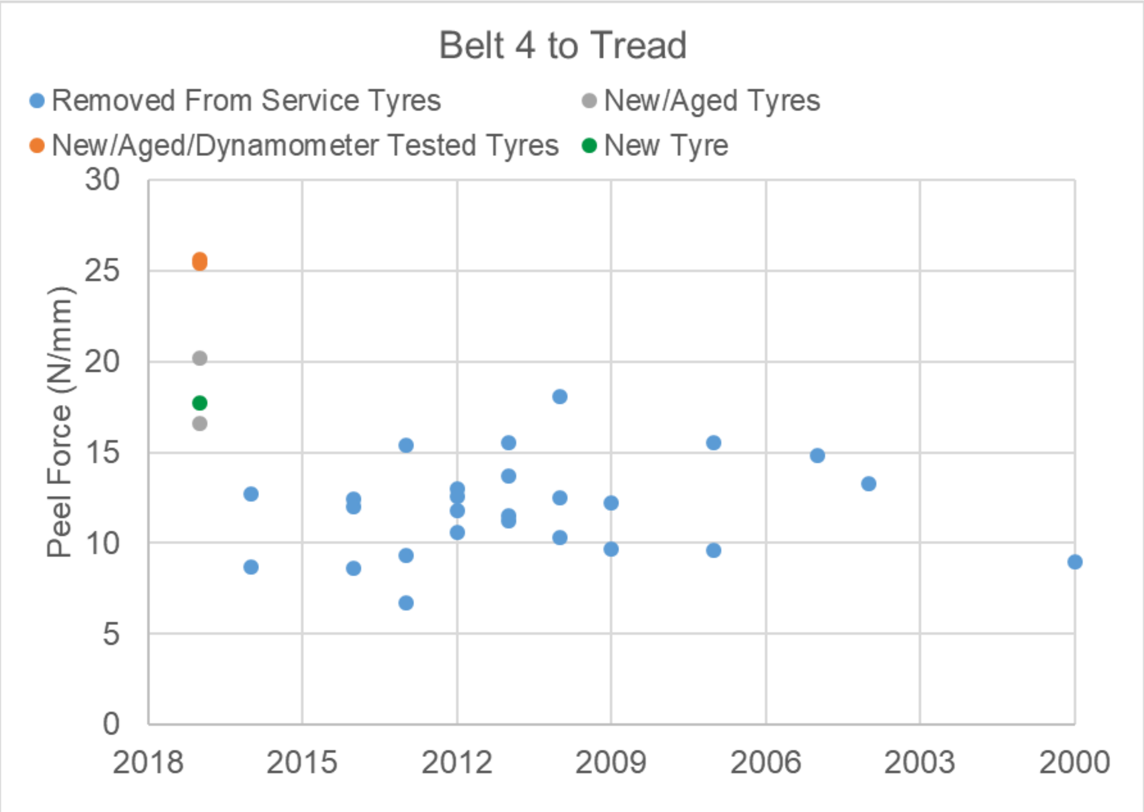


Chart 26: Interfacial peel force– Belt 4 to tread compound.

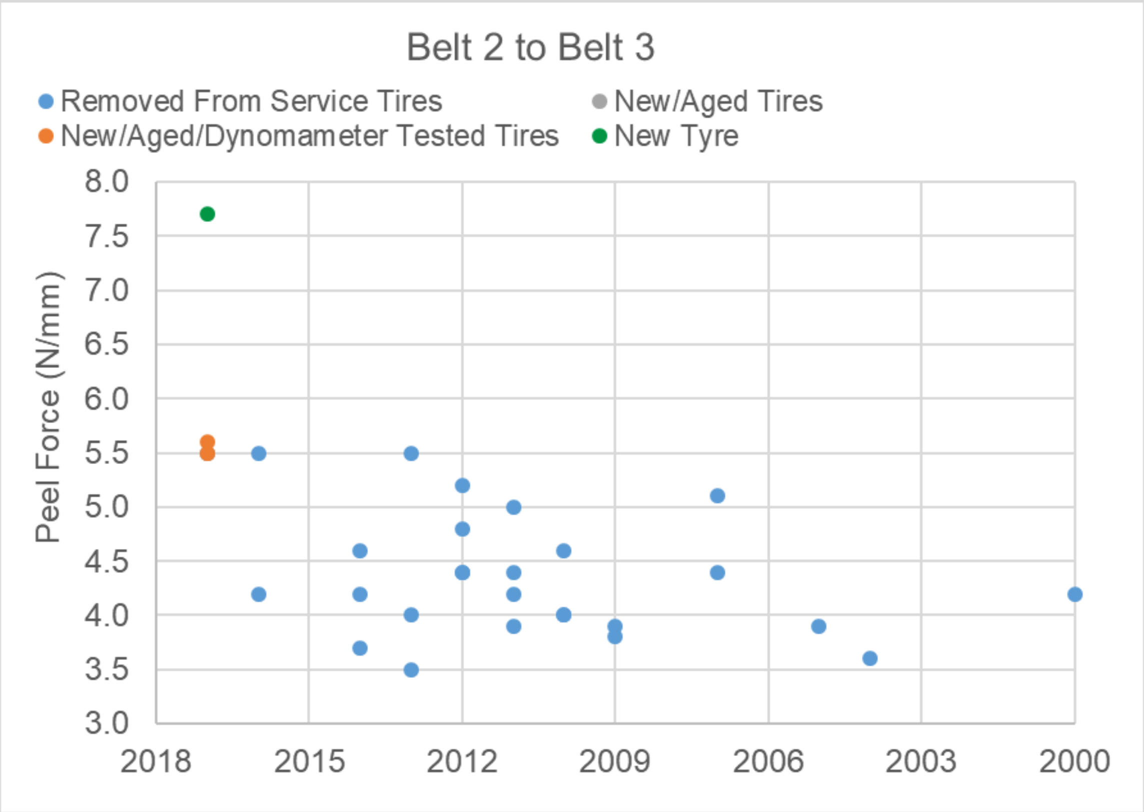


Chart 27: Interfacial peel force– Belt 2 to Belt 3.

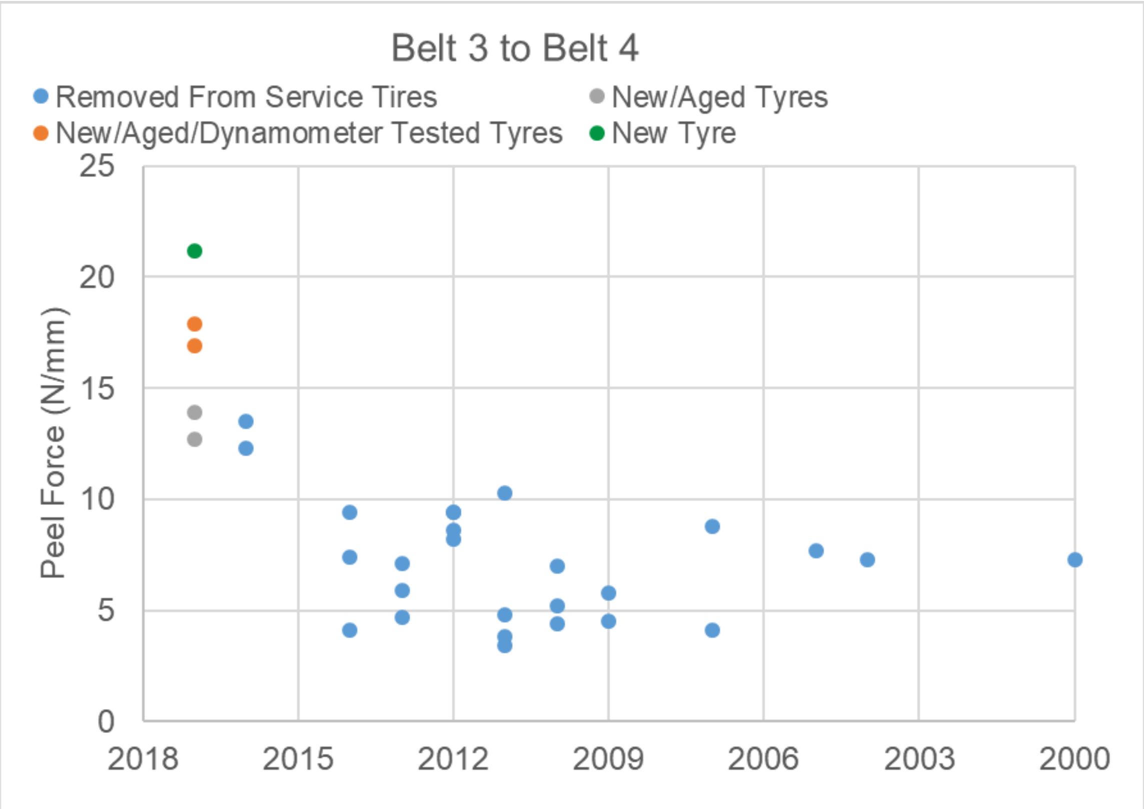


Chart 28: Interfacial peel force– Belt 3 to Belt 4.

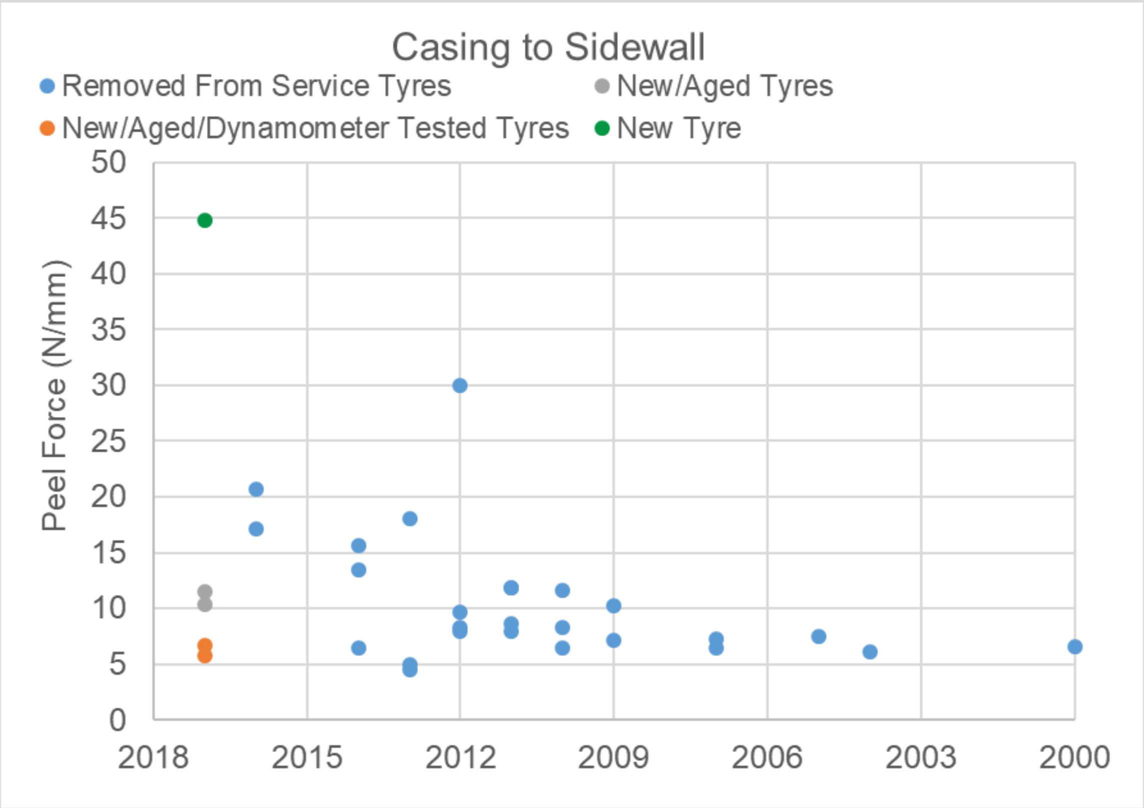


Chart 29: Interfacial peel force– Casing to sidewall.

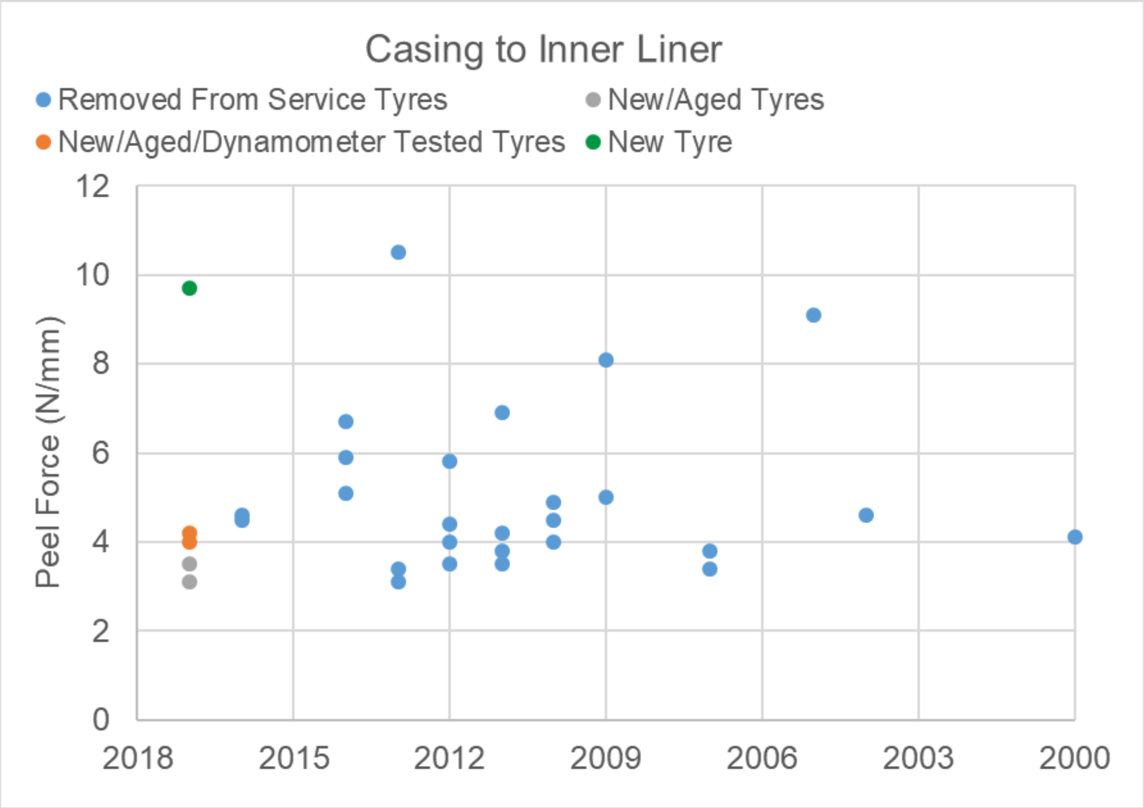


Chart 30: Interfacial peel force– Casing to innerliner.

During peel force testing, surface corrosion was noted on the steel tyre cords of the following belts:

- Tyre 6 Belt 3
- Tyre 7 Belt 2
- Tyre 8 Belt 4
- Tyre 14 Belt 4
- Tyre 15 Belt 4
- Tyre 16 Belt 4
- Tyre 20 Belt 4
- Tyre 22 Belt 4
- Tyre 30 Belt 4 and Belt 3
- Tyre 35 Belt 3
- Tyre 37 Belt 3
- Tyre 39 Belt 4
- Tyre 42 Belt 3
- Tyre 43 Belt 3
- Tyre 44 Belt 4 and Belt 3
- Tyre 47 Belt 4 and Belt 3

Photographs of the observed corrosion can be found in Appendix 3. The most likely explanation for the presence of this corrosion is that cuts in the tread compound have enabled moisture to enter the tyre casing and reach the steel belt layers.

5.8 Interfacial Peel Force Tests – Elevated Temperature

Samples at key interfaces within each sample tyre were extracted, and subjected to peel force testing at elevated temperature (100°C). Tables 25 and 26 below summarise the data obtained.

Status	Assigned Tyre No.	Belt 4 to Tread Hot (N/mm)	Belt 2 to Belt 3 Hot (Working Belts) (N/mm)
New	1	18.5	3.0
New Oven-Aged	2	8.1	3.1
New Oven-Aged	3	11.6	2.9
Dynamometer	4	14.5	3.0
Dynamometer	5	16.1	2.9
2011	6	7.5	2.0
2012	7	3.7	2.0
2011	8	6.5	1.8
2011	10	6.3	2.3
2013	11	2.8	1.9
2012	12	4.9	2.5
2011	13	4.2	2.6
2012	14	3.6	2.1
2010	15	5.9	2.2
2014	16	3.2	2.2
2013	17	11.9	2.6
2012	18	5.5	2.4
2014	19	5.8	1.9
2010	20	3.9	2.1
2010	21	10.0	2.1
2014	22	5.1	2.0
2013	26	1.9	1.9

Table 25: Elevated temperature interfacial peel force test results.

Production Year	TRL-Assigned Tire No.	Belt 4 to Tread Hot (N/mm)	Belt 2 to Belt 3 Hot (Working Belts) (N/mm)
2000	30	4.4	1.9
2009	35	7.0	1.7
2004	37	9.5	1.9
2009	39	9.7	2.0
2016	42	4.2	1.8
2007	43	5.0	2.4
2007	44	4.7	1.6
2016	46	4.5	2.5
2005	47	10.6	1.9

Table 26: Elevated temperature interfacial peel force test results (cont.)

This data is also summarised graphically in the charts 31 to 32 presented below:

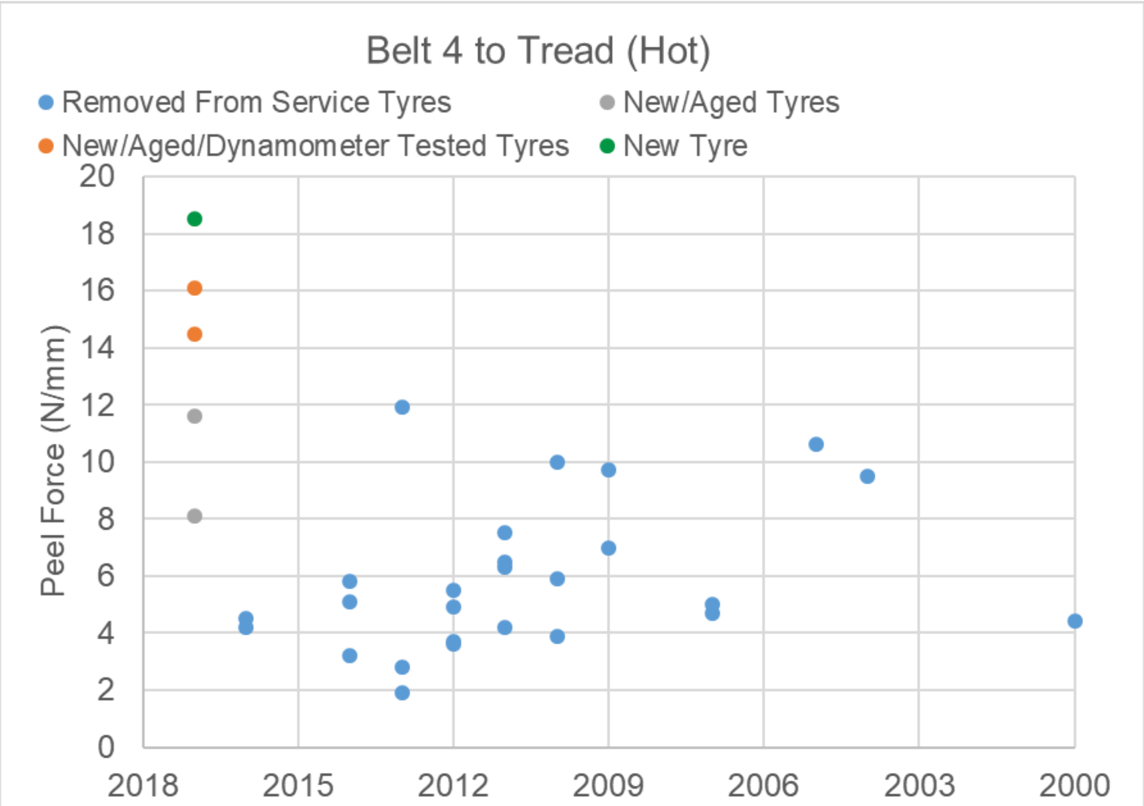


Chart 31: Interfacial peel force– Belt 4 to tread (hot test sample).

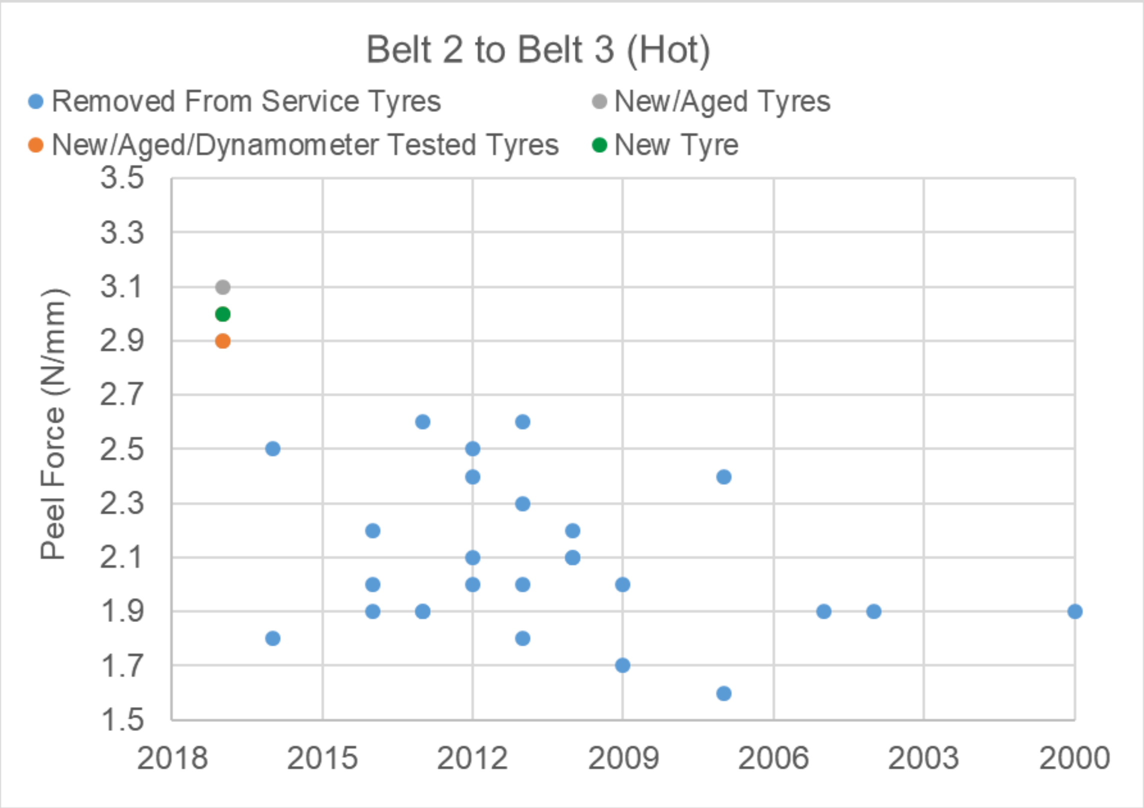


Chart 32: Interfacial peel force– Belt 2 to Belt 3 (hot test sample).

5.9 Ply Cord Physical Properties

Tables 27 and 28 below summarise the data obtained as a result of the analysis of the steel ply cords of each of the sample tyres.

Status	Assigned Tyre No.	Peak Load (N)	Strain at Peak (%)
New	1	1401	2.49
New Oven-Aged	2	1406	2.58
New Oven-Aged	3	1411	2.34
Dynamometer	4	1346	2.20
Dynamometer	5	1355	2.22
2011	6	1360	2.35
2012	7	1377	2.54
2011	8	1374	2.52
2011	10	1375	2.32
2013	11	1367	2.45
2012	12	1370	2.37
2011	13	1333	2.13
2012	14	1341	2.26
2010	15	1389	2.34
2014	16	1379	2.28
2013	17	1403	2.31
2012	18	1376	2.31
2014	19	1391	2.39
2010	20	1360	2.39
2010	21	1346	2.31
2014	22	1364	2.55
2013	26	1386	2.47

Table 27: Ply cord physical properties.

Production Year	TRL-Assigned Tire No.	Peak Load (N)	Strain at Peak (%)
2000	30	1340	2.51
2009	35	1253	2.36
2004	37	1327	2.43
2009	39	1309	2.14
2016	42	1357	2.66
2007	43	1358	2.52
2007	44	1282	2.34
2016	46	1335	2.59
2005	47	1397	2.19

Table 28: Ply cord physical properties.

This data is also summarised graphically in the charts 33 to 34 presented below:

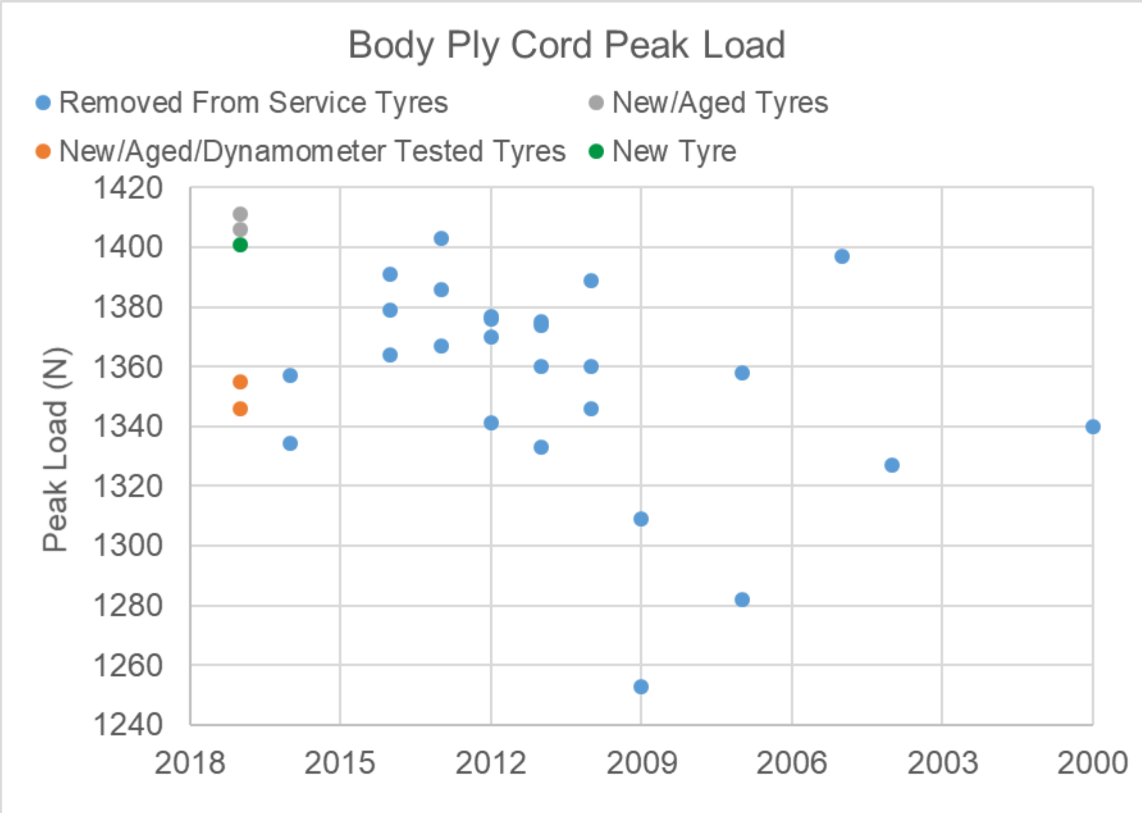


Chart 33: Ply cord peak load.

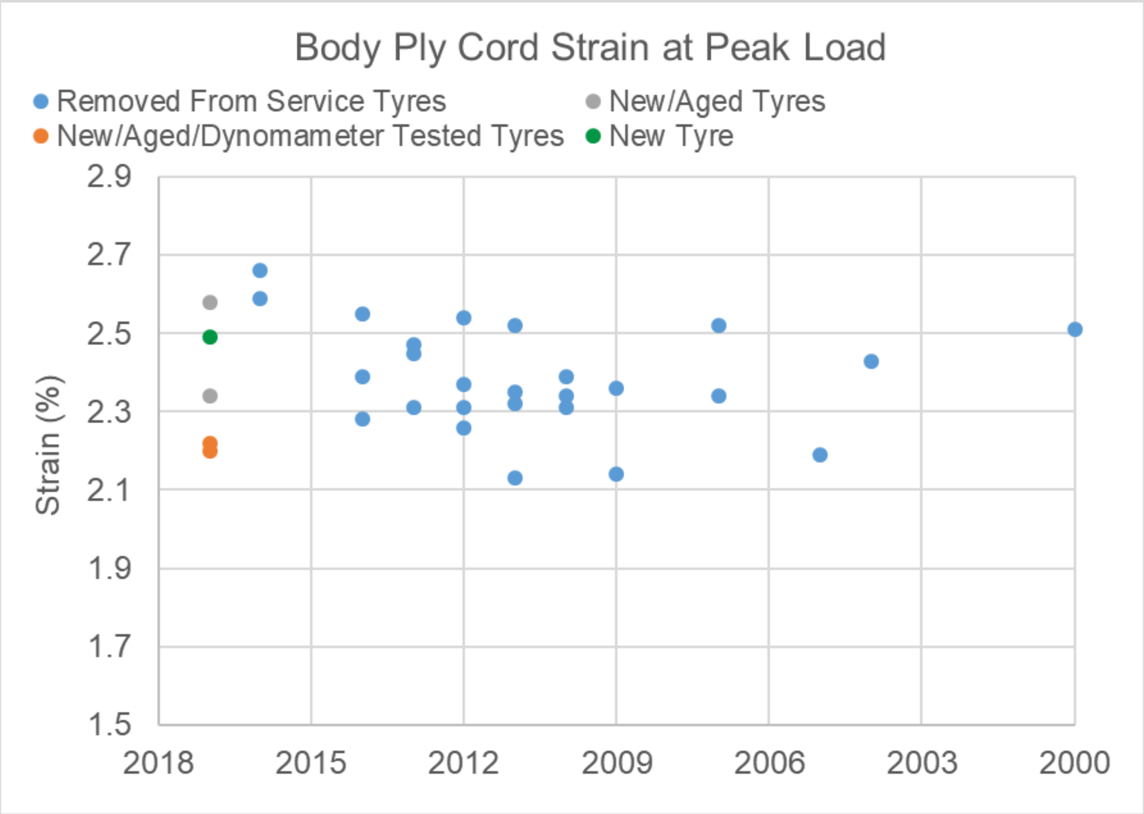


Chart 34: Ply cord peak strain.

5.10 Innerliner Permeability

Tables 29 and 30 below summarise the data obtained as a result of the permeability testing of the innerliner of each test tyre.

		Permeability (cc/m^2.day)				
Status	**TRL-Assigned Tire No.**	**Replicate 1**	**Replicate 2**	**Replicate 3**	**Replicate 4**	**Average Permeability**
2017	1	72.4	82.0	83.2	84.9	80.6
2017	2	98.3	83.7	91.5	88.8	90.6
2017	3	95.6	96.5	78.1	82.4	88.2
2017	4	91.0	99.1	79.5	73.6	85.8
2017	5	73.4	80.7	77.3	81.9	78.3
2011	6	75.4	81.8	81.0	64.2	75.6
2012	7	68.4	59.9	78.3	77.4	71.0
2011	8	68.5	86.2	65.1	63.1	70.7
2011	10	82.7	71.3	64.8	N/A	72.9
2013	11	78.6	66.4	80.8	82.1	77.0
2012	12	69.4	71.7	72.9	68.5	70.6
2011	13	76.1	60.6	59.3	65.0	65.3
2012	14	65.6	73.5	56.6	73.8	67.4
2010	15	58.1	68.8	59.8	49.6	59.1
2014	16	124.0	146.0	109.0	54.9	108.5
2013	17	59.5	54.9	65.5	51.9	58.0
2012	18	76.0	94.0	63.7	68.3	75.5
2014	19	95.5	111.0	76.9	83.7	91.8
2010	20	60.2	61.7	73.8	68.3	66.0
2010	21	82.2	88.6	70.0	67.6	77.1
2014	22	73.0	75.7	80.8	63.2	73.2
2013	26	107.0	111.0	70.3	89.4	94.4

Table 29: Innerliner permeability.

		Permeability (cc/m^2.day)				
Status	**TRL-Assigned Tire No.**	**Replicate 1**	**Replicate 2**	**Replicate 3**	**Replicate 4**	**Average Permeability**
2000	30	99.9	93.6	134.0	119.0	112.0
2009	35	59.4	59.2	59.5	46.0	56.0
2004	37	82.3	65.0	77.6	62.4	71.8
2009	39	69.3	55.3	59.9	52.8	59.3
2016	42	53.7	90.0	66.4	50.0	65.0
2007	43	69.1	69.3	61.1	49.7	62.3
2007	44	76.8	71.1	81.0	75.1	76.0
2016	46	65.3	62.8	51.4	55.7	58.8
2005	47	99.4	87.9	103.0	85.3	94.0

Table 30: Innerliner permeability (cont.)

Note: Due to the limited amount of innerliner compound supplied by the US lab from Tyre 10, only three (3) test replicates were possible.

This data is also summarised graphically in the chart 35 presented below:

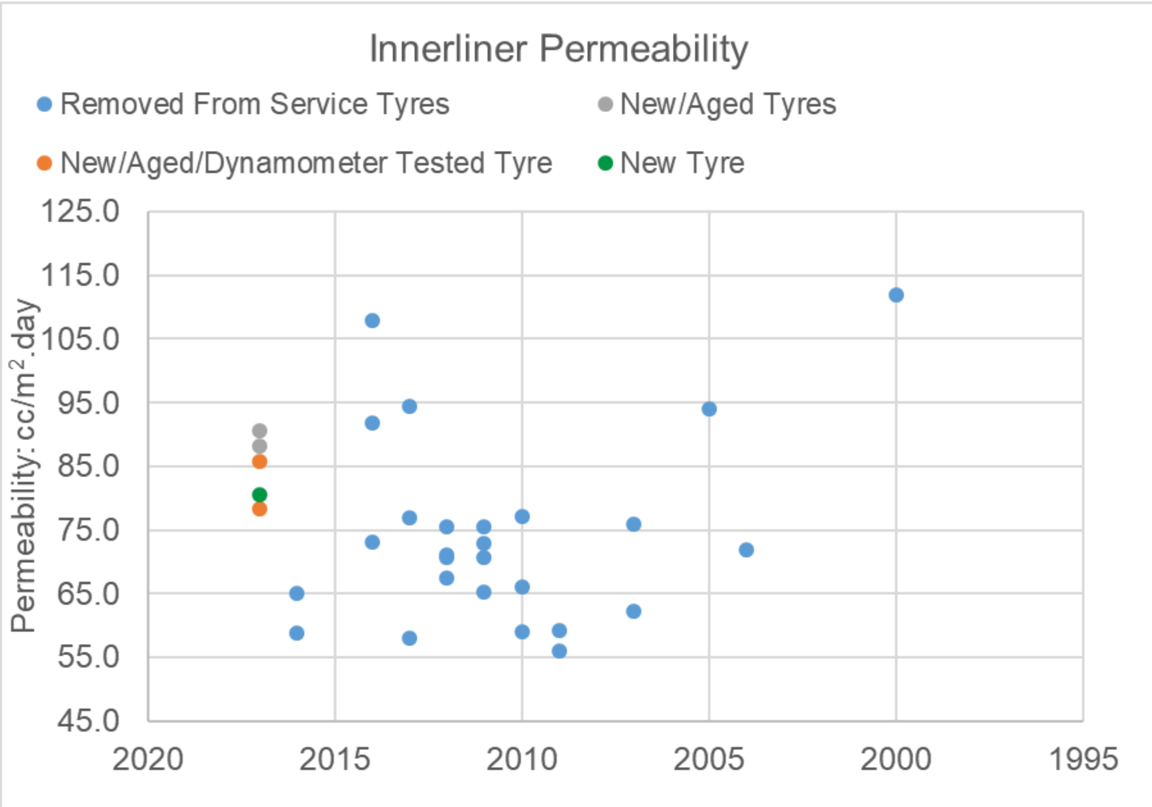


Chart 35: Innerliner permeability.

6. LIMITATIONS

Although the information is believed to be reliable, the data is provided without implied warranties of any kind.

Smithers Rapra is an ISO/IEC 17025 laboratory. However, unless a test is specifically stated to be included within the scope of our accreditation, it should be assumed not to be so. Note that any opinions or interpretations given are outside the scope of our UKAS accreditation.

This report has been prepared solely based on information supplied up to the point of its completion and has been accepted in good faith.

The results relate only to the samples tested and to the particular tests carried out and cannot prove that the material is generally fit for any intended purpose. The samples were tested as received and to the supplier's instructions and no responsibility can be taken for them being unrepresentative.

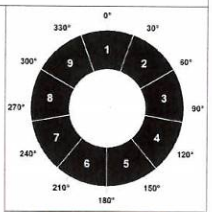
Smithers Rapra will destroy all the supplied material(s) relating to this contract twelve months after the work is completed unless a written request is received within that time that the client wishes to have the material returned.

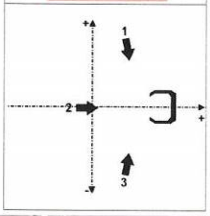
Smithers Rapra shall not be liable or obligated under any contract, negligence, strict liability or other legal or equitable theory to any party for any amounts representing loss of revenues, loss of profits, loss of business or indirect, consequential, special or punitive damages, even if advised of the possibility of such damages.

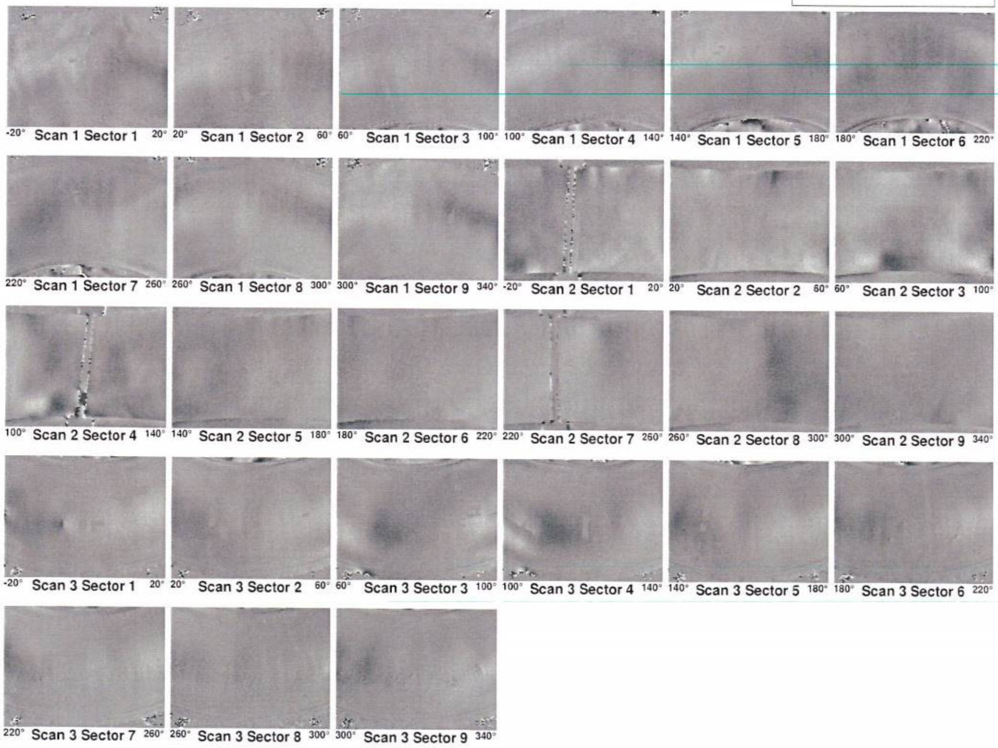
APPENDIX 1 – Shearography Test Results

Tire Test Report

Date:	22.05.2018 13:44
File:	d:\ittdata\1803975_InitialScan000001.vie Tire #1
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°

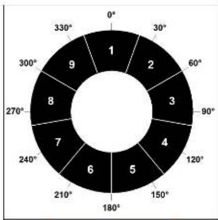




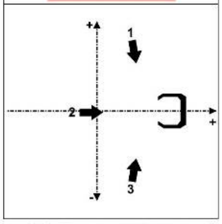


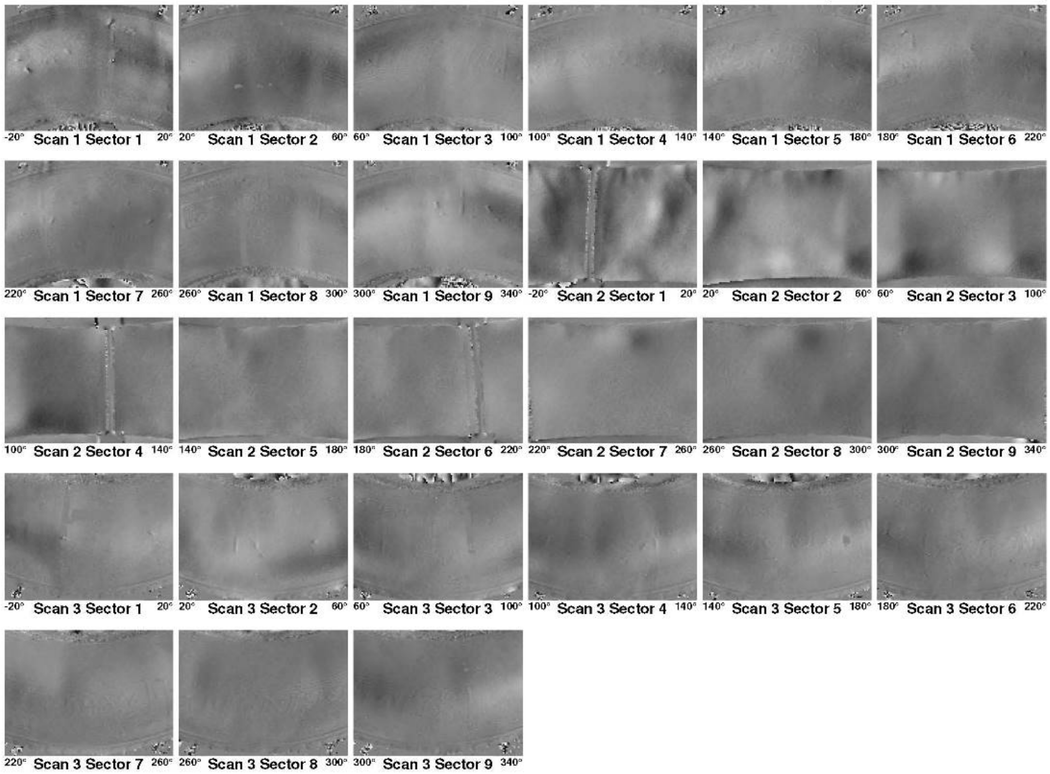
Tyre #1

Tire Test Report



Date:	19.07.2018 10:40
File:	d:\ittdata\1803974_after_oven_age000001.vie Tire #2
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°





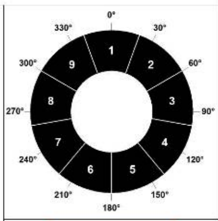
TYRE #2

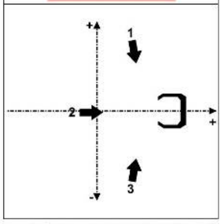
Smithers Rapra | Shawbury | Shropshire, SY4 4NR | +44 (0) 1939 250383 | www.smithersrapra.com

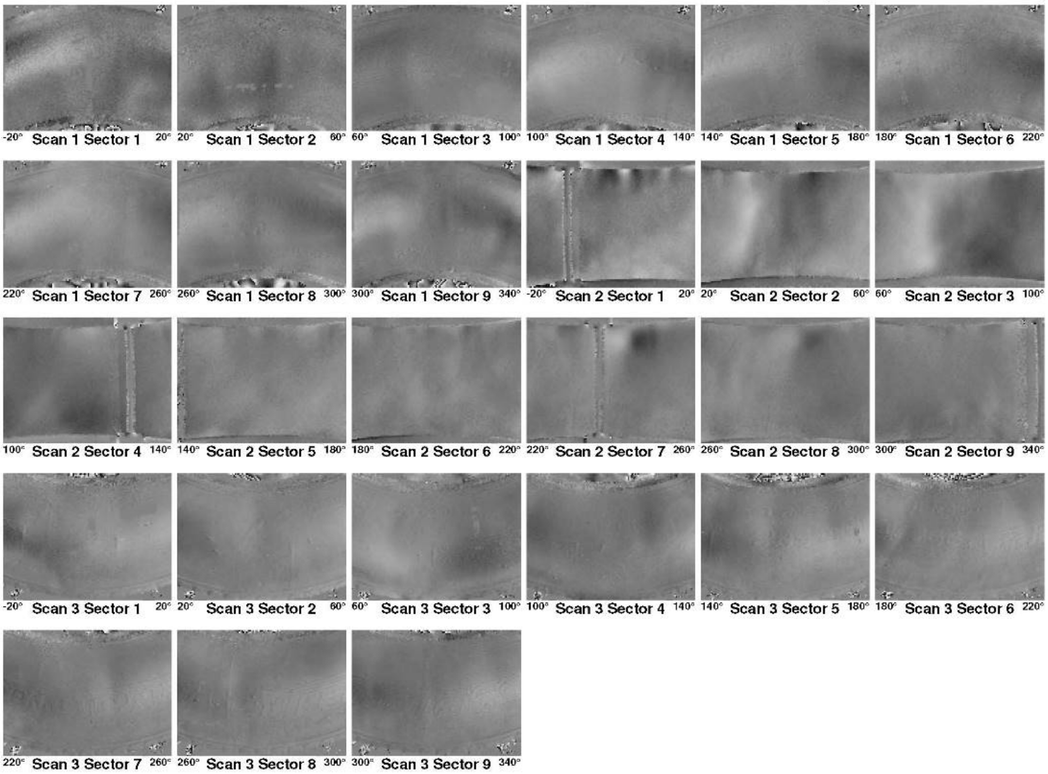
Smithers Rapra and Smithers Pira Ltd | Registered in England & Wales No. 5761324 | Registered Office as above

Tire Test Report

Date:	19.07.2018 13:25
File:	d:\ittdata\1803973_after_oven_age000004.vie Tire #3
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°



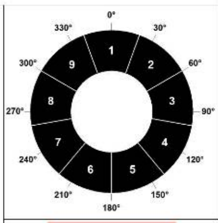


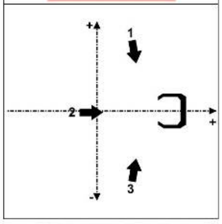


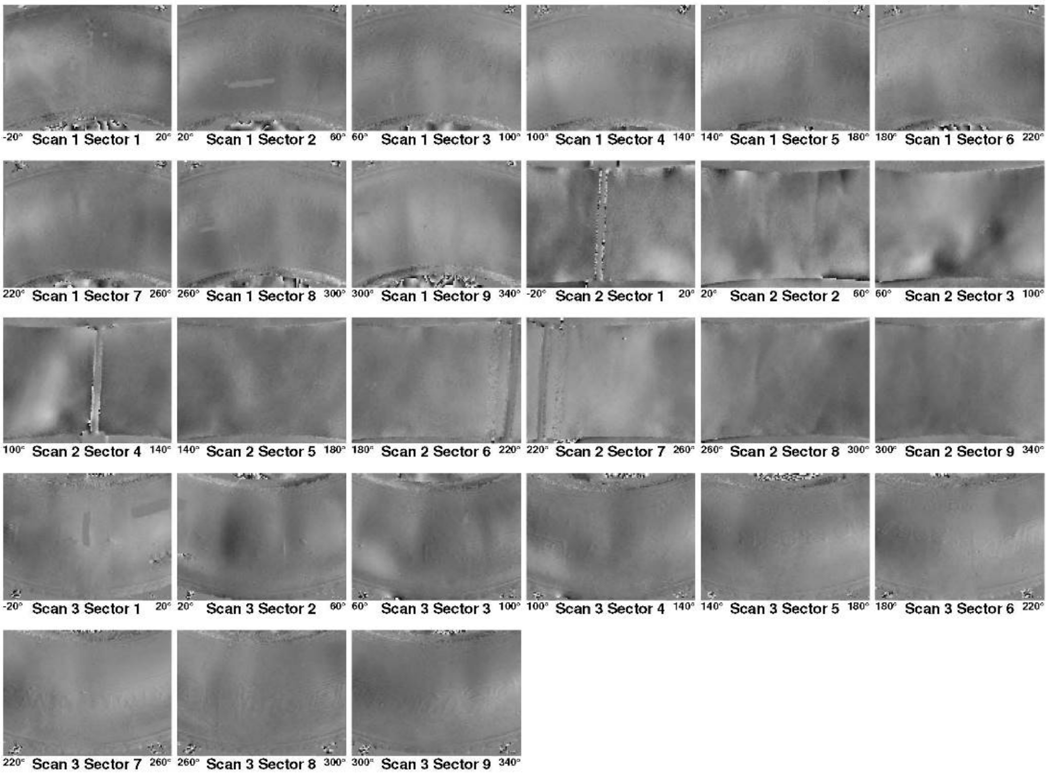
TYRE #3

Tire Test Report

Date:	23.07.2018 09:01
File:	d:\ittdata\1803989_after_48hrs000001.vie
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°



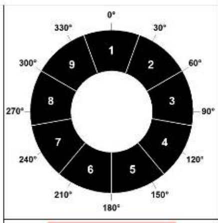


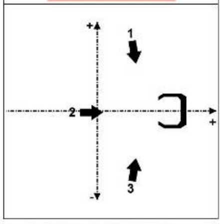


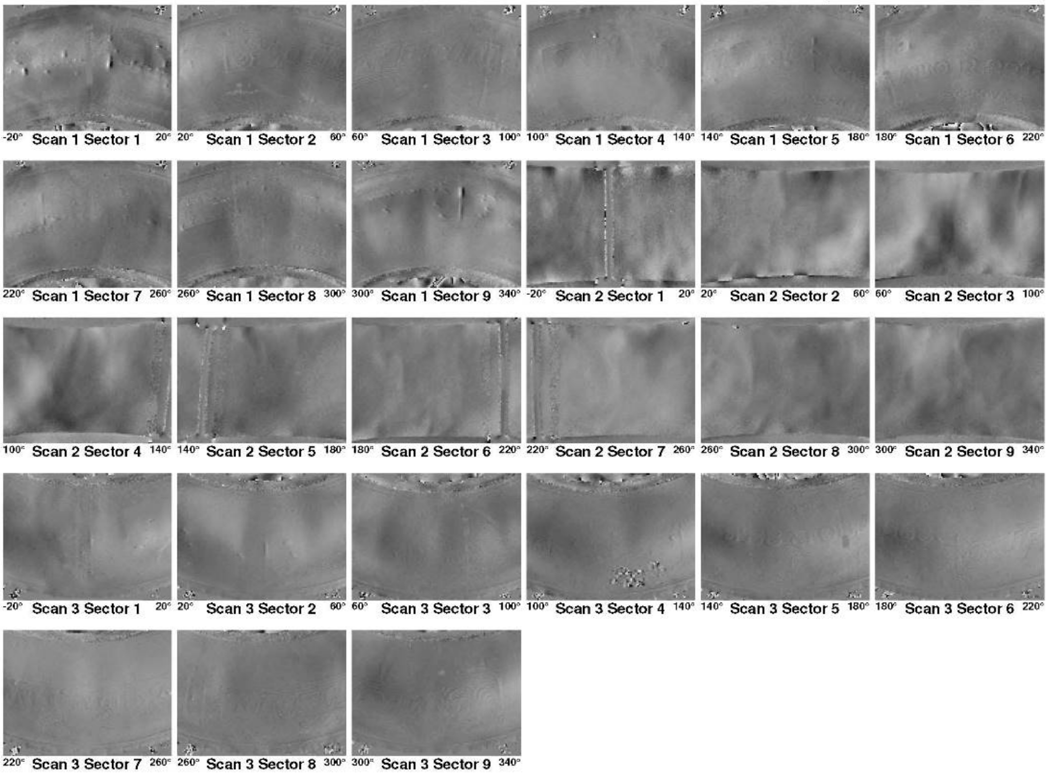
TYRE #4

Tire Test Report

Date:	23.07.2018 08:31
File:	d:\ittdata\1803988_after_48hrs000001.vie
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°



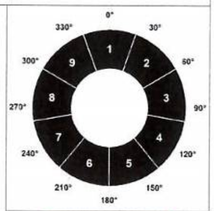


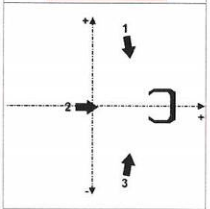


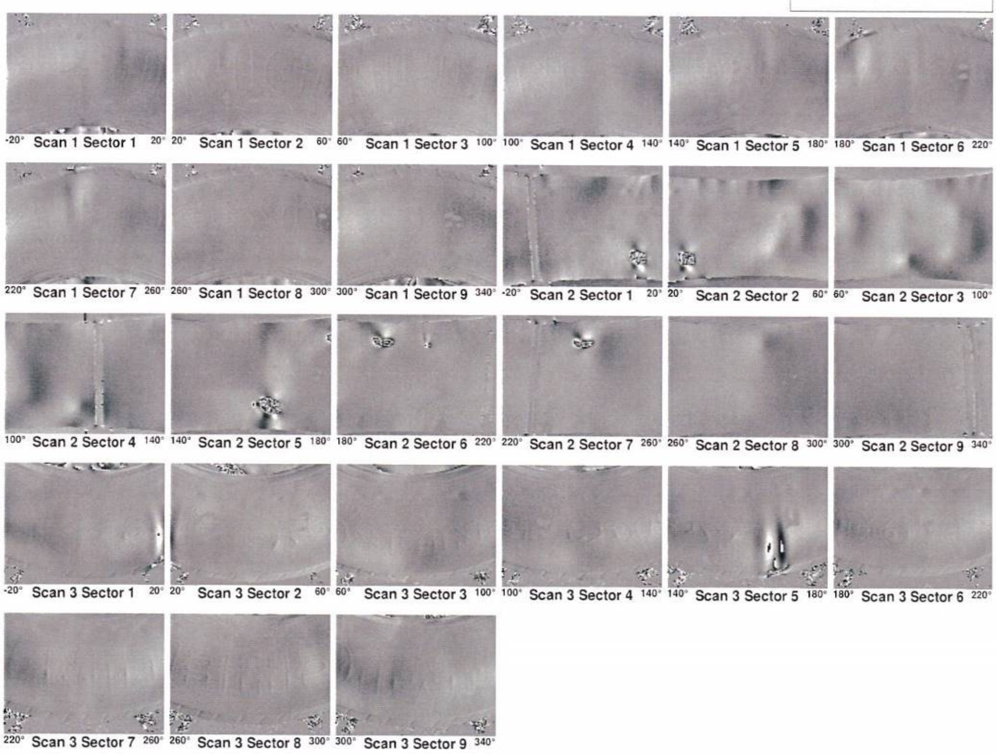
TYRE #5

Tire Test Report

Date:	16.05.2018 10:42
File:	d:\ittdata\1803986_InitialScan000001.vie Tire #6
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°



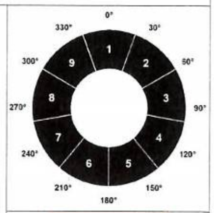


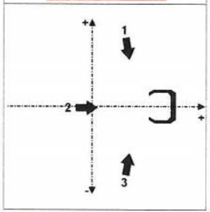


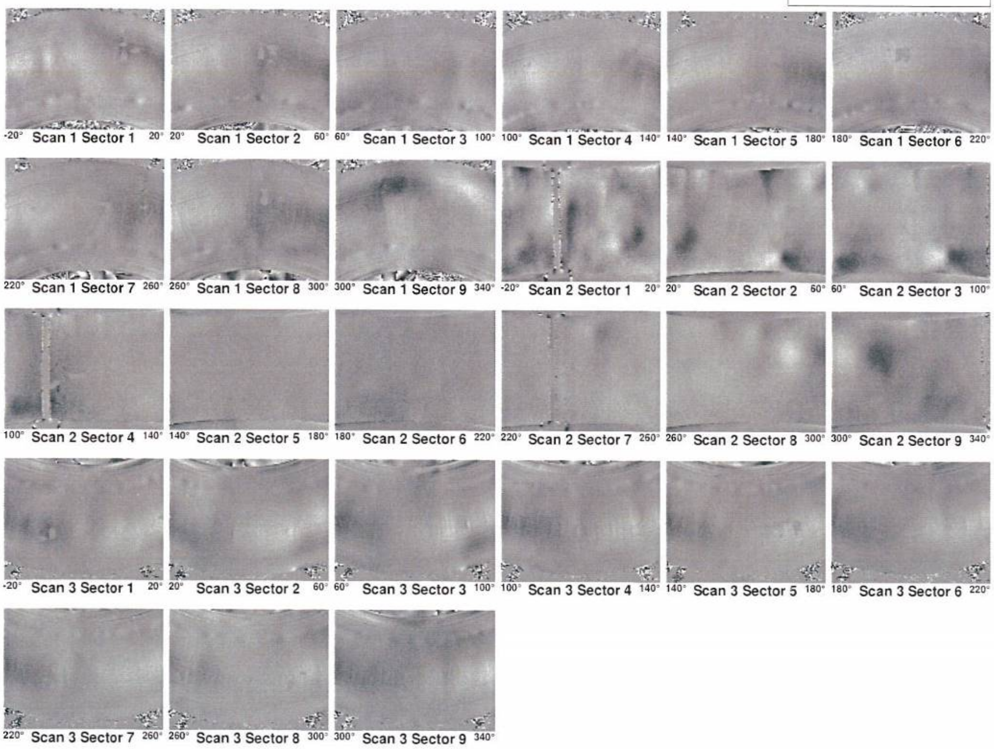
TYRE #6

Tire Test Report

Date:	22.05.2018 20:04
File:	d:\ittdata\1803982_InitialScan000001.vie Tire #7
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°



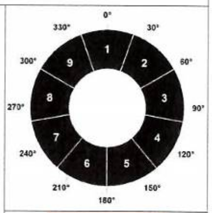


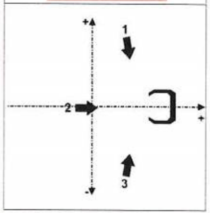


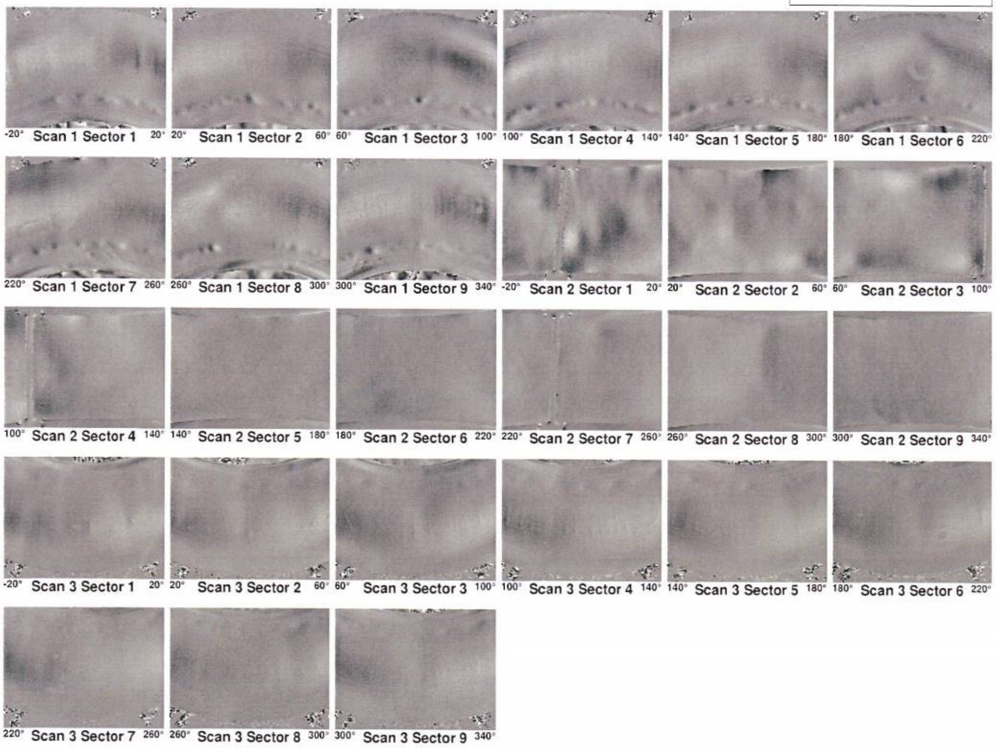
TYRE #7

Tire Test Report

Date:	16.05.2018 13:57	
File:	d:\ittdata\1803979_InitialScan000001.vie	Tire #8
Description:	295_80R22_5	
Operator:	bs	
Test file:	D:\ITTSettings\295_80R22_5tst.tst	
Scan number:	All Scans	
Number of sectors:	9, 9, 9	
Vacuum:	50, 50, 50 mBar	
Horizontal head position:	330, 50.2, 330 mm	
Vertical head position:	549.8, 159.9, 549.8 mm	
Head tilt:	-80, 0, -80°	



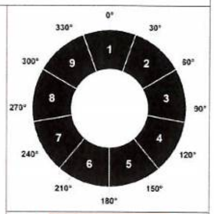


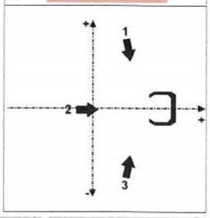


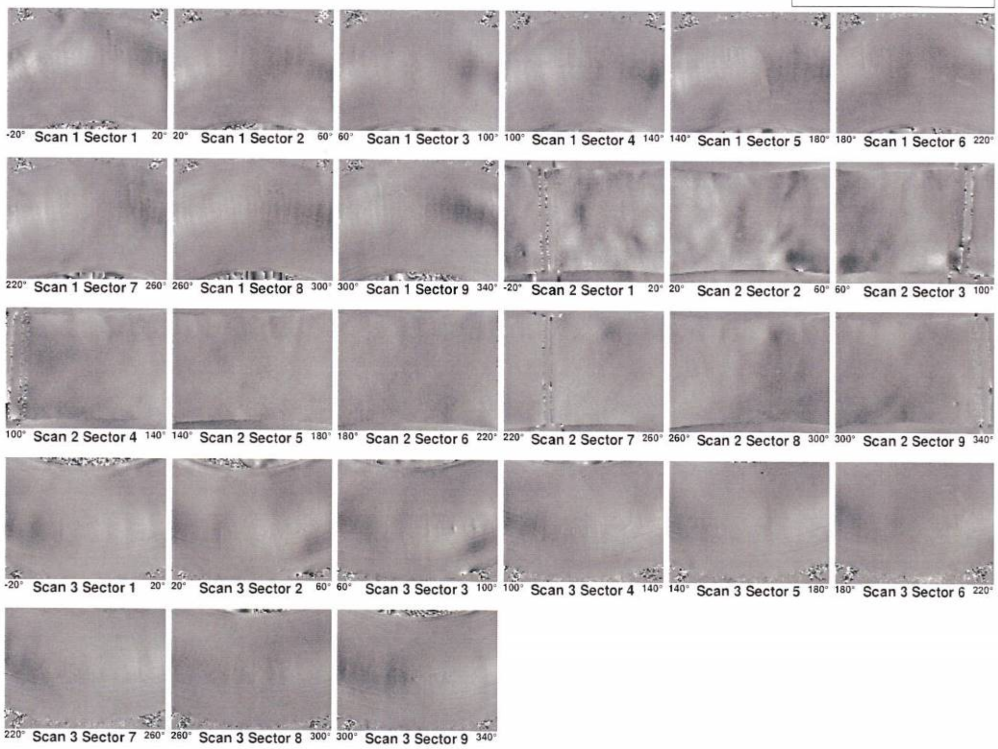
TYRE #8

Tire Test Report

Date:	22.05.2018 20:40
File:	d:\ittdata\1803980_InitialScan000001.vie Tire #10
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°







TYRE # 10

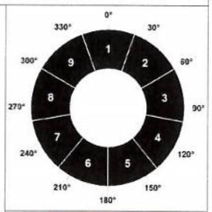
Tire Test Report

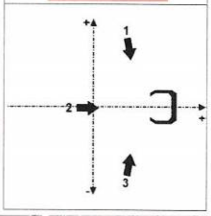
Date: 22.05.2018 09:00
File: d:\ittdata\1803971_InitialScan000001.vie Tire #11

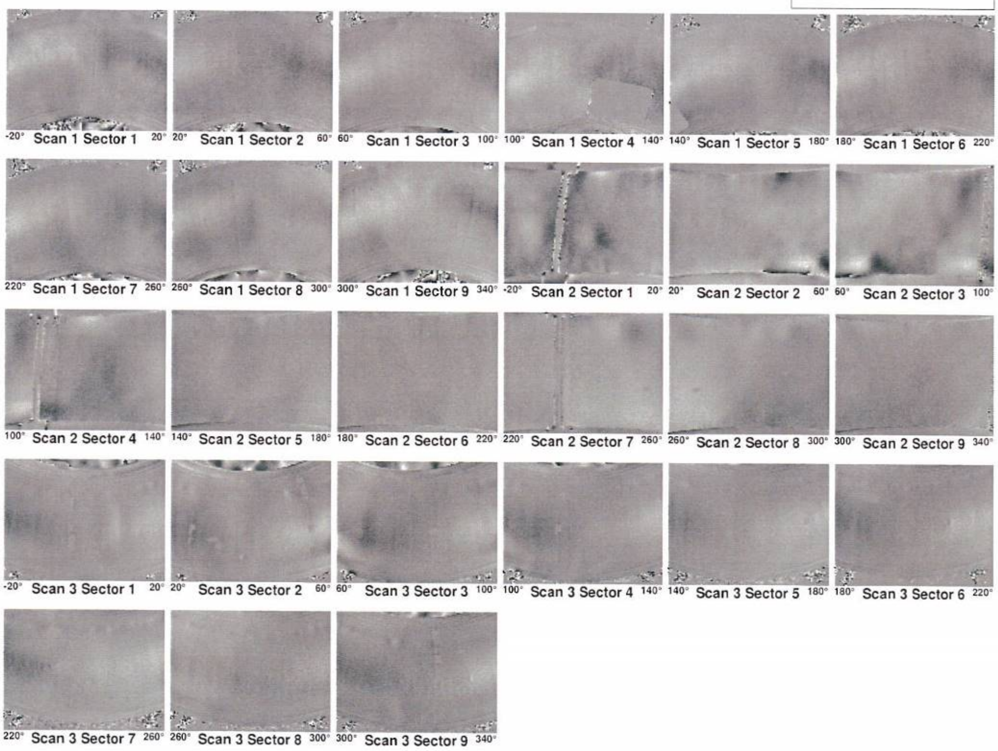
Description: 295_80R22_5
Operator: bs
Test file: D:\ITTSettings\295_80R22_5tst.tst

Scan number: All Scans

Number of sectors: 9, 9, 9
Vacuum: 50, 50, 50 mBar
Horizontal head position: 330, 50.2, 330 mm
Vertical head position: 549.8, 159.9, 549.8 mm
Head tilt: -80, 0, -80°



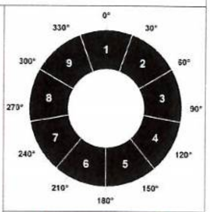


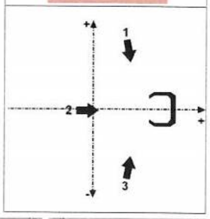


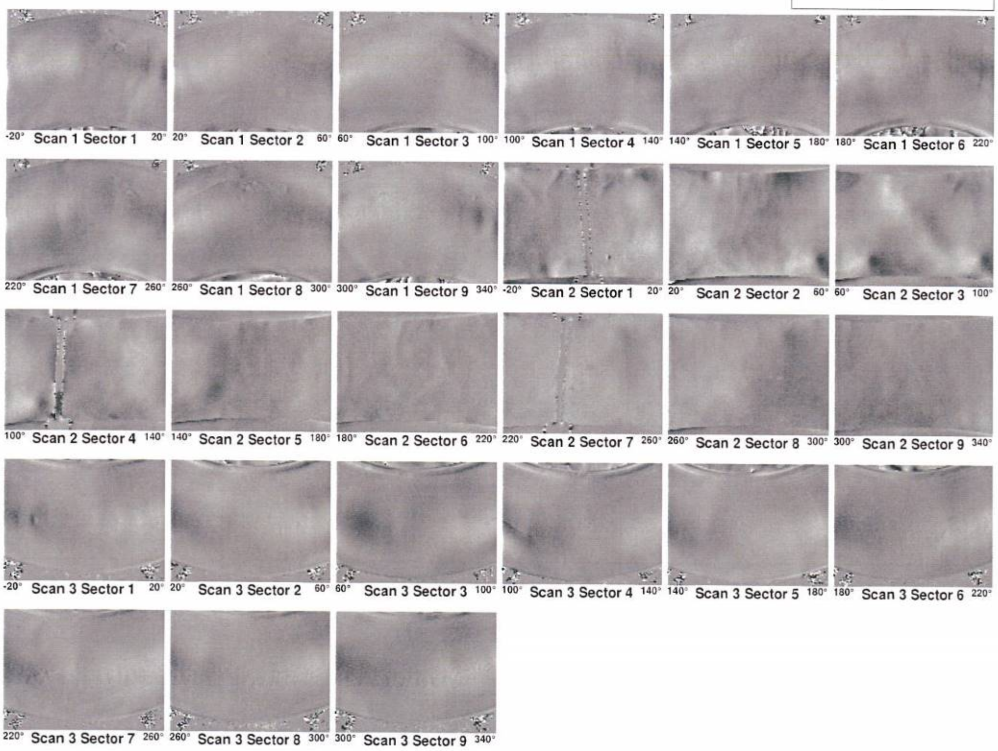
TYRE #11

Tire Test Report

Date:	22.05.2018 19:29	
File:	d:\ittdata\1803972_InitialScan000001.vie	Tire #12
Description:	295_80R22_5	
Operator:	bs	
Test file:	D:\ITTSettings\295_80R22_5tst.tst	
Scan number:	All Scans	
Number of sectors:	9, 9, 9	
Vacuum:	50, 50, 50 mBar	
Horizontal head position:	330, 50.2, 330 mm	
Vertical head position:	549.8, 159.9, 549.8 mm	
Head tilt:	-80, 0, -80°	



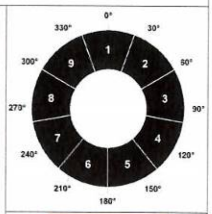


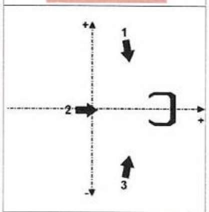


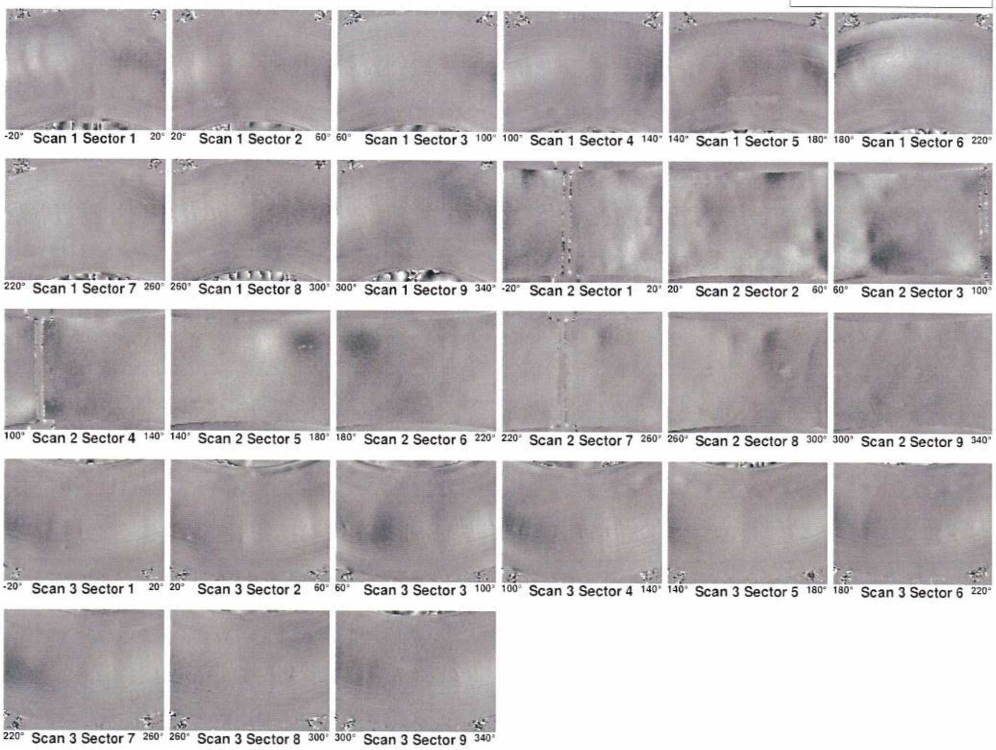
TYRE #12

Tire Test Report

Date:	22.05.2018 19:45
File:	d:\ittdata\1803981_InitialScan000001.vie Tire #13
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°



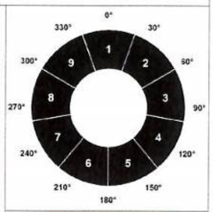


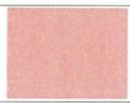


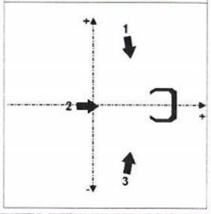
TYRE #13

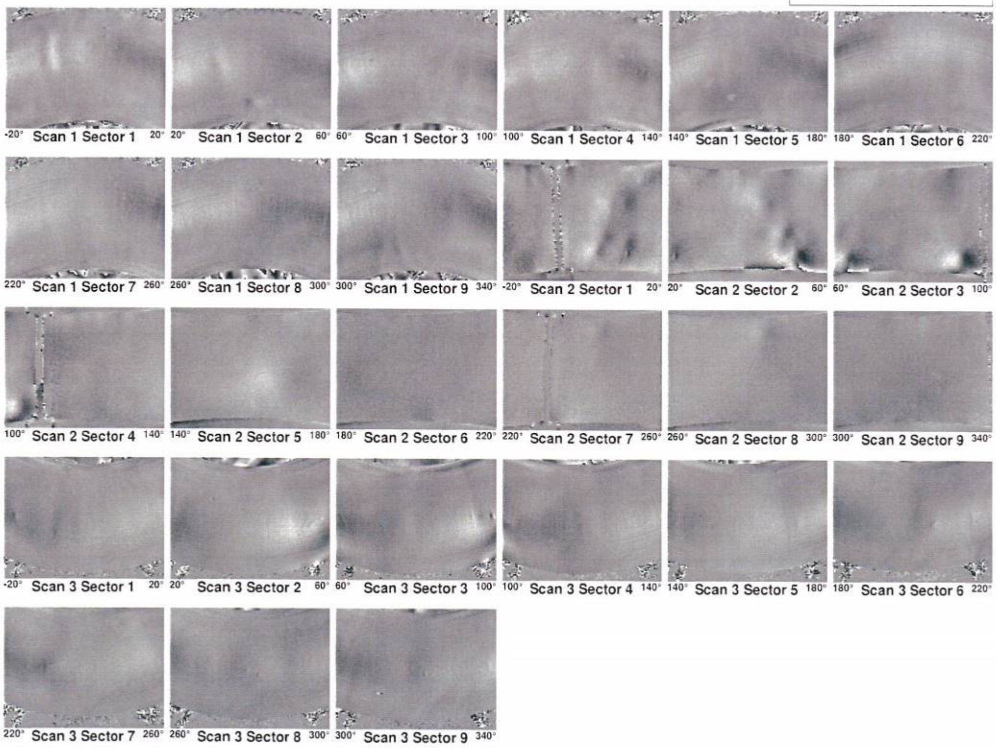
Tire Test Report

Date:	22.05.2018 21:28
File:	d:\ittdata\1803983_InitialScan000001.vie Tire #14
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°





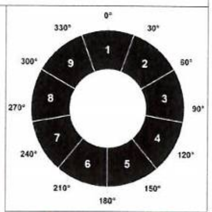


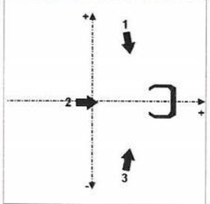


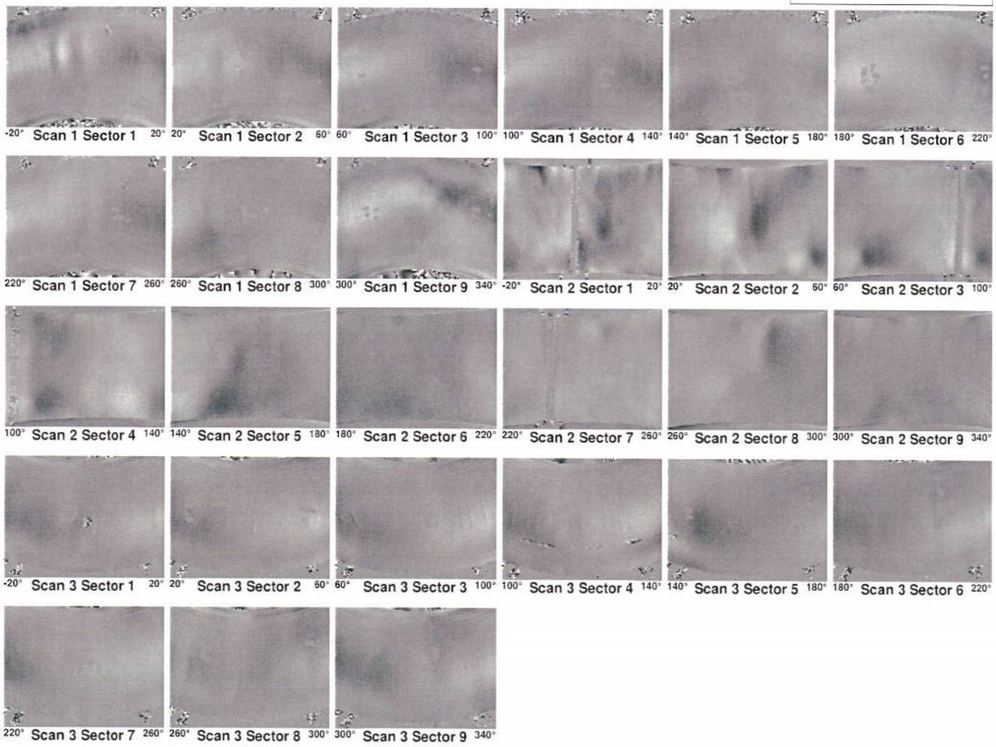
TYRE #14

Tire Test Report

Date:	16.05.2018 11:05
File:	d:\ittdata\1803976_InitialScan000001.vie Tire #15
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°



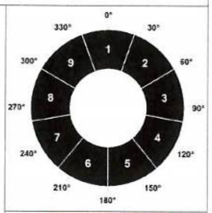


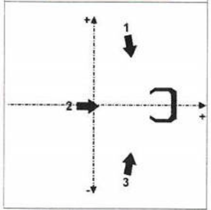


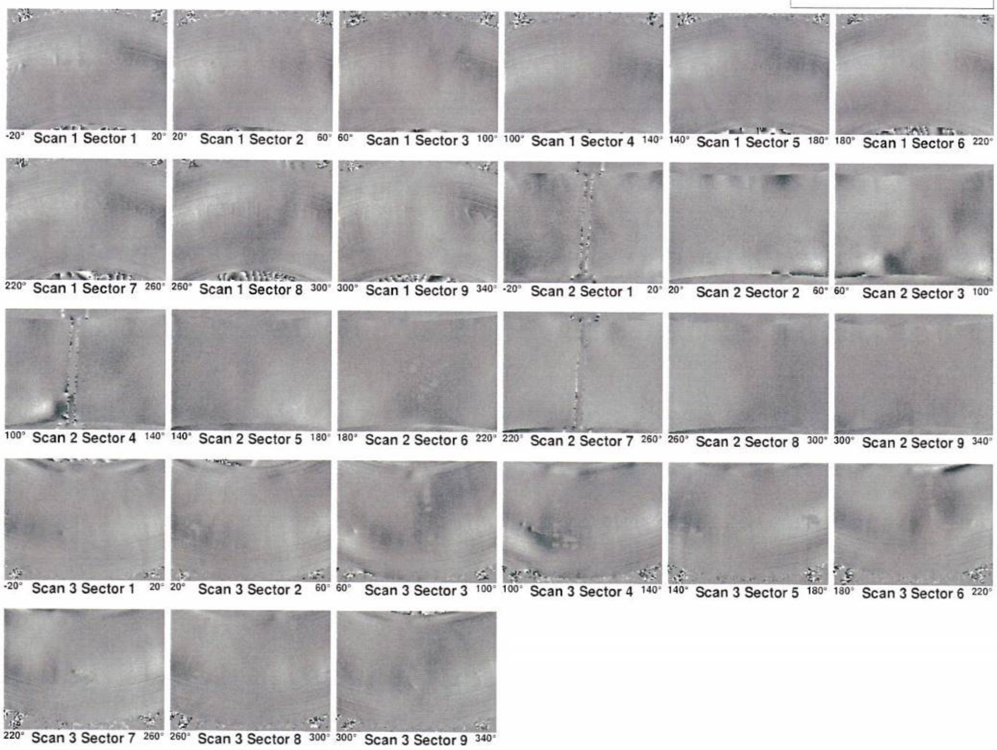
TYRE #15

Tire Test Report

Date:	22.05.2018 09:46
File:	d:\ittdata\1803985_InitialScan000001.vie Tire #16
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°



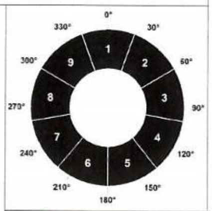


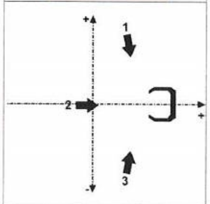


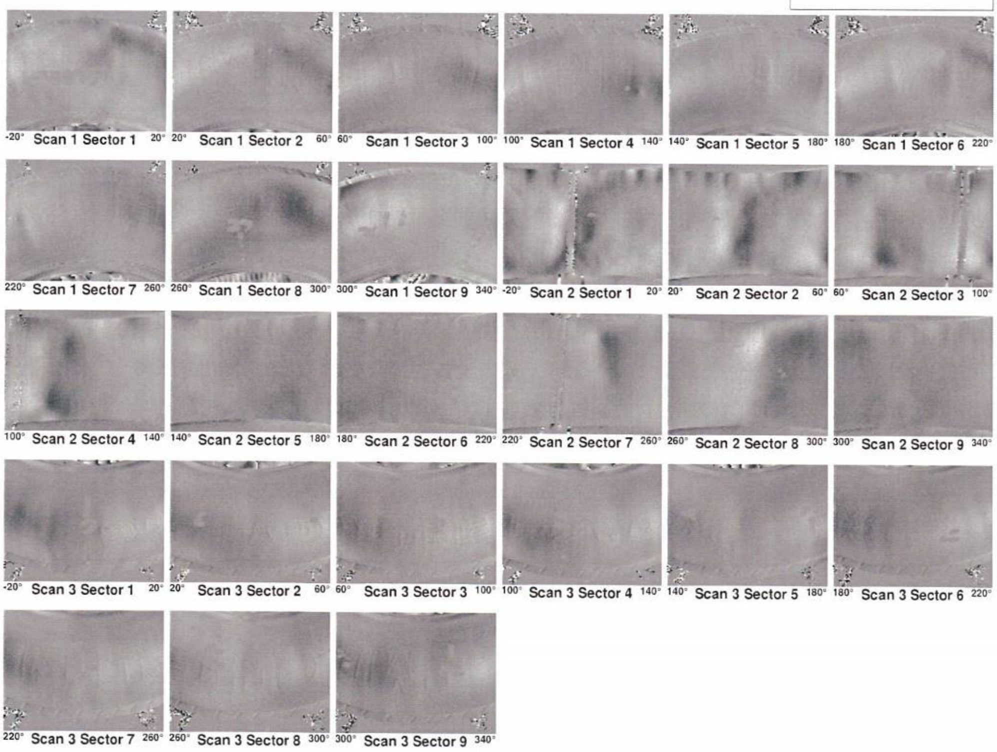
TYRE #16

Tire Test Report

Date:	16.05.2018 13:27
File:	d:\ittdata\1803987_InitialScan000001.vie Tire #17
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°



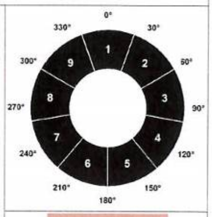


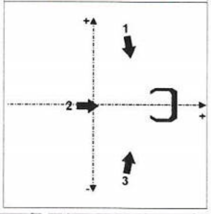


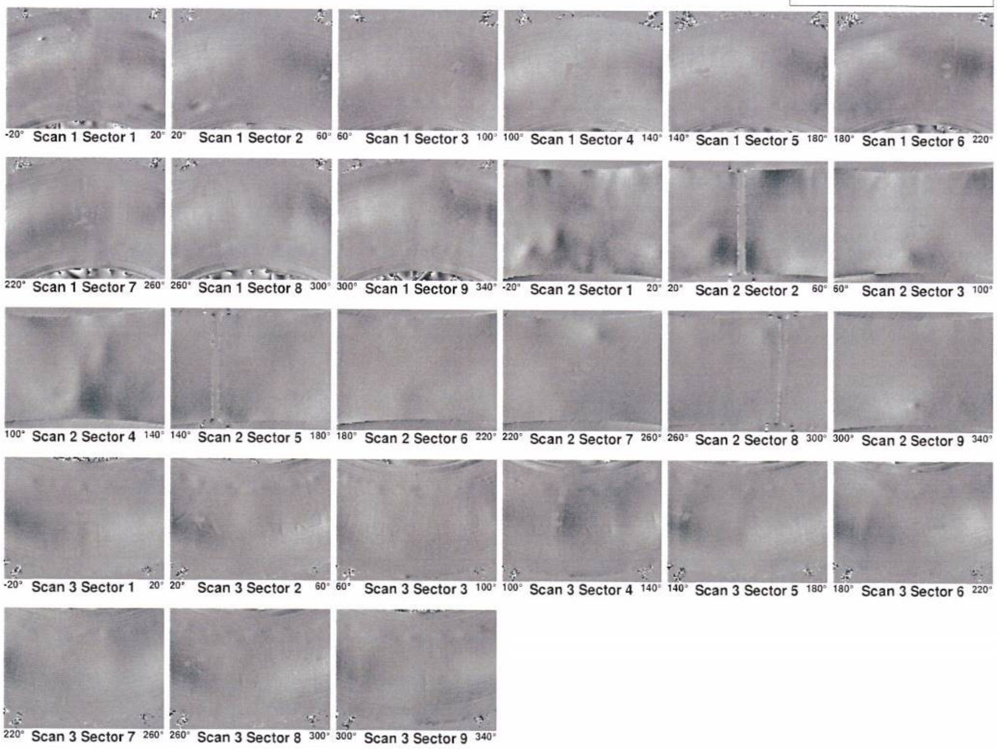
TYRE #17

Tire Test Report

Date:	16.05.2018 14:55
File:	d:\ittdata\1803984_InitialScan000001.vie Tire #18
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°



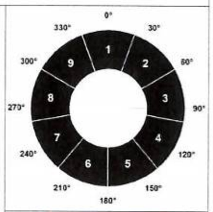


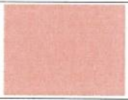


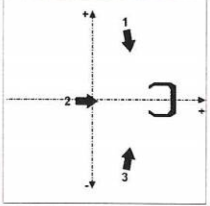
TYRE #18

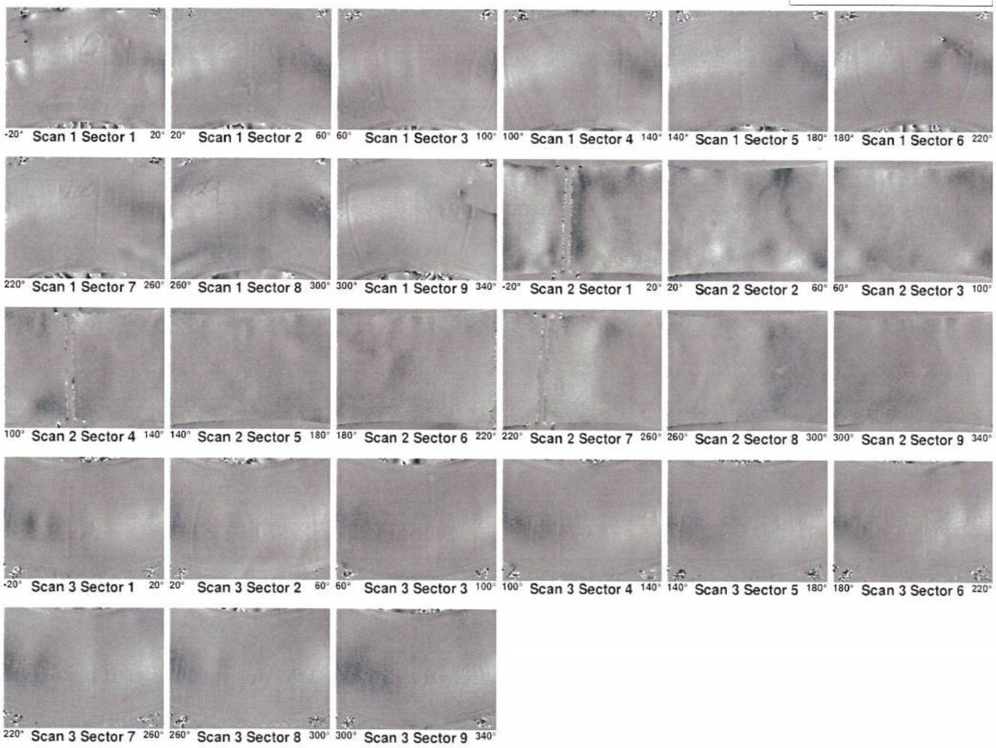
Tire Test Report

Date:	22.05.2018 14:30
File:	d:\ittdata\1803970_InitialScan000001.vie Tire #19
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°





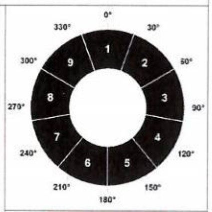


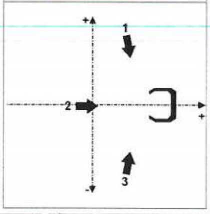


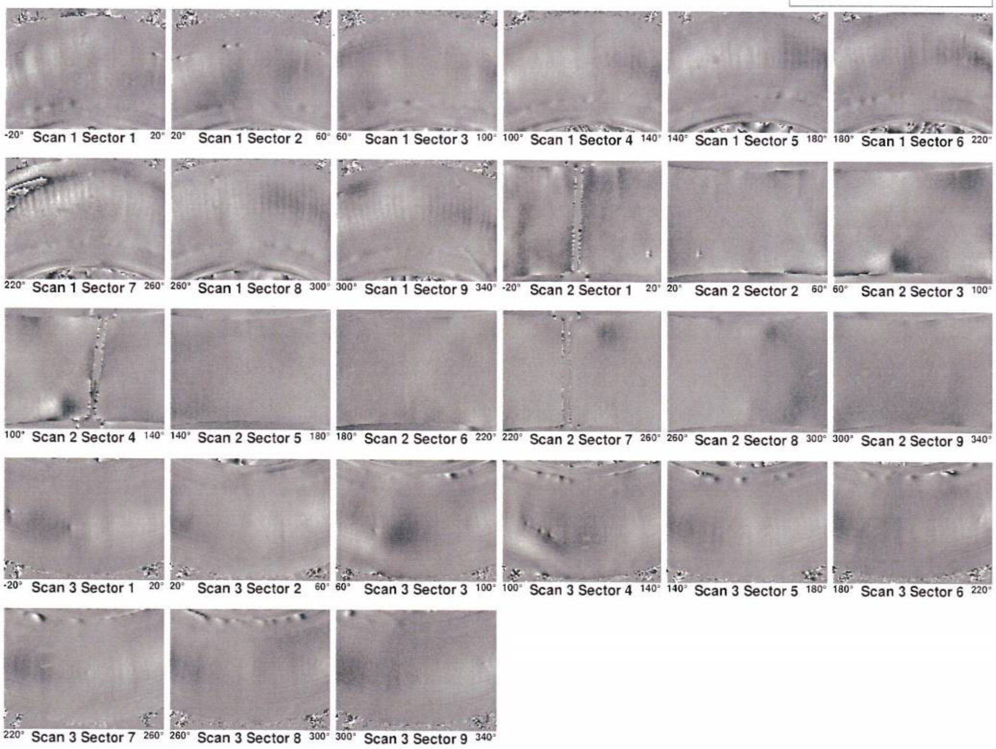
TYRE #19

Tire Test Report

Date:	22.05.2018 10:44
File:	d:\ittdata\1803977_InitialScan000001.vie Tire #20
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°



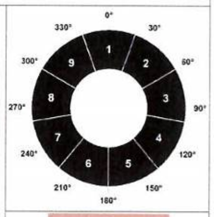


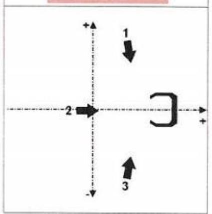


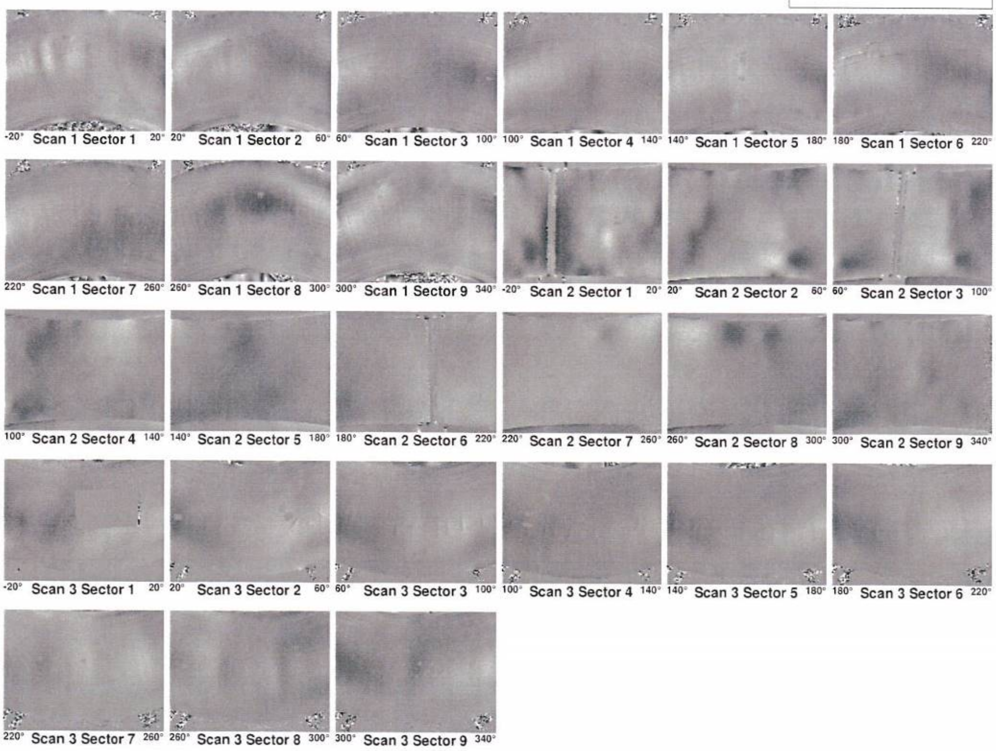
TYRE #20

Tire Test Report

Date:	16.05.2018 13:42
File:	d:\ittdata\1803978_InitialScan000001.vie Tire #21
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°

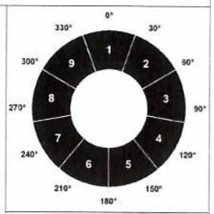




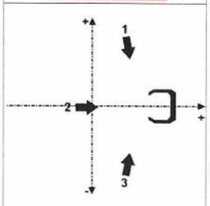


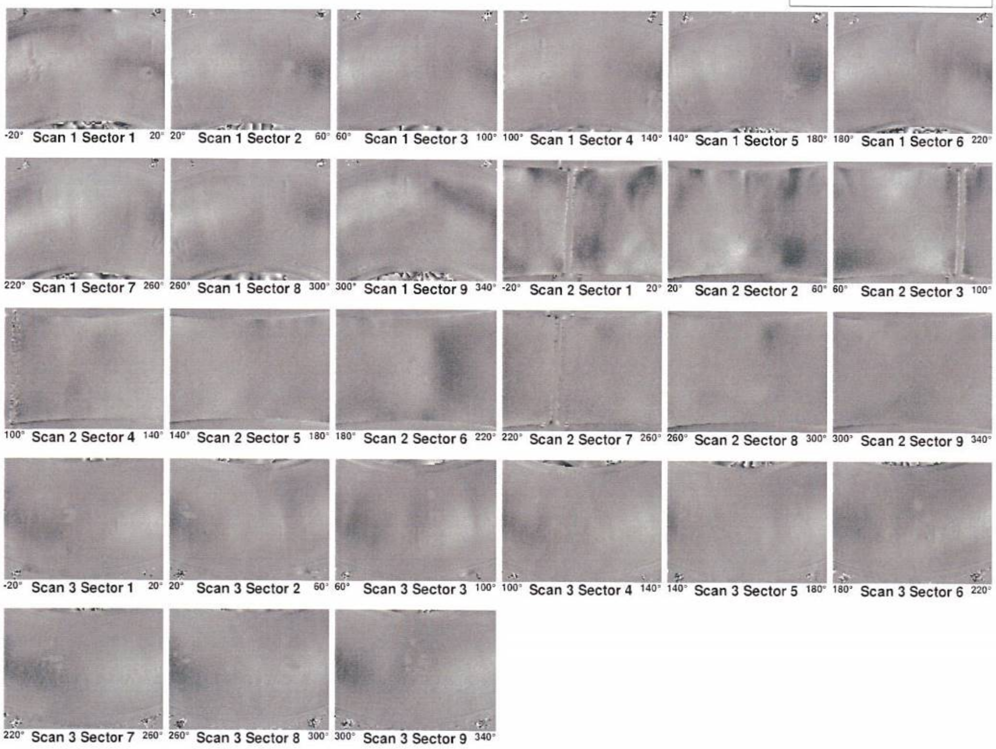
TYRE #21

Tire Test Report



Date:	16.05.2018 14:18
File:	d:\ittdata\1803969_InitialScan000001.vie Tire #22
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°



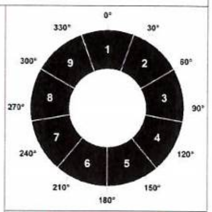


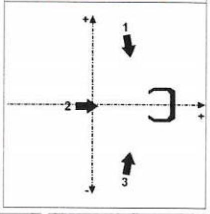
TYRE #22

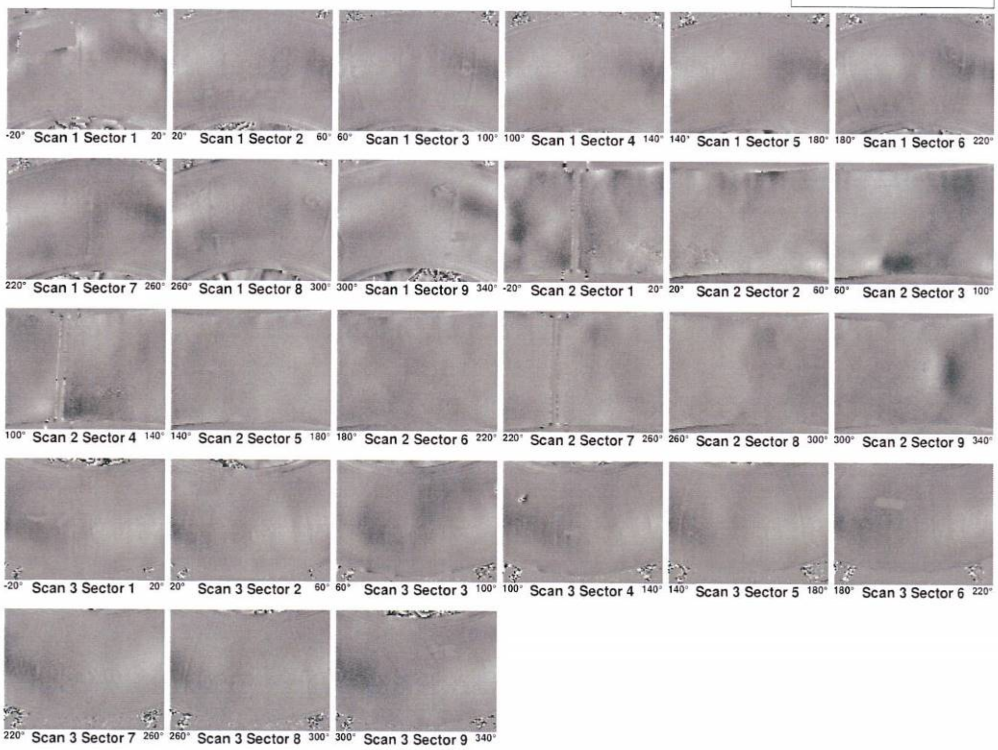
Tire Test Report

Date:	22.05.2018 11:31
File:	d:\ittdata\1803968_InitialScan000001.vie
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°

Tire # 26



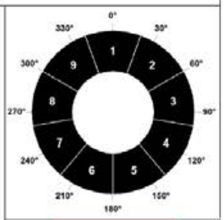


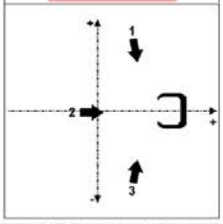


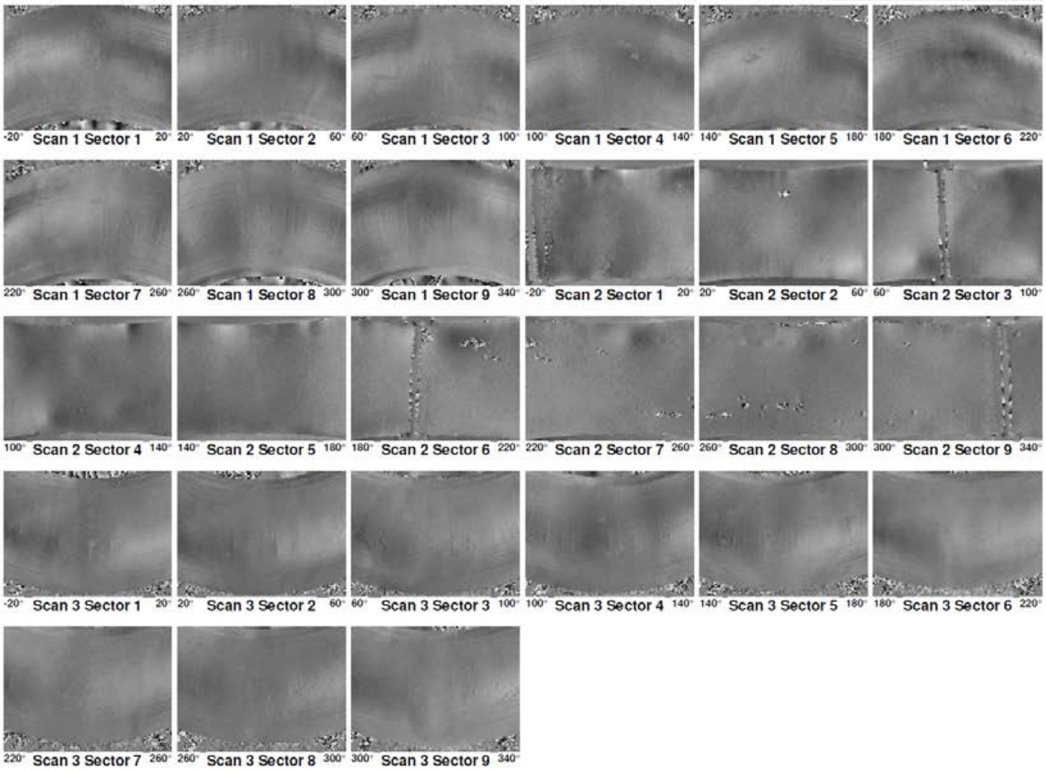
TYRE #26

Tire Test Report

Date:	10.12.2018 10:34
File:	d:\ittdata\1809216_Initial000003.vie
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°



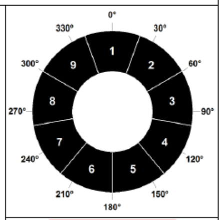


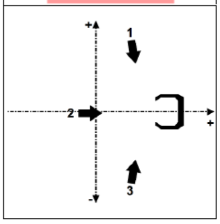


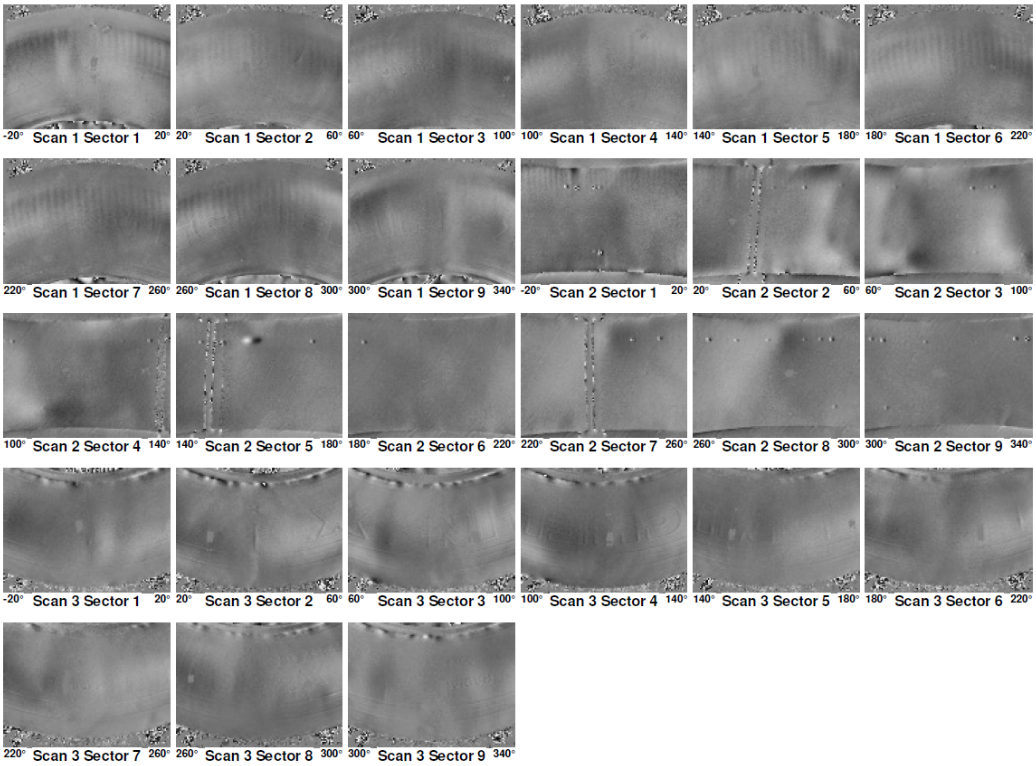
TYRE #30

Tire Test Report

Date:	10.12.2018 08:28
File:	d:\ittdata\1809214_Initial000001.vie
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°



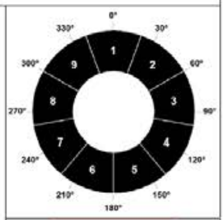


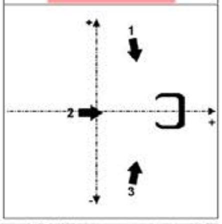


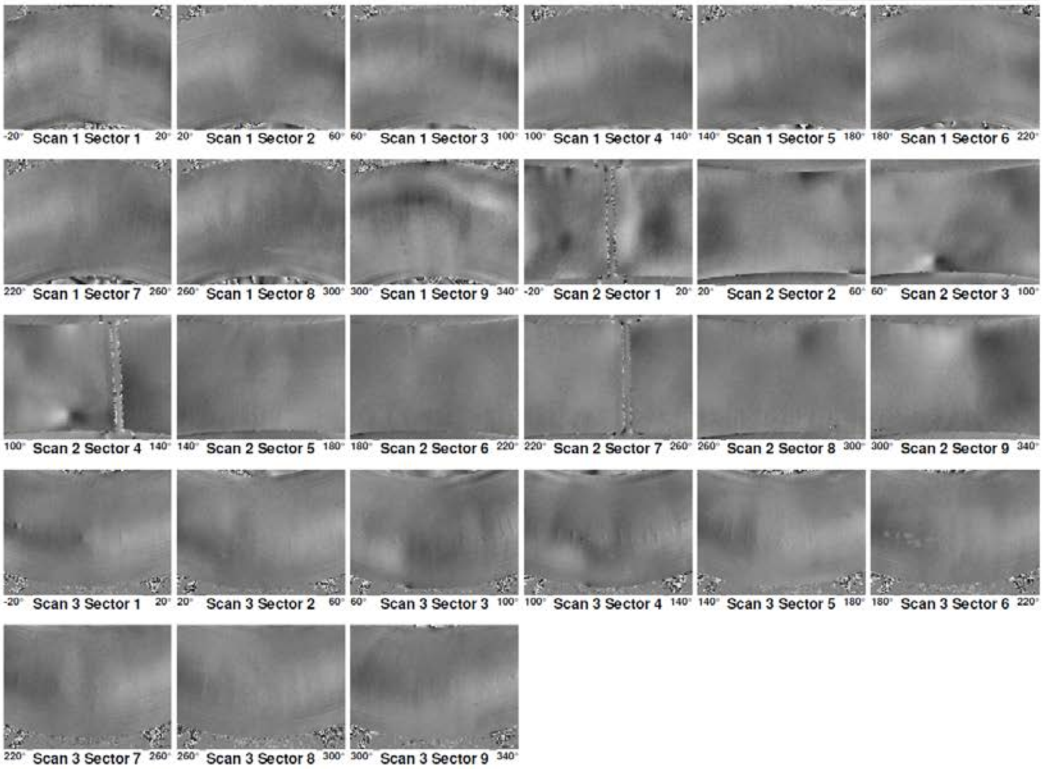
TYRE #35

Tire Test Report

Date:	10.12.2018 06:27
File:	d:\ittdata\1809209_Initial000001.vie
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°



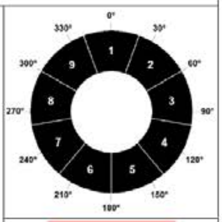


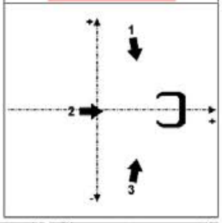


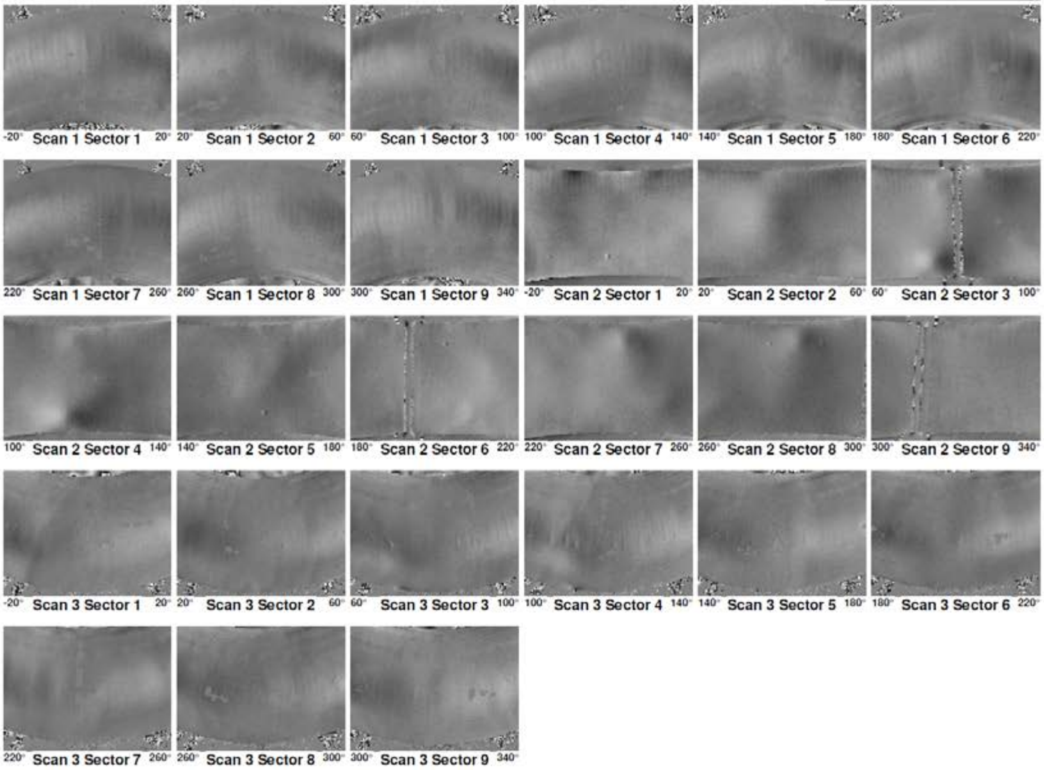
TYRE #37

Tire Test Report

Date:	10.12.2018 10:20
File:	d:\ittdata\1809215_Initial000003.vie
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°



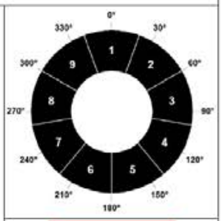


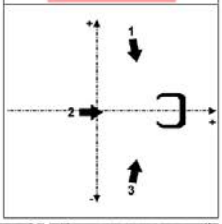


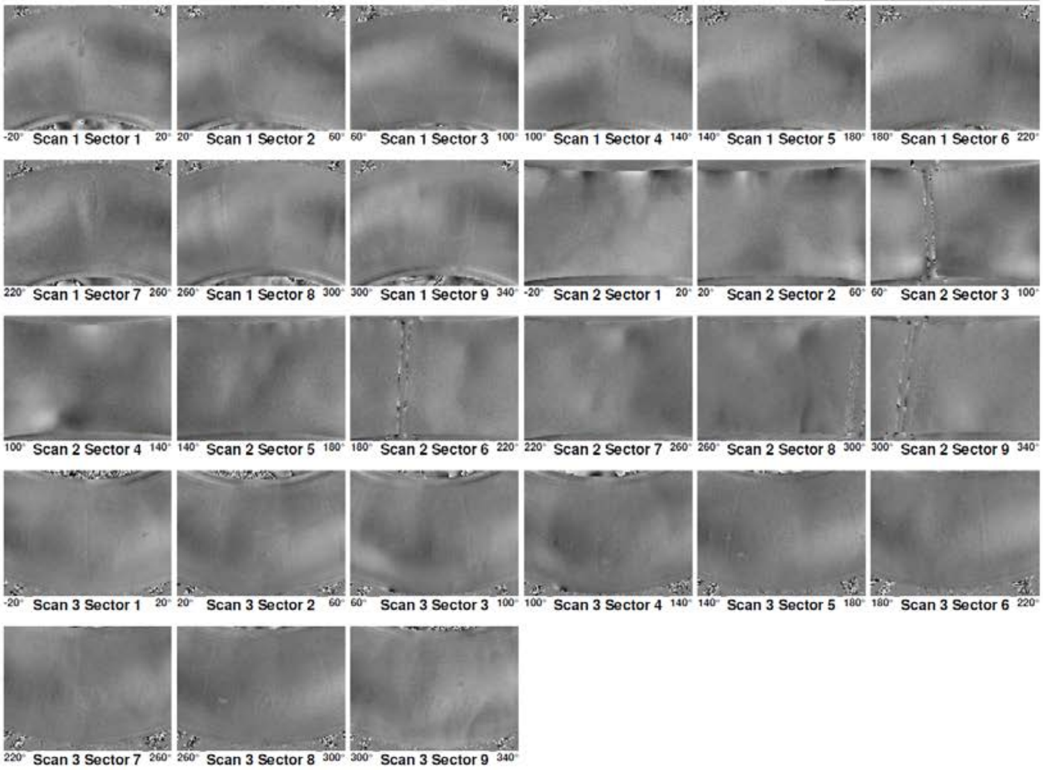
TYRE #39

Tire Test Report

Date:	10.12.2018 11:24
File:	d:\ittdata\1809210_Initial000003.vie
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°



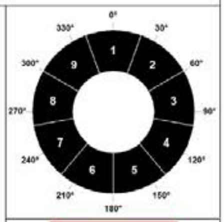


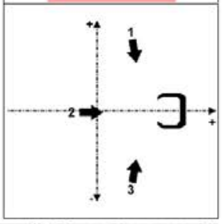


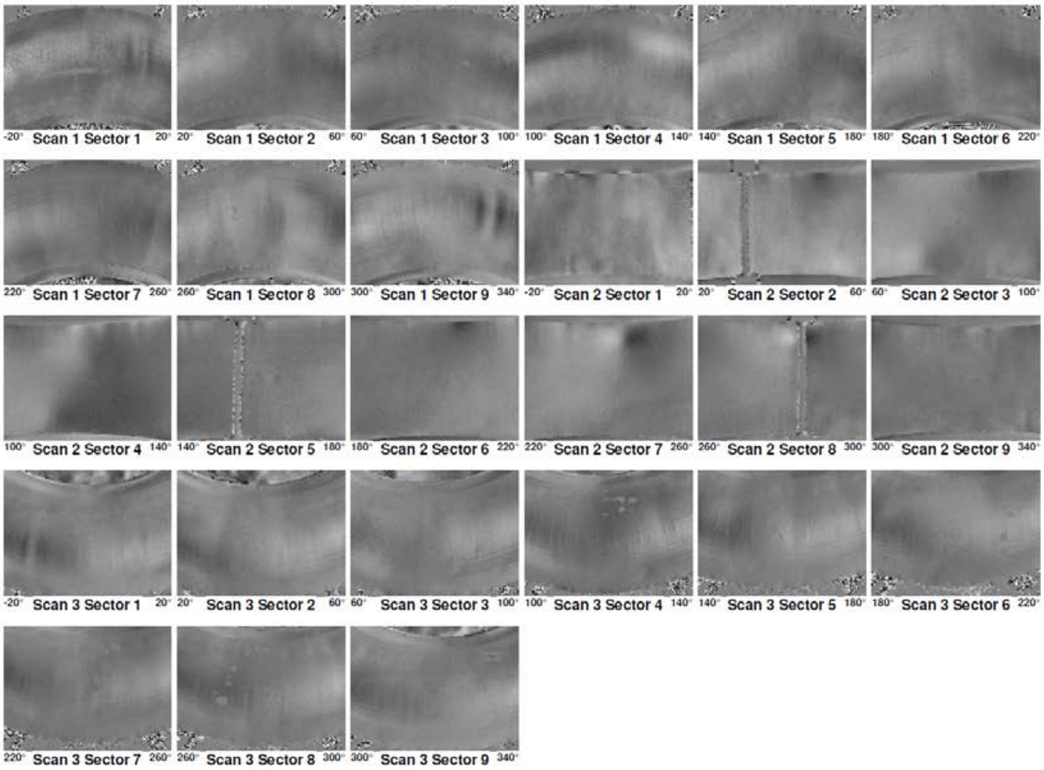
TYRE #42

Tire Test Report

Date:	11.12.2018 07:34
File:	d:\ittdata\1809213_Initial000005.vie
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°



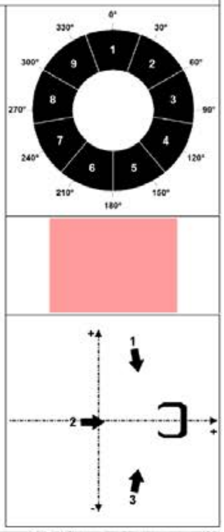


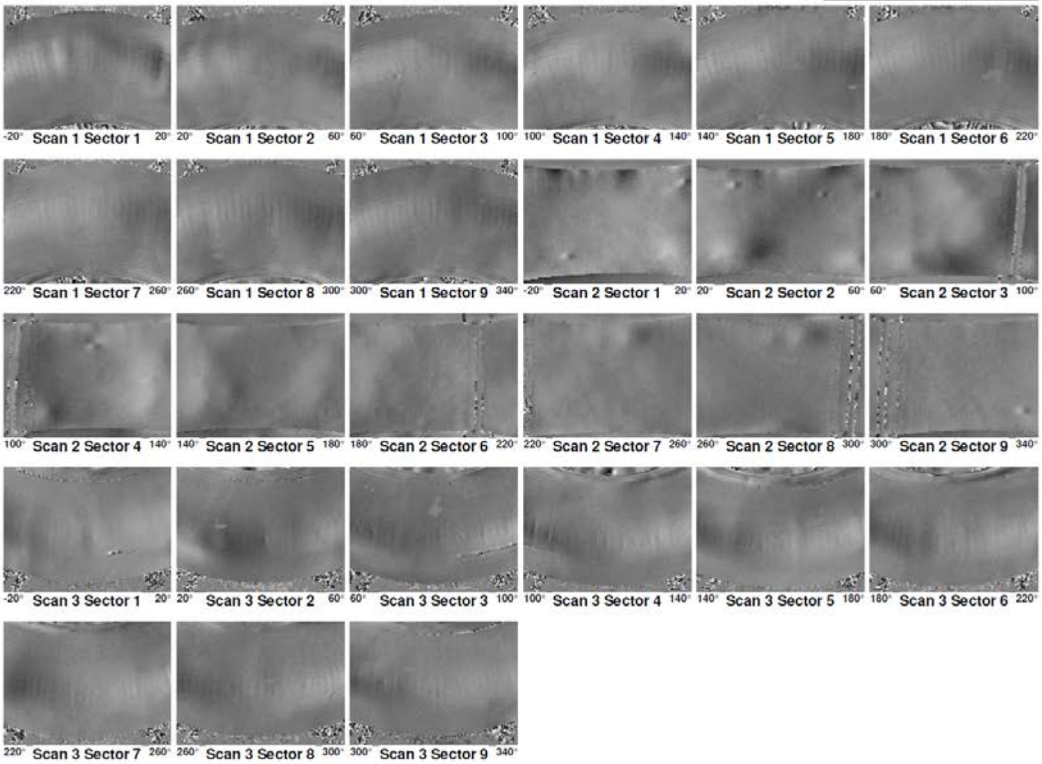


TYRE #43

Tire Test Report

Date:	10.12.2018 06:09
File:	d:\ittdata\1809212_Initial000001.vie
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°

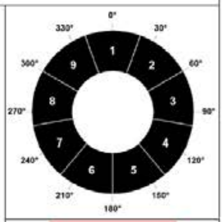


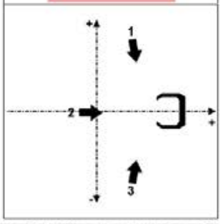


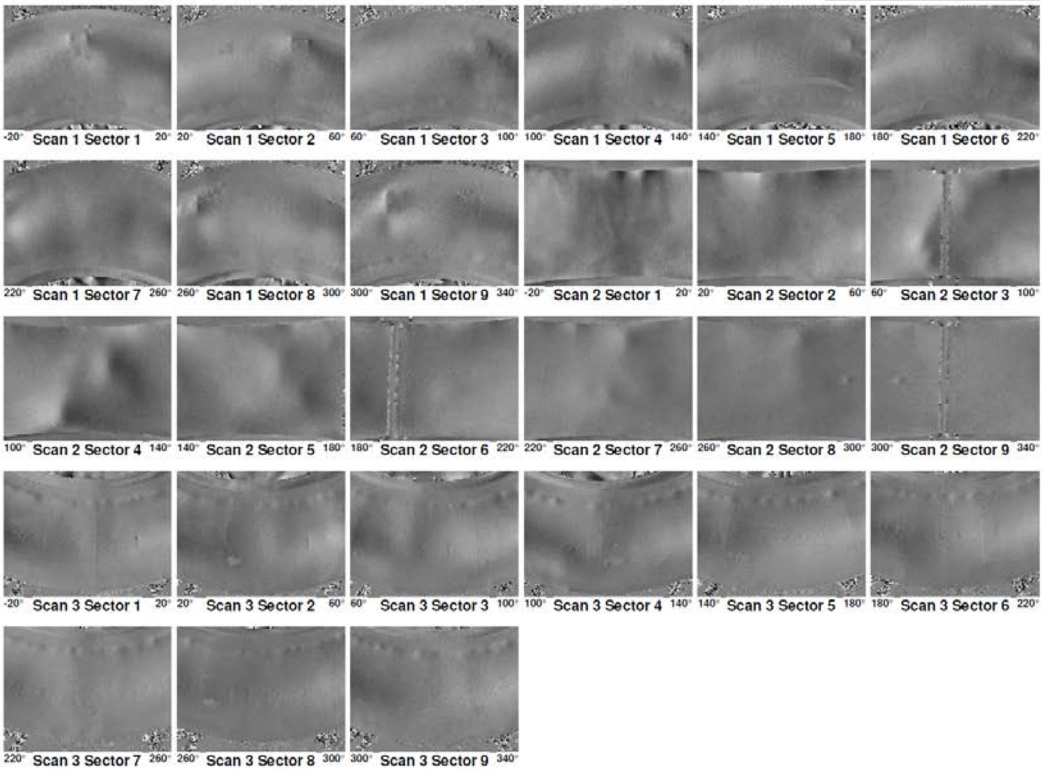
TYRE #44

Tire Test Report

Date:	10.12.2018 10:54
File:	d:\ittdata\1809211_Initial000003.vie
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°

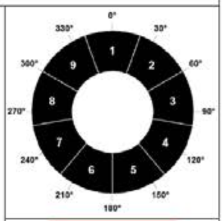




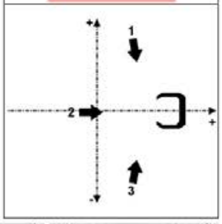


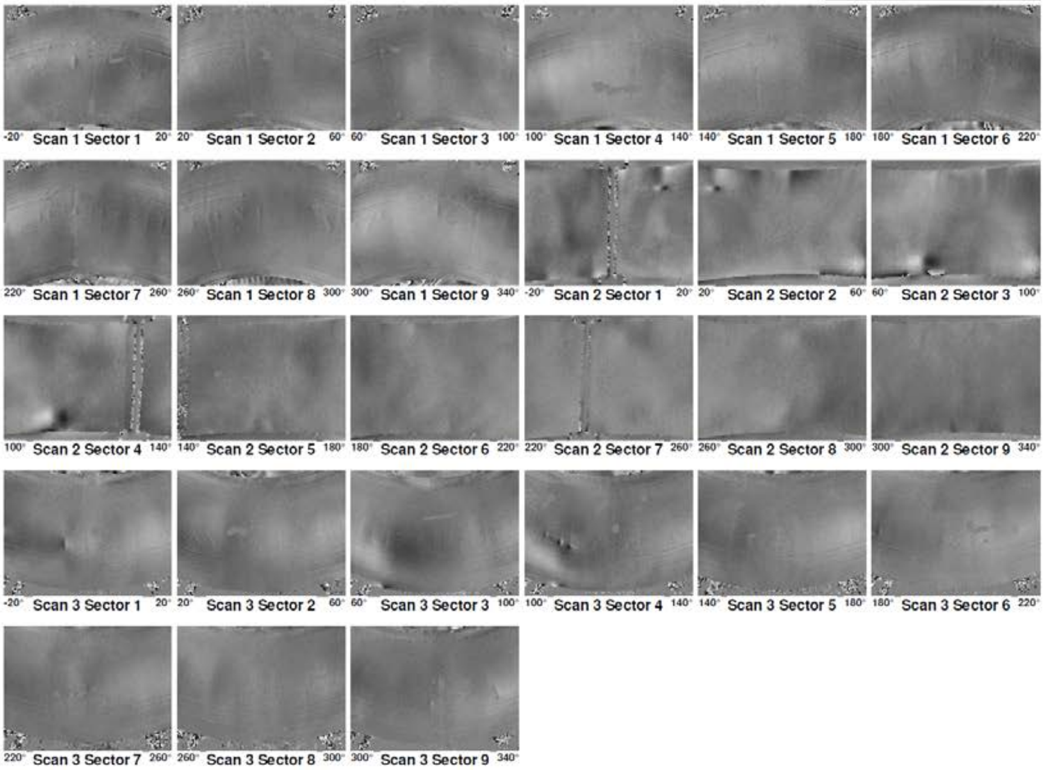
TYRE #46

Tire Test Report



Date:	07.01.2019 08:57
File:	d:\ittdata\1900055_XZE2+000001.vie
Description:	295_80R22_5
Operator:	bs
Test file:	D:\ITTSettings\295_80R22_5tst.tst
Scan number:	All Scans
Number of sectors:	9, 9, 9
Vacuum:	50, 50, 50 mBar
Horizontal head position:	330, 50.2, 330 mm
Vertical head position:	549.8, 159.9, 549.8 mm
Head tilt:	-80, 0, -80°

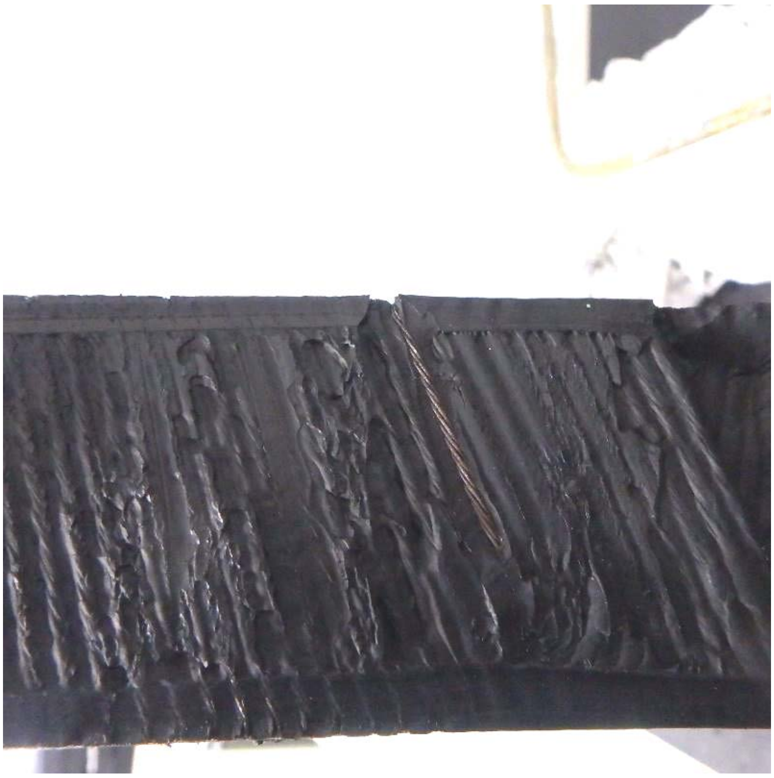




TYRE #47

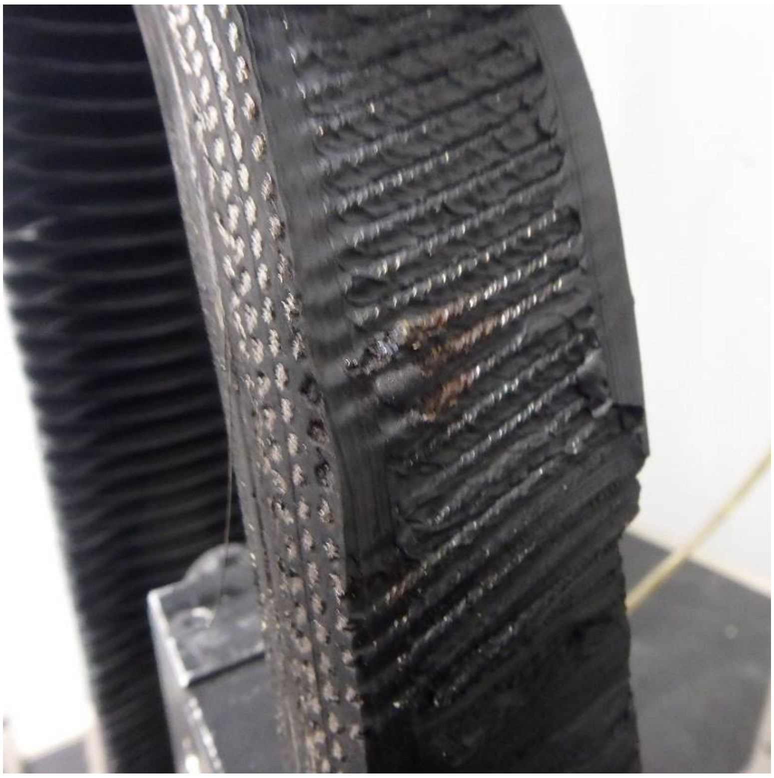
APPENDIX 2 – Interfacial Peel Force Test Sample Photographs

Corrosion Noted on Peel Force Specimens

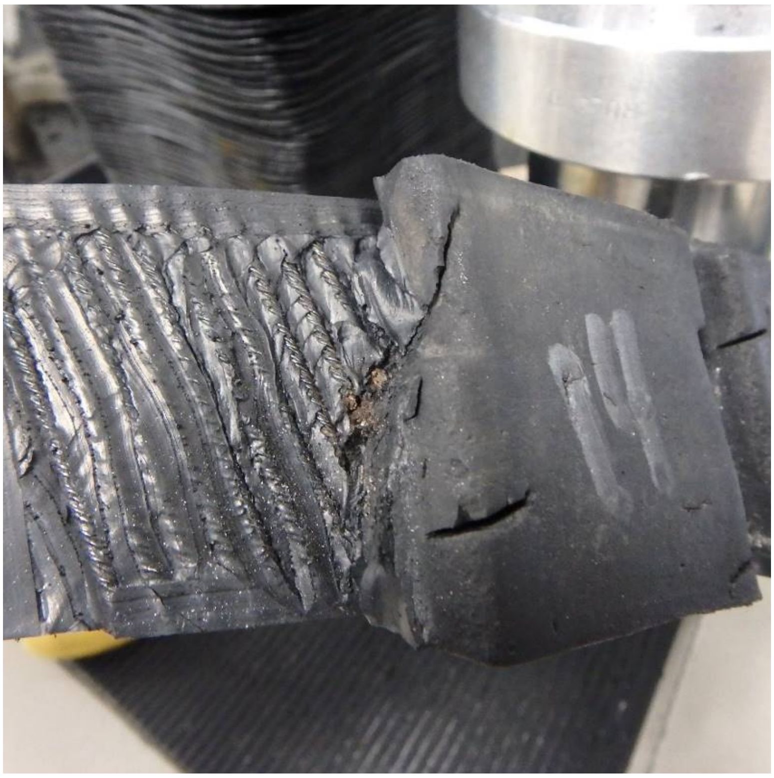


Photograph 1: Tyre 6 Belt 3

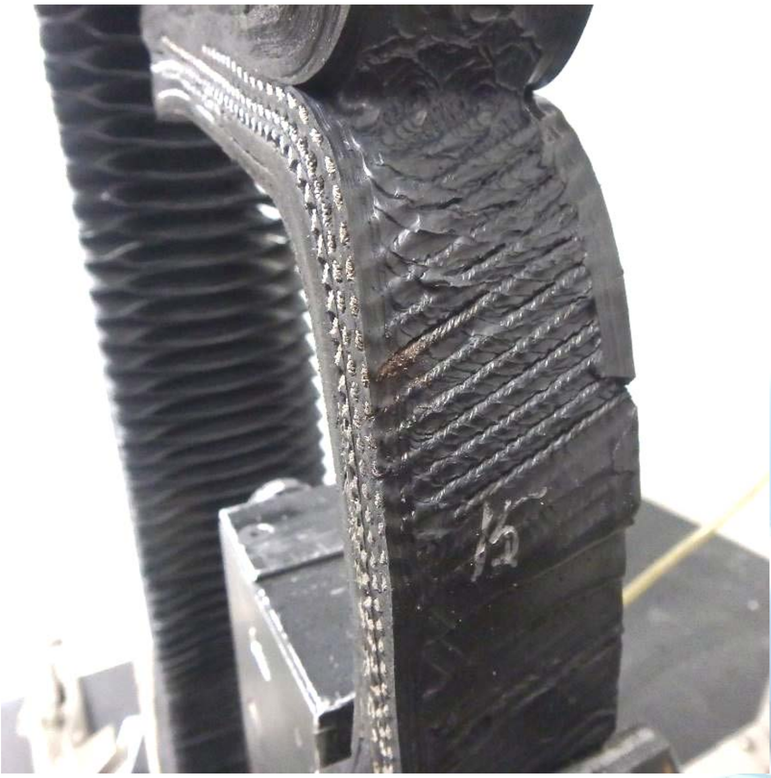
Photograph 2: Tyre 7 Belt 2



Photograph 3: Tyre 8 Belt 4



Photograph 4: Tyre 14 Belt 4



Photograph 5: Tyre 15 Belt 4

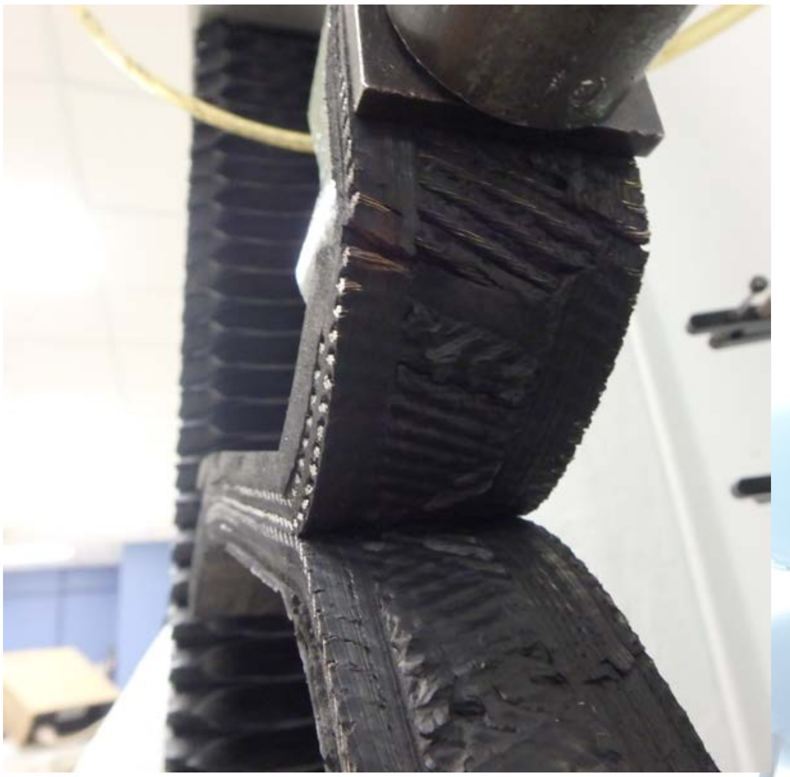
Photograph 6: Tyre 16 Belt 4

Photograph 7: Tyre 20 Belt 4

Photograph 8: Tyre 22 Belt 4

Photograph 9: Tyre 30 Belt 4

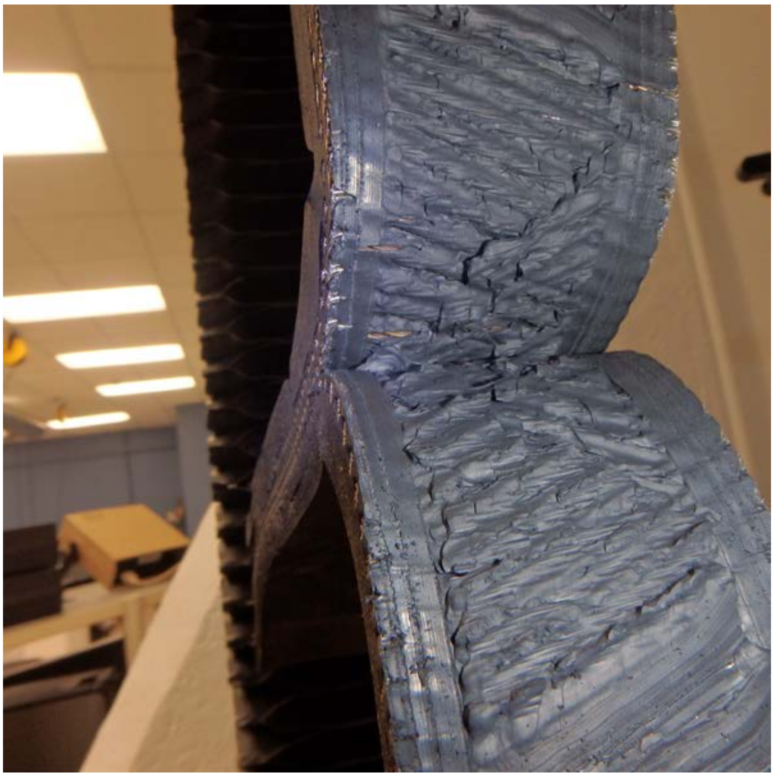
Photograph 10: Tyre 30 Belt 3



Photograph 11: Tyre 35 Belt 3

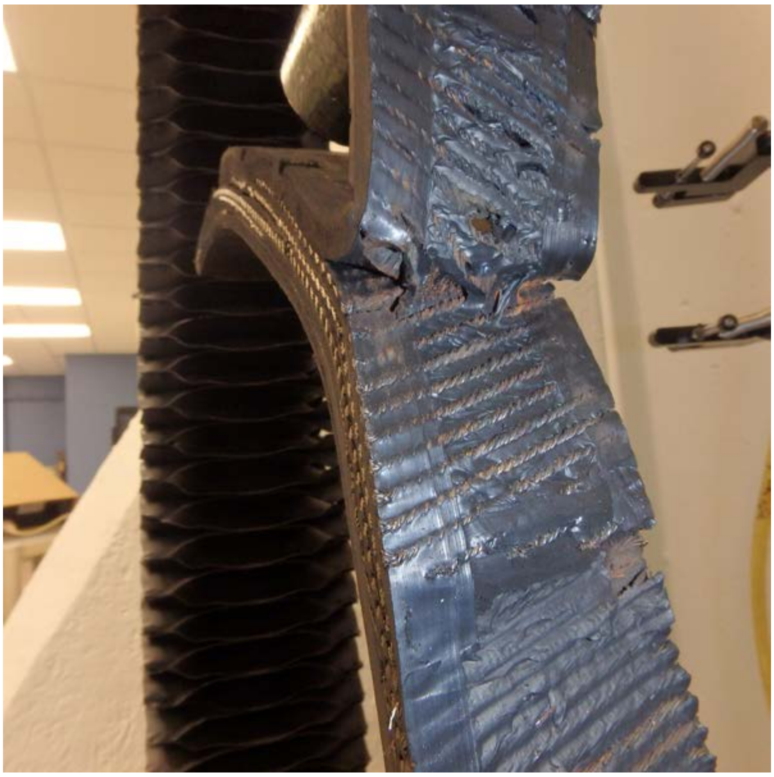

Photograph 12: Tyre 37 Belt 3


Photograph 13: Tyre 39 Belt 4

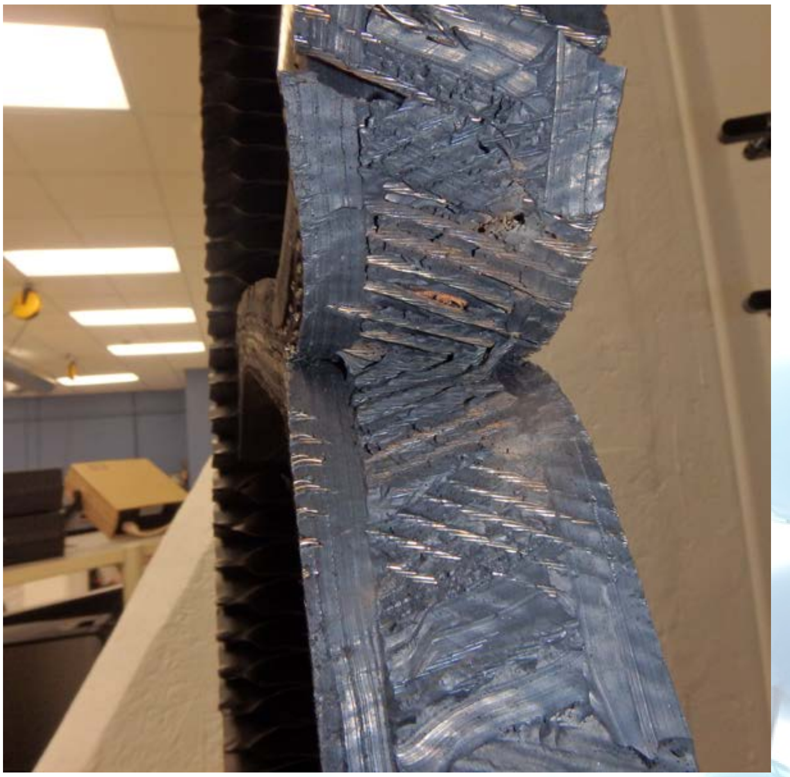


Photograph 14: Tyre 42 Belt 3

Photograph 15: Tyre 43 Belt 3



Photograph 16: Tyre 44 Belt 4



Photograph 17: Tyre 44 Belt 3


Photograph 18: Tyre 47 Belt 3 and 4.

End of Report

Smithers Rapra and Smithers Pira Limited
CONDITIONS OF BUSINESS (Conditions)

DEFINITIONS

"Client" means the person(s), firm or company who purchases the Goods and/or Services from Company;
"Company" means Smithers Rapra and Smithers Pira Limited (registration number: 5761324 and whose registered office is at Shrewsbury Road, Shawbury, Shropshire, SY4 4NR), trading as Smithers Rapra or Smithers Pira;
"Conditions" means the terms and conditions set out in this document as amended from time to time;
"Contract" means any contract between Company and the Client for the sale and purchase of Goods and/or provision of Services, incorporating these Conditions;
"Deliverables" means the report produced in connection with the Services or the deliverables set out in the Order;
"Force Majeure Event" has the meaning given to it in Condition 13;
"Goods" means any goods agreed in the Contract to be supplied to the Client by Company (including any parts of them);
"Intellectual Property Rights" means any patent, registered design, copyright (including rights in software), design right, database right, moral right, trade mark, service mark, domain name, rights in confidential information and all similar property rights anywhere in the world in each case whether registered or not and including any application for registration of the foregoing;
"Order" means the Client's order for the supply of Goods and/or Services as set out in the Client's purchase order form, the Client's written acceptance of Company's quotation or overleaf, as the case may be;
"Services" means any services including the Deliverables agreed in the Contract to be supplied to the Client by Company;
"Specification" means the specification for the Work, including any relevant plans, drawings or samples that is agreed in writing by the Client and Company;
"Testing Intellectual Property Rights" means all Intellectual Property Rights in or arising out of or in connection with the Services or the production of the Goods in the testing methods, consultative methodologies or any other services provided by Company;
"Work" means Goods and/or Services;
"Working Day" means a day (other than a Saturday or Sunday) on which the banks are ordinarily open for business in the City of London.

1. FORMATION OF CONTRACT

1.1 Each Order for Work by the Client from Company shall be deemed to be an offer by the Client to purchase Work in accordance with these Conditions. Company hereby objects to any additional, contradictory or different terms contained in any initial or subsequent order or communication from the Client pertaining to the Work. Any notice by the Client objecting to these Conditions must be in writing separate from any form purchase order. Company's failure to object specifically to provisions contained in any communication from the Client shall not be deemed a waiver of the provisions contained in these Conditions.

1.2 No Order placed by the Client shall be deemed accepted by Company until a written or electronic acknowledgement of order is issued by Company following the Company's receipt of the Order that covers the full cost of the Work.

1.3 The Contract constitutes the entire agreement between the parties. The Client acknowledges that it has not relied on any statement, promise, representation, assurance or warranty made or given on behalf of Company which is not set out in the Contract.

1.4 All other terms, conditions or warranties whatsoever (including any terms or conditions which the Client purports to apply under any purchase order, confirmation, specification or other document whatsoever and whenever) are excluded from any contract between the parties unless expressly accepted by Company in writing.

1.5 Without prejudice to Company's right not to accept an order, quotations shall be available for acceptance for a maximum period of 20 Working Days from the dates thereof.

1.6 All of the Conditions shall apply to supply of both Goods and Services except where applicability to one or the other is specified.

2. **PRICES**

2.1 The price for the Goods is, unless otherwise stated, quoted exclusive of all costs or charges in relation to packaging, labelling, loading, unloading, carriage, freight and insurance which shall be paid by the Client when it pays for the Work.

2.2 The price for the Work is exclusive of amounts in respect of value added tax (VAT) or other similar taxes or levies. The Client shall, on receipt of a valid VAT invoice from Company, pay to Company such additional amounts in respect of VAT as are chargeable on the supply of the Work.

2.3 All requests for variations or addition to the Work must be made by the Client in writing. In the event of any variation or addition being so requested and agreed to by Company, Company shall be entitled to make an adjustment to the price of the Work fairly reflecting such variation or addition.

2.4 Company may, by giving notice to the Client at any time before delivery, increase the price of the Works to reflect any increase in the cost of the Work that is due to:

(a) any factor beyond Company's control (including foreign exchange fluctuations, increases in taxes and duties, and increases in labour, materials and other manufacturing costs);

(b) any request by the Client to change the delivery dates, quantities or types of Goods ordered or scope of the Services; or

(c) any delay caused by any instructions of the Client or failure of the Client to give Company adequate or accurate information or instructions.

2.5 The price for the Work prior to any adjustments described above in this Condition 2 shall be the price set out in the Order.

3. DELIVERY AND ACCEPTANCE OF GOODS

3.1 Unless otherwise agreed in writing by Company delivery of the Goods shall take place at the location set out in the Order or such other location as the parties may agree (Delivery Location) at any time after Company notifies the Client that the Goods are ready.

3.2 Any dates specified by Company for delivery of the Work are intended to be an estimate only and time for delivery shall not be of the essence. Company shall not be liable for any delay occurred by a Force Majeure Event or the Client's failure to supply Company with adequate delivery instructions or any other instructions that are relevant to the delivery of the Work. Delivery of the Goods shall be completed on the Goods' arrival at the Delivery Location.

3.3 If for any reason the Client does not accept delivery of any of the Goods within five Working Days of Company giving the Client notice that the Goods are ready then:

(a) the Goods shall be deemed to have been delivered at 9.00am on the fifth Working Day following the day on which Company notified the Client that the Goods were ready;

(b) risk in the Goods passes to the Client (including for loss or damage caused by the Client's negligence); and

(c) Company shall store the Goods until actual delivery takes place and charge the Client for all related costs and expenses (including without limitations storage and insurance).

3.4 If ten Working Days after Company notified the Client that the Goods were ready for delivery the Client has not accepted delivery of them, Company may sell or otherwise dispose of part or all of the Goods and, after deducting reasonable storage and selling costs, account to the Client for any excess over than the price of the Goods or charge for any shortfall below the price of the Goods.

3.5 Where applicable, the Client will provide at its expense at the place of delivery adequate and appropriate equipment and manual labour for loading the Goods.

3.6 If Company delivers to the Client a quantity of Goods of up to 5% more or less than the quantity ordered by the Client, the Client shall not be entitled to object to or reject the Goods or any of them by reason of the surplus or shortfall and shall pay for the Goods delivered at the pro rata Contract rate.

3.7 Company shall be entitled at its discretion to make delivery of the Goods by instalments and to invoice the Client for each instalment individually. Where the Goods are to be delivered in instalments, each delivery shall constitute a separate contract and any delay, failure to deliver or defect on an instalment shall not entitle the Client to treat the Contract as a whole as repudiated or to refuse to accept subsequent instalments

3.8 Company shall only be liable for the non-delivery of Goods (even if caused by Company's negligence) if the Client gives written notice to Company within 10 Working Days of the date when the Goods would, in the ordinary course of events, have been delivered.

3.9 If the Client gives notice to Company in accordance with Condition 3.8 Company's liability shall be limited to the costs and expenses incurred by the Client in obtaining replacement Work of similar description and quality in the cheapest market available, less the price of the Work.

4. PASSING OF RISK AND LEGAL TITLE

4.1 The Goods shall be at the risk of the Client on completion of delivery.

4.2 Full legal, beneficial and equitable title to and property in the Goods shall remain vested in Company (even though it has been delivered and risk has passed to the Client) until the earlier of:

(a) payment in full, in cash or cleared funds, for all of the Goods has been received by Company and all other money payable by the Client to Company on any other account or under the Contract or any other contract has been received by Company; or

(b) the Client resells the Goods, in which case title to the Goods shall pass to the Client at a time specified in clause 4.4.

4.3 Until title to the Goods has passed to the Client, the Client shall:

(a) store the Goods separately from all other goods held by the Client so that they remain readily identifiable as Company's property;

(b) not remove, deface or obscure any identifying mark or packaging on or relating to the Goods;

(c) maintain the Goods in satisfactory condition and keep them insured against all risks for their full price on Company's behalf from the date of delivery;

(d) notify Company immediately if it becomes subject to any of the events listed in clause 12.1; and

(e) give Company such information relating to the Goods as Company may require from time to time.

4.4 Subject to clause 4.5, the Client may resell or use the Goods in the ordinary course of its business (but not otherwise) before Company receives payment for the Goods. However, if the Client resells the Goods before that time:

(a) it does so as principal and not as Company's agent; and

(b) title to the Goods shall pass from Company to the Client immediately before the time at which resale by the Client occurs.

4.5 If before title to the Goods passes to the Client the Client becomes subject to any of the events listed in clause 12.1, then, without limiting any other right or remedy Company may have:

(a) The Client's right to resell Goods or use them in the ordinary course of its business ceases immediately; and

(b) Company may at any time:

(i) require the Client to deliver up all Goods in its possession which have not been resold, or irrevocably incorporated into another product; and

(ii) if the Client fails to do so promptly, enter any premises of the Client or of any third party where the Goods are stored in order to recover them.

5. PROVISION OF SERVICES

5.1 Company shall provide the Services to the Client and shall use all reasonable endeavours to meet any performance dates for the Services specified in the Order, but any such dates shall be estimates only and time shall not be of the essence for the performance of the Services.

5.2 Where Company is to perform Services at the Client's premises, the Client shall procure safe access to the premises and the provision of adequate power, lighting, heating and other such facilities or supplies for Company's employees or agents in accordance with the demands of any applicable legislation and as Company shall reasonably require.

5.3 Company shall have the right to make any changes to the Services which are necessary to comply with any applicable law or safety requirement, or which do not materially affect the nature or quality of the Services, and Company shall notify the Client in any such event.

5.4 Company warrants to the Client that the Services will be provided using reasonable care and skill. If the Services do not comply with the warranty set out in this Condition 5.4, Company shall, at its option, re-perform the defective services, or refund the price of the defective Services in full.

5.5 The Services are addressed solely to the Client unless otherwise agreed in writing by Company. The information contained within the Deliverables shall be confidential and shall not be disclosed or relied upon for any purpose without Company's prior written consent.

6. PAYMENT

6.1 Subject to these Conditions, Company may invoice the Client for the Goods on or at any time after the completion of delivery. In respect of Services Company may submit interim invoices in respect of each stage of Work completed for the Client.

6.2 The Client shall pay each invoice submitted by Company:

(a) within 30 days of the date of the invoice; and

(b) in full and in clear funds to a bank account nominated in writing by Company; and

(c) time for payment shall be of the essence of the Contract.

6.3 Notwithstanding any other provision, all payments payable to Company under the Contract shall become due immediately upon termination of the Contract for whatever reason.

6.4 The Client shall make all payments due under the Contract without any deduction whether by way of set-off, withholding, counterclaim, discount, abatement or otherwise unless the Client has a valid court order requiring an amount equal to such deduction to be paid by Company to the Client.

6.5 If payments received from the Client are not stated to refer to a particular invoice, Company may appropriate such payment to any outstanding invoice addressed to the Client from Company.

6.6 No indulgence granted by Company to the Client concerning the Client's obligations under this Clause 6 shall be or be deemed to be a credit facility but if any such facility is granted to the Client by Company, Company may withdraw it at its sole discretion at any time.

6.7 Company reserves the right to vary the payment terms of this Contract in the event that it considers payment in advance (in part or whole) is necessary.

6.8 No disputes arising under the Contract nor delays beyond the reasonable control of Company shall interfere with prompt payment in full by the Client.

6.9 In the event of default in payment by the Client, Company shall be entitled at its option to treat the whole Contract as repudiated by the Client or to suspend all further Work on any contract or contracts between Company and the Client without notice and to charge interest on any amount outstanding at the rate of 8% per annum above the base rate of National Westminster Bank plc in force at the time when payment was due. Such interest shall accrue on a daily basis from the due date to the actual payment of the overdue amount, whether before or after judgment. The Client shall pay the interest together with the overdue amount.

6.10 The Client shall also pay Company's cost of collection (including legal fees and disbursements). Payments received may be applied by Company against any obligation owed by the Client to Company. Company may refuse or delay further Services if the Client fails to pay promptly any amounts due to Company.

7. CUSTOMER OBLIGATIONS

7.1 The Client shall:

(a) ensure that the terms of the order and (if submitted) the Specification is complete and accurate;

(b) Co-operate with in all matters relating to the Work;

(c) provide Company, its employees, agents, consultants and subcontractors, if required access to the Client's premises, office accommodation and other facilities as reasonably required by Company to provide the Work;
(d) provide Company with such information and materials as Company may reasonably require to supply the Work, and ensure that such information is accurate in all material respects;
(e) obtain and maintain all necessary licences, permissions and consents which may be required for the Work before the date on which the Work is to start;
(f) Keep and maintain all materials, equipment, documents and other property of Company (Company Materials) at the Client's premises in safe custody at its own risk, maintain Company Materials in good condition until returned to Company, and not dispose of or use Company Materials other than in accordance with Company's written instructions or authorisation; and
7.2 If Company's performance of any of its obligations in respect of the Work is prevented or delayed by any act or omission by the Client or failure by the Client to perform any relevant obligation (Client Default):
(a) Company shall without limiting its other rights or remedies have the right to suspend performance of the Work until the Client remedies the Client Default, and to rely on the Client Default to relieve it from the performance of any of its obligations to the extent the Client Default prevents or delays Company's performance of any of its obligations;
(b) Company shall not be liable for any costs or losses sustained or incurred by the Client arising directly or indirectly from Company's failure or delay to perform any of its obligations as set out in this Condition 7.2; and
(c) The Client shall reimburse Company on written demand for any costs or losses sustained or incurred by Company arising directly or indirectly from the Client Default.

8. WARRANTY AND WARRANTY LIMITATIONS

8.1 Company warrants that on delivery the Goods shall:
(a) conform in all material respects with their description and any applicable specification; and
(b) be free from material defects in design, material and workmanship.
8.2 Subject to Condition 8.3, if:
(a) the Client gives notice in writing to Company within a reasonable time of discovery that some or all of the Goods do not comply with the warranty set out in Condition 8.1;
(b) Company is given a reasonable opportunity of examining such Goods; and
(c) the Client (if asked to do so by Company) returns such Goods to Company's place of business at the Client's cost; and
(d) Company in its reasonable opinion having examined the Goods finds that the Goods do not comply with the warranty set out at Condition 8.1; Company shall, at its option, repair or replace the defective Goods, or refund the price of the defective Goods in full.
8.3 Company shall not be liable for the failure of Goods to comply with the warranty set out in Condition 8.1, if:
(a) the Client makes any further use of such Goods after giving notice in accordance with Condition 8.2; or
(b) the defect arises because the Client failed to follow Company's oral or written instructions as to the storage, commissioning, installation, use and maintenance of the Goods or (if there are none) good trade practice; or
(c) the defect arises as a result of Company following any drawing, design or the Specification supplied by the Client; or
(d) the Client alters or repairs such Goods without Company's written consent; or
(e) the defect arises as a result of fair wear and tear, wilful damage, negligence, or abnormal storage or working conditions; or
(f) the Goods differ from the description as a result of changes made to ensure they comply with applicable statutory or regulatory standards.
8.4 Except as provided in this Condition 8, Company shall have no liability to the Client in respect of the failure of Goods to comply with the warranty set out in Condition 8.1.
8.5 These Conditions shall apply to any repaired or replacement Goods supplied by Company.
8.6 Except as provided in this Condition 8 and Condition 5.4, all warranties, conditions or other terms implied by statute or common law, whether written or oral, are to the fullest extent permitted by law excluded from the Contract.

9. LIABILITY/INDEMNIFICATION

9.1 This Condition 9 together with Condition 3, Condition 5.4 and Condition 8 set out the entire liability of Company (including any liability for the acts or omissions of its subcontractors and any member of its group) in respect of any breach of these Conditions or the Contract and any representation, statement or tortuous act or omission including negligence arising under or in connection with the Contract.
9.2 Nothing in these Conditions shall exclude or limit Company's liability for:
(a) death or personal injury caused by Company's negligence, or the negligence of its employees, agents or sub-contractors (as applicable);
(b) fraud or fraudulent misrepresentation;
(c) breach of the terms implied by section 12 of the Sale of Goods Act 1979;
(d) breach of the terms implied by section 2 of the Supply of Goods and Services Act 1982 (title and quiet position);
(e) defective products under the Consumer Protection Act 1987.
9.3 Company is not responsible for the performance, adequacy, or safety of any material, product, or process of the Client being tested or evaluated by Company. Company is not responsible for the Client's use of the information or concepts generated as part of the Services, and shall not be liable for any loss or damage resulting from such use.
9.4 Subject to Condition 9.2:
(a) Company shall not be liable to the Client, whether in contract, tort (including negligence), breach of statutory duty, or otherwise, for any loss of profit or indirect or consequential loss arising under or in connection with the Contract.
(b) Company's total aggregate liability to the Client arising out of, or in connection with the performance or contemplated performance of this Contract and any other agreements between the Client and Company whether in contract, tort (including negligence), breach of statutory duty or otherwise shall in no event exceed the price of the Work to which the claim relates.
9.5 The Client agrees to indemnify Company and each of its affiliates and their respective shareholders, directors, members, managers, officers, employees, and agents (collectively the Indemnified Parties) against all liabilities, damages, costs and expenses, including, without limitation, legal fees, consultant's fees, costs of investigation and disbursements, incurred by any Indemnified Party as a result of or in connection with any third party claim involving any product, service, operation or activity of Client.

10. CONFIDENTIAL INFORMATION AND INTELLECTUAL PROPERTY RIGHTS

10.1 All data, information and reports are produced for the benefit of the Client only. Company accepts no liability arising from unauthorised use of such information or reports by a third party.
10.2 All Intellectual Property Rights belonging to or otherwise in the control of either party prior to entering into the Contract shall remain the property of the party owning such Intellectual Property Rights.
10.3 All Testing Intellectual Property Rights shall be owned by the Company.
10.4 Save for the Testing Intellectual Property Rights, all Intellectual Property Rights in or arising out of or in connection with the Services shall be owned by the Client.
10.5 The Client acknowledges that, in respect of any third party Intellectual Property Rights, the Client's use of any such Intellectual Property Rights is conditional on the Company obtaining a written licence from the relevant licensor on such terms as will entitle the Company to license such rights to the Client. Unless expressly agreed in writing by Company and set out in the Order:

(a) the Client shall not reproduce or abstract for the purpose of advertising or otherwise any Deliverable or other information from the Work or use the name of Company either expressly or by implication in any of its advertising or sales promotional material;

(b) all drawings, documents, records, computer software and other information supplied by Company (Documents) are vested in and shall remain the property of Company;

(c) nothing in the Contract shall be deemed to have given the Client a licence or any other right to use any of Company's Intellectual Property Rights;

(d) the Client will not give away, loan, exhibit, sell or in any way use any Documents or extracts therefrom or copies thereof.

10.6 For the avoidance of any doubt if Company agrees to an assignment of any of the Intellectual Property Rights owned by Company, Company shall be granted a royalty-free, irrevocable, non-exclusive, worldwide right to use such Intellectual Property Rights assigned under this Condition 10.6 to the Client.

10.7 Company's confidential and sensitive information including, but not limited to, information contained in any proposal, order acknowledgment, or invoice provided by Company to the Client and the terms or existence of the Contract shall be kept confidential and shall not be disclosed by the Client to any third party or otherwise made public without Company's prior written consent, except as may be required by law in which case the Client shall notify Company of such disclosure, if legally possible, in good time prior to making the disclosure.

10.8 The Client shall indemnify Company against all indebtedness, costs, expenses, damages and loss (including any direct, indirect or consequential losses, loss of profit, loss of reputation and all interest, penalties and legal cost (calculated on a full indemnity basis) and other professional costs and expenses) suffered by Company arising out of or in connection with any claim by a third party against Company for the use of any material supplied by the Client or for following the Specification for an infringement of the third party's intellectual property.

11. CLIENT'S INFORMATION/SAMPLES

11.1 The Client shall be solely responsible for ensuring that all drawings, information, advice and recommendations given to Company, either directly or indirectly by the Client or by the Client's agents, servants, consultants or advisers, are accurate and sufficient for completion of the Work. Examination or consideration by Company of such drawings, information, advice or recommendations shall in no way limit the Client's responsibility hereunder unless Company specifically agrees in writing to accept responsibility.

11.2 Company shall not disclose to any third party any knowledge or information relating to the Work which is, on receipt by Company, marked 'confidential' by the Client for a period of five (5) years, or unless and until such information becomes public knowledge, whichever is earlier.

11.3 Company retains the right to return or dispose of the samples at the Client's cost after a period of 6 months unless otherwise agreed with the Client. Storage of the samples beyond the initial 6 month period will be charged for, invoiced in advance for the agreed period (minimum additional 6 months).

12. TERMINATION

12.1 Company may, as it thinks fit, (without prejudice to any other rights or remedies it may have against the Client) immediately suspend further performance of the Contract or cancel any outstanding provision of the Work or any other contract between the Client and Company by notice in writing to the Client without incurring any liability to the Client and all outstanding sums in respect of the Work delivered to the Client shall become immediately due if:

(a) the Client suspends, or threatens to suspend, payment of its debts or is unable to pay its debts as they fall due or admits inability to pay its debts or (being a company) is deemed unable to pay its debts within the meaning of section 123 of the Insolvency Act 1986, or (being a partnership) has any partner to who any of the foregoing apply;

(b) the Client commences negotiations with all or any class of its creditors with a view to rescheduling any of its debts, or makes a proposal for or enters into any compromise or arrangement with its creditors other than (where the Client is a company) these events take place for the sole purpose of a scheme for a solvent amalgamation of the Client with one or more other companies or the solvent reconstruction of the Client;

(c) a creditor or encumbrancer of the Client attaches or takes possession of, or a distress, execution, sequestration or other such process is levied or enforced on or sued against, the whole or any part of its assets and such attachment or process is not discharged within 14 days;

(d) an application is made to court, or an order is made, for the appointment of an administrator or if a notice of intention to appoint an administrator is given or if an administrator is appointed over the Client;

(e) a floating charge holder over the assets of the Client has become entitled to appoint or has appointed an administrative receiver;

(f) a person becomes entitled to appoint a receiver over the assets of the Client or a receiver is appointed over the assets of the Client;

(g) any event occurs, or proceeding is taken, with respect to the Client in any jurisdiction to which it is subject that has an effect equivalent or similar to any of the events mentioned in Condition 12(a) to 12(f) (inclusive);

(h) the Client suspends, threatens to suspend, ceases or threatens to cease to carry on all or substantially the whole of its business;

(i) the Client commits a material breach of any of its obligations under the Contract which is incapable of remedy;

(j) any sum payable under the Contract is not paid within 7 days of its due date for payment in accordance with this Contract;

(k) the Client fails to remedy a breach of its obligations under the Contract (except as to payment) which is capable of remedy, or persists in any breach of any of its obligations under the Contract after having been requested in writing by Company to remedy or desist from such breach within a period of 14 days.

13. FORCE MAJEURE

Company shall not be in breach of this Contract or liable for delay in performing, or failing to perform any obligation under this Contract arising from or attributable to acts, events, omissions or accidents beyond its reasonable control, including but not being limited to any of the following: by direction of government, war, industrial dispute, strike, breakdown of machinery or plant, acts of God, terrorism, riot, flood, storms, earthquakes, extreme adverse weather conditions, lock-outs, accident, fire (any one a Force Majeure Event). If the Force Majeure Event prevails for a continuous period of more than 2 months, Company may terminate this Contract by giving 14 days' written notice to all the other parties. On the expiry of this notice period, the Contract will terminate. Such termination shall be without prejudice to the rights of the parties in respect of any breach of this Contract occurring prior to such termination. Company shall be entitled to recover all sums owing to it in respect of the Work provided and costs incurred prior to the date of termination.

14. OBLIGATION ON TERMINATION

14.1 On termination of the Contract for any reason:

(a) the Client shall immediately pay to Company all of Company's outstanding unpaid invoices and interest and, in respect of Work supplied but for which no invoice has yet been submitted, Company shall submit an invoice, which shall be payable by the Client immediately on receipt;

(b) the Client shall return all of Company Materials and any deliverables which have not been fully paid for. If the Client fails to do so, then Company may enter the Client's premises and take possession of them. Until they have been returned, the Client shall be solely responsible for their safe keeping and will not use them for any purpose not connected with the Contract;

(c) the accrued rights and remedies of the parties as at termination shall not be affected, including the right to claim damages in respect of any breach of the Contract which existed at or before the date of termination or expiry; and

(d) Conditions which expressly or by implication have effect after termination shall continue in full force and effect

15. GENERAL/LEGAL

15.1 All agreements contained herein shall apply to and bind the assignees and successors in interest of Company and the Client. Facsimile signatures or other reliable means of authentication by which the Client signifies its assent to this Agreement shall be effective to bind the Client to this Contract.

15.2 The waiver by Company of any right or remedy under the Contract is only effective if given in writing and shall not be deemed to be a waiver of any later breach or default. No failure or delay by Company to exercise any right or remedy provided under the Contract or by law shall constitute a waiver of that or any other right or remedy, nor shall it preclude or restrict the further exercise of that or any right or remedy. No single or partial exercise of such right or remedy shall preclude or restrict the further exercise of that or any other right or remedy.

15.3 If any court or competent authority finds that any provision or part provision of this Contract is invalid, illegal or unenforceable, that provision or part provision shall to the extent required, be deemed to be deleted, and the validity and enforceability of the other provisions of the Contract shall not be affected. If any invalid, unenforceable or illegal provision of the Contract would be valid, enforceable and legal if some part of it were deleted, the provision shall apply with the minimum modification necessary to make it legal, valid and enforceable.

15.4 The headings are used for the convenience of the parties only and shall not affect the construction or interpretation of this Contract. Any clerical errors are subject to correction.

15.5 The Contract and any dispute or claim arising out of or in connection with it shall be governed and interpreted exclusively according to the Law of England and shall be subject to the exclusive jurisdiction of the English Courts to which the parties irrevocably submit.

15.6 Notwithstanding any different or additional terms or conditions contained in the Client's purchase order or other communication, Company accepts the Client's order only on the condition that the Client expressly accepts and assents to the terms and conditions contained in this Contract. The Client's acceptance of any Work shall be deemed to be acceptance of these Conditions.

15.7 Company may at any time assign, charge, subcontract, transfer or deal in any other manner with all or any of its rights or obligations under the Contract or any part of it to any person. The Client may not assign, charge, subcontract, transfer or deal in any other manner with all or any of its rights or obligations under the Contract without the prior written consent of Company.

15.8 A person who is not a party to the Contract (including without limitation any employee, officer, agent, representative or subcontractor or either party) shall not have any right to enforce any term of the Contract which expressly or by implication confers a benefit on that person without the express prior written agreement of Company and the Client.

15.9 All notices between the parties relating to this Contract must be in writing and sent pre-paid first class or sent by facsimile or email to:

(a) in the case of the Client the registered office of the addressee (if it is a company) or (in any other case) to any address, facsimile number or email address of the Client set out in any document which forms part of the Contract or such other address as shall be notified to Company by the Client in writing; and

(b) in the case of Company, the address set out below:

Smithers Rapra and Smithers Pira Limited
Shawbury
Shrewsbury
Shropshire SY4 4NR
UK
Facsimile No.: +44 (0) 1939 251 118
Email Address: info@smithers.com

or other such address, facsimile number or email address as shall be notified to the Client by Company in writing.

15.10 Notices shall be deemed to have been received: in the case of first class post, 2 days after posting (exclusive of the day of posting) and if sent by facsimile or email transmission, at 10:00 am local time on the first usual Working Day in the country of receipt following transmission, subject to being able to show that the notice was sent to the correct facsimile number or email address.

15.11 Nothing in this Contract is intended to, or shall be deemed to, establish any partnership or joint venture between any of the parties, constitute any party the agent of another party, nor authorise any party to make or enter into any commitments for or on behalf of any other party.

15.12 The Contract constitutes the entire agreement between the parties. The Client acknowledges that it has not relied on any statement, promise or representation made or given by or on behalf of Company which is not set out in the Contract. Any samples, drawings, descriptive matter or advertising issued by Company and any descriptions or illustrations contained in Company's catalogues or brochures are issued or published for the sole purpose of giving an approximate idea of the Services described in them. They shall not form part of the Contract or any other contract between Company and the Client for the sale of the Goods or the provision of Services.

15.13 In performing the Services, Company shall operate as, and have the status of, an independent contractor and shall not operate or have the status of agent, employee or representative of the Client.

15.14 Solicitation of Employees. During the performance of the Contract and for a period of one year thereafter, the Client shall not, directly or indirectly, solicit the services of or hire any of the employees of The Smithers Group, Inc. or its affiliated companies for the direct or indirect benefit of client or any third party. Client understands and acknowledges that this obligation regarding solicitation is necessary and reasonable to protect legitimate business interests.

16. ANTI-BRIBERY

16.1 The Client shall:

(a) comply with all applicable laws, statutes, regulations and codes relating to anti-bribery and anti-corruption including but not limited to the Bribery Act 2010 (Relevant Requirements);

(b) not engage in any activity, practice or conduct which would constitute an offence under sections 1, 2 or 6 of the Bribery Act 2010 if such activity, practice or conduct had been carried out in the UK;

(c) comply with any Anti-Bribery Policy as Company may provide to it from time to time (Relevant Policy);

(d) have and shall maintain in place throughout the term of this Agreement its own policies and procedures, including adequate procedures under the Bribery Act 2010, to ensure compliance with the Relevant Requirements, the Relevant Policy and Condition 16.1(b) and will enforce them where appropriate;

(e) promptly report to Company any request or demand for any undue financial or other advantage of any kind received by the Client in connection with the performance of this Agreement;

(f) immediately notify Company in writing if a foreign public official becomes an officer or employee of the Client or acquires a direct or indirect interest in the Client, and the Client warrants that it has no foreign public officials as officers, employees or direct or indirect owners at the date of this Agreement;

(g) the Client shall provide such supporting evidence of compliance as Company may reasonably request.

16.2 The Client shall ensure that any person associated with it who is performing Services or providing Goods in connection with this Agreement does so only on the basis of a written contract which imposes on and secures from such person terms equivalent to those imposed on the Client in this Condition 16 (Relevant Terms). The Client shall be responsible for the observance and performance by such persons of the Relevant Terms, and shall be directly liable to Company for any breach by such persons of any of the Relevant Terms.

16.3 For the purpose of this Condition 16, the meaning of adequate procedures and foreign public official and whether a person is associated with another person shall be determined in accordance with section 7(2) of the Bribery Act 2010 (and any guidance issued under section 9 of that Act), sections 6(5) and 6(6) of that Act and section 8 of that Act respectively. For the purpose of this Condition 16, a person associated with the Client includes but is not limited to any Sub-Contractor.

17. **DATA PROTECTION**

17.1 To the extent a Client provides Personal Data (as hereafter defined) to the Company in connection with Company's Work on behalf of the Client, both parties will comply with the following conditions and all applicable requirements of the Data Protection Legislation (as hereafter defined). This Clause 17 is in addition to, and does not relieve, remove or replace, a party's obligations under the Data Protection Legislation, or other similar laws to which the party is subject. "Personal Data" means any information relating to an identified or identifiable natural person living within the European Economic Area.

17.2 The parties acknowledge that for the purposes of the Data Protection Legislation, where the Client transfers the Personal Data of a third party to the Company for processing as part of the provision of Company's Goods or Services to the Client, the Client is the Data Controller and the Company is the Data Processor (where "Data Controller" and "Data Processor" have the meanings defined in the Data Protection Legislation).

17.3 Without prejudice to the generality of the foregoing clauses, the Client will ensure that it has all necessary appropriate consents and notices in place to enable lawful transfer of the Personal Data to the Company for the duration and purposes of this Contract.

17.4 As used herein, "Data Protection Legislation" shall mean the General Data Protection Regulation (GDPR) and any applicable national implementing laws, regulations and secondary legislation, and subsequent successor legislation.