NHTSA TIRE AGING TEST DEVELOPMENT PROJECT: PHASE 1 - PHOENIX, ARIZONA TIRE STUDY

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ABSTRACT

Phase 1 of the NHTSA Tire Aging Test Development Project consisted of the analysis of six different tire models collected from privately owned vehicles in the Phoenix, Arizona USA metropolitan area during the spring of 2003. This study was conducted to provide a better understanding of service-related tire degradation and to serve as the "real-world" baseline for the development of laboratory-based accelerated service life test for tires (often referred to as a "tire aging test"). On-road tires and full-size spare tires, as well as the corresponding vehicle information were collected through 22 Phoenix-area retailers in exchange for new tires at no charge to the study's participants. Within the six different tire models studied, a total of 174 on-road tires and 9 full-size spare tires retrieved from Phoenix of varied ages and mileages were compared to 82 new, un-used versions of themselves. The tires were either subjected to one of two whole-tire roadwheel tests or cut apart for material properties analysis. The results were correlated against the absolute age and mileage (if original equipment) of the tires and will be discussed in this paper. The raw dataset and project notes are available for download at (VIN redacted for vehicle owner privacy): http://www-nrd.nhtsa.dot.gov/vrtc/ca/tires.htm

INTRODUCTION

In late 2000, the U.S. House of Representatives' Committee on Energy and Commerce conducted an inquiry into the fatalities and injuries resulting from the tread separation failures of Firestone Radial ATX, Radial ATX II, and Wilderness AT tires on specific models of Ford, Mercury, and Mazda light trucks and SUVs. During these hearings, members of Congress inquired as to the possibility of a tire aging test (i.e. accelerated service life test) that could evaluate the risk of failure at a period later in service than that evaluated by current regulations, which only test new tires. As a result of the committee's actions, the House drafted the Transportation Recall, Enhancement, Accountability, and Documentation ("TREAD") Act [H.R. 5164], which was enacted on November 1, 2000. The TREAD Act contained provisions mandating the USDOT National Highway Traffic Safety Administration (NHTSA) to update the passenger car and light truck tire safety standards (however the legislation did not contain specific requirements for a tire aging test).

In response to the TREAD Act, NHTSA conducted tire safety research in support of what would become the new Federal Motor Vehicle Safety Standard (FMVSS) No. 139, "New pneumatic radial tires for light vehicles". During these efforts, the agency conducted a comprehensive review of literature and had numerous consultations with industry regarding the effects of service life (i.e. age and mileage) on tire durability. The agency concluded that while an industry-wide recommended practice for conducting accelerated service life testing of tires did not exist, some methods were seeing limited use and warranted evaluation. The agency decided to conduct a study to provide a better understanding of service-related tire degradation and to serve as the "real-world" baseline for the development of laboratory-based accelerated service life test for tires (often referred to as a "tire aging test"). This would involve studying "field" tires collected from on-vehicle use in the U.S., thoroughly examining national accident statistics for trends involving tire service life, and conducting test "tire aging" test development.

Tire Service Life in the U.S.

The average tread life of a passenger car tire in the U.S. was approximately 44,700 miles in 2004 [1], which represents an 86% increase from an approximate 24,000 miles in 1973. Using an average miles traveled by passenger vehicles of 12,497 miles in 2004 [2] and 9,992 miles in 1973 [3], the average tire service life was calculated to be around 3.6 years in 2004 and 2.4 years in 1973. This suggests roughly a 49% increase in average tire service life over a thirty year period.

The current U.S. Federal motor vehicle safety standard for light vehicle tires contains performance tests for new tires only. The longest of these tests is currently the Endurance and Low Pressure test sequence, which is 35.5 hrs. These performance tests are based on the premise that acceptable performance when the tire is new results in acceptable performance throughout the service life of the tire. However, the agency noticed in data from the aforementioned Firestone tire investigation [4], as well as many similar cases, that defective tire designs generally performed well in their first couple years of service and only began to fail after years of use.

METHODOLOGY

Phase 1 of the NHTSA Tire Aging Test Development Project consisted of the collection of 12 different tire models from use on private vehicles in the Phoenix, Arizona USA metropolitan area. The Phoenix metropolitan area was selected as the collection location for the following reasons:

1. Agency data indicated that states with high average ambient temperatures have higher tire failure rates. Phoenix, AZ has an annual normal daily mean temperature of 23.4 Deg. C (74.2 Deg. F). [5] It also has a mean number of 169 days with a maximum temperature of 32.2 Deg. C (90 Deg. F) or higher. [6]
2. A study conducted by the Ford Motor Company of the rates of degradation of tire material properties in six U.S. cities [7] indicated that the Phoenix, Arizona metropolitan area had the highest degradation rates of the six cities studied. These results were attributed to the exponential increase in the rate of the degradative reaction with temperature occurring in the relatively high mean and maximum temperatures of the Phoenix area.
3. Maricopa County (Phoenix metro area), Arizona was a large population center of over 3 million residents [8] and possessed a large infrastructure of tire retail centers.
4. The diminished need for minimum tire tread depth to facilitate wet and snow traction in the arid climate of the Southwest [9], as well as a relatively less aggressive roadway aggregate, can result in longer tire service lives in that region.

In late 2002, NHTSA researchers used industry statistics on the most popular tire brands, sizes, manufacturers, etc. to construct a preliminary list of models for the study. Tire manufacturers were contacted for help in narrowing down models to those that were in production from 1998 to 2003, had no ‘significant’ design changes in that period, and were available for purchase in Arizona. During the February 25th to March 17th, 2003 timeframe the agency sent a team of Federal and contractor staff from the NHTSA Vehicle Research and Test Center (VRTC) in Ohio to Maricopa County (Phoenix), Arizona. The team’s assignments were to recruit tire retail locations for collection centers, establish storage and transportation logistics, train retail staff on retrieval procedures, and launch the tire collection program.

Sixteen tire retailer locations and six vehicle dealerships agreed to participate in the tire collection program. A centrally located warehouse and a small fleet of moving vans were leased to facilitate short-term tire storage and transportation. After the first three weeks, the launch team returned from Phoenix and the program was administrated remotely from the VRTC until the end of April 2003. At the conclusion of the project, all Phoenix-retrieved tires were shipped back to the VRTC for processing and distribution to the test labs.

The details of the tire collection program were as follows: The vehicle sample population was primarily comprised of random vehicles entering tire retail locations, as well as past customers of the businesses that were contacted by the retailer’s employees for interest in participation. However, a small number of tires were retrieved from vehicles on auto dealer lots. For vehicles entering a collection location, service personnel checked the tires against a collection list updated by the VRTC each day. If the tires matched the exact specifications on the collection list, met age/mileage requirements, and the vehicle had current Arizona license plates, NHTSA offered to pay for the installation of a new set of tires with a road-hazard warranty at no charge to the customer in exchange for their current tires (including full-size spares). Mini-spare tires were not collected.

Table 1 documents the data collected at the retrieval of the tires. Vehicle information such as the vehicle brand, model, odometer mileage, and vehicle identification number (redacted from public release) were collected. For each tire, the mounting location at collection time, inflation pressure, and sidewall information were recorded. In total, over 493 on-road tires of 12 different models were collected from local residents' vehicles (See Table 10 in the Appendix for a list of the 12 tire models collected).

Table 1.
Data Collected from Tires at Retrieval

Category	Test
Tire	DOT Code
	Brand / model / size / load index / speed rating
	Inflation pressure
	Position on vehicle
	Original date of sale if known
Vehicle	Arizona license plates (Yes/No)
	VIN (redacted from public dataset)
	Make / model
	Model year
	Mileage
Collection Location	Store identification number
	Date of retrieval

Following the Phoenix tire collection, VRTC staff separated full-size spare and non-Arizona tires from the main on-road tire population through searches of tire collection sheets, vehicle identification numbers, photos, and vehicle registrations. About 10% of sample tires were eliminated from testing because the vehicle was not registered in Arizona for entire service life of tire. This was done to prevent tires that may have been in service in other lower-temperature regions of the country from confounding the results of the analysis of Phoenix tires.

Within the population of the 12 tire models, an acceptable distribution of age and mileage could only be obtained for five original equipment tire models (i.e. tire model on the vehicle when purchased new) and one replacement tire model. This result can be attributed to the technicians' ability to watch for a specific vehicle model when searching for "original equipment" (OE) tire models, but not for "replacement market" tire models. Replacement tires were not on any specific vehicle and therefore a good distribution of each model was difficult to obtain. Consequently, the six Phoenix-retrieved tire models with the best distribution of age and mileage were selected for testing (See Table 2).

Table 2.
Six Tire Models Selected for Phase 1 Testing

NHTSA Tire ID	OE Fitment?	Tire Brand	Tire Model	Tire Size	Load Range	Speed Rating
B	Yes	BFGoodrich	Touring T/A SR4	P195/65R15	89	S
C	Yes	Goodyear	Eagle GA	P205/65R15	92	V
D	Yes	Michelin	LTX M/S	P235/75R15XL	108	S
E	Yes	Firestone	Wilderness AT	P265/75R16	114	S
H	No	Pathfinder[1]	ATR A/S	LT245/75R16	120/116E	Q
L	Yes	General	Grabber ST	255/65R16	109	H

[1] Manufactured for the Discount Tire Company by the Kelly-Springfield Tire & Rubber Company, a subsidiary of the Goodyear Tire & Rubber Company

Information on the 265 tires tested in Phase 1 is listed in Table 3. The "age" of the tires was determined by subtracting the build date in the DOT code from the date the tire was collected from service. This method of determining age was considered the most accurate, since once tires are depressurized when dismounted from the wheel, the thermo-oxidative degradation (aging) of tire rubber compounds should slow dramatically.

Table 3.
Phase 1 Sample Size

Tire Position	Number of Tires	Average Age (years)	Standard Deviation (years)	Oldest Tire (years)
On-road	174	2.66	1.76	7.38
Spare	9	4.08	3.34	10.7
New	82	-	-	-
Total	**265**			

The Phase 1 test tires were subjected to either testing on an indoor 1.7-m (67-inch) laboratory roadwheel or a cut-tire analysis of tire component materials properties. Some tires were excluded from the final dataset due to an invalid roadwheel test (i.e. valve leak, wheel failure, test machine failure, etc.) or the fact that they were not true zero-mileage full-size spare tires. The results from 183 tires retrieved from Phoenix of varying ages and mileages were compared to 82 new, un-used versions of themselves to determine overall rates of degradation in whole-tire or component material properties. Table 4 documents the distribution of the Phase 1 tires between the various tests.

Table 4.
Total Tires Tested In Phase 1

Tire Position	Roadwheel Tests	Materials Tests	Total
New	45	37	82
On-road	103	71	174
Spare	8	1	9
Total	156	109	**265**

Phase 1 Tire Tests

In Phase 1, the new and Phoenix-retrieved tires of the six models selected for testing were subjected to one or more tests listed in Table 5 at independent tire testing laboratories. The results of key measures will be discussed in the following sections.

Table 5.
Phase 1 Tire Data Collected

Test Category	Test
Nondestructive Inspection	Crack Coding
	Puncture/Repair Coding
	Shearography
	Tread Depth
	Tread Durometer
Laboratory Roadwheel Testing	Stepped-Up Speed to Failure
	Stepped-Up Load to Failure
Destructive Inspection	Innerliner Compound Analysis
	Innerliner Permeability
	Microscopy
Mechanical Properties of Compounds	Indentation Modulus Profile
	Peel Strength
	Shore Hardness
	Tensile Properties
Dynamic Properties of Compounds	Dynamic Mechanical Analysis
	Interlaminar Shear Strain
	Micro-DeMattia Crack Growth
	Two-ply Laminate Fatigue
Chemical Properties of Compounds	Crosslink Density
	Fixed Oxygen by Weight

RESULTS AND DISCUSSION

The testing conducted in Phase 1 of the NHTSA Tire Aging Test Development Project generated an extremely large and varied set of data for use in test development. It is not possible to discuss the results of all of these tests in one short paper. Therefore the results presented in this paper focus on the changes with age and mileage in intuitive measures such as retrieval condition, whole tire roadwheel performance, and mechanical properties.

Tire Retrieval Data

Data were collected from the Phoenix tires during the removal process for both the on-road tires and full-size spare tires. The inflation pressure of each tire was recorded by the service technician at the collection facility before the tire was removed from the vehicle. Figure 1 documents the retrieval pressures versus the age of the tire for 453 on-road tires, separated into either the passenger or light truck category for analysis. (Results for the full-size spare tires are analyzed in a separate section.)

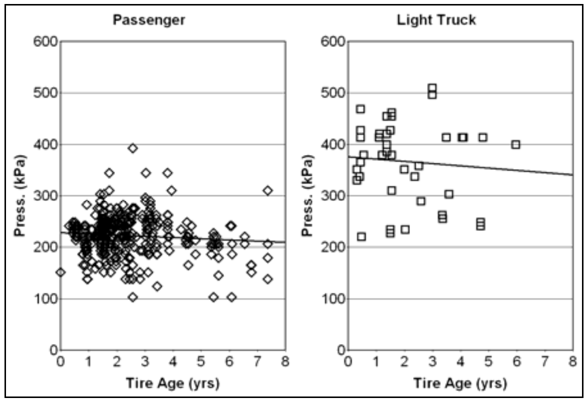

Figure 1. Inflation Pressure at Retrieval vs. Tire Age, Phoenix-Retrieved Non-Spare Tires, All Tire Models.

For the data presented in Figure 1, the average inflation pressure at retrieval for the 11 passenger tire models was 223 kPa (32 psi), and for the load range E light truck tires the average was 367 kPa (53 psi). While a large amount of scatter was seen for both the passenger and light truck tire models, the mean tire inflation pressure levels did not deviate significantly with the increasing age of the tires. Out of the 12 tire models collected, the light truck tires had the widest distribution in inflation pressures at retrieval. This might be attributed to their use on full-size pickup trucks of varying payload capacities ("½ ton" vs. "¾ ton"), use in dual tire configurations, or the use of lower inflation pressures by some vehicle owners for better ride quality when lightly loaded.

The minimum cold inflation pressures available in the Tire and Rim Association (T&RA) Yearbook [10] load limit tables are 180 kPa (26 psi) for passenger tires and 250 kPa (36 psi) for light truck tires. Though a small number of these tires were retrieved from vehicles on dealer lots, approximately 11% (44/411) of passenger vehicle tires and 14% (6/42) of light truck tires had retrieval pressures below the respective minimum T&RA pressures.

Nondestructive Inspection

Tread Depth - Per the ASTM F 421-00 standard test method, tread depths of the six tire models selected for testing (of the twelve collected) were measured in each groove of the tire at a minimum of six locations around the circumference of the tire and then averaged. The average tread depth versus mileage is displayed in Figure 2. New tires are denoted by a "0" mileage on the x-axis. Since the actual mileage is only known for original equipment (OE) tires, only OE tires are plotted. The U.S. Uniform Tire Quality Grading Standards (UTQGS) treadwear grade is listed in the legend for each tire model. A summary of the linear curve fits to the data in Figure 2 is contained in Table 6.

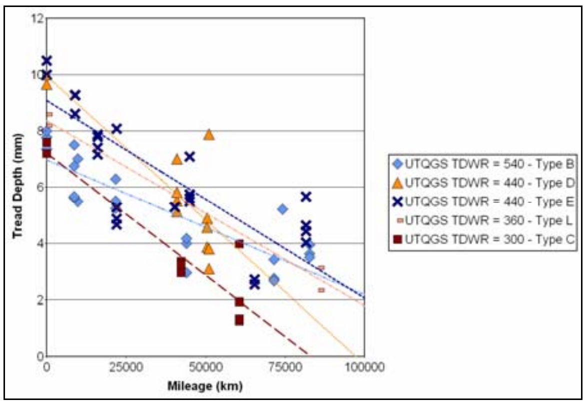

Figure 2. Tire Tread Depth at Retrieval vs. Mileage, Phoenix-Retrieved Non-Spare Tires, 5 Tire Models (Original Equipment Tires only).

One obvious trend in Figure 2 is a relatively linear reduction in average tire tread depth with known mileage.

Table 6.
Treadwear Rates vs. Mileage from Linear Fits

Vehicle Class	UTQGS Treadwear Grade	NHTSA Tire ID	Slope of Linear Fit	Y - Intercept (mm)	R^2
Passenger	540	B	-5E-05	7.0	0.73
Passenger	300	C	-9E-05	7.2	0.94
LT/SUV	440	D	-1E-04	9.9	0.83
LT/SUV	440	E	-7E-05	9.1	0.69
LT/SUV	360	L	-7E-05	8.4	0.99

In general, the treadwear rates of tires retrieved from Phoenix showed good correlation to known mileage, with the treadwear grade being somewhat predictive of treadwear rate within a vehicle class.

Shearographic Interferometry - Shearography is a non-destructive testing method that identifies and measures the internal separations present between layers of a tire. These separations are considered undesirable in terms of tire durability. The shearography machine uses lasers to map the interior surface of the tire at normal atmospheric pressure, and once again under vacuum conditions. Internal separations in the tire will spread apart under the vacuum, causing the interior surface of the tire to exhibit raised areas resembling bubbles above the internal separations. The resulting difference between mapping images of the two surfaces can be used to identify and measure the total internal separations (cracks or delaminations) within a tire.

Figure 3 displays the results of full bead-to-bead shearography of the six Phoenix-retrieved tire models versus the age of the tires at retrieval. New tires of each model had essentially no measurable separation when tested. For some tire models, the total level of internal separation was observed to be higher in older tires. However, the shearography measure did not appear to correlate strongly with age overall.

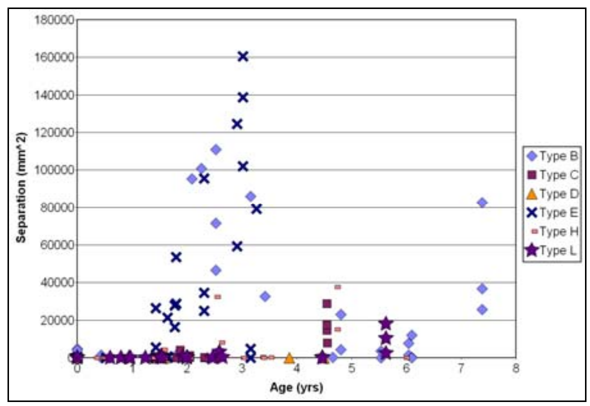

Figure 3. Bead to Bead Shearography Separation @ 50 mbar Vacuum vs. Age, Phoenix-Retrieved Non-Spare Tires, 6 Tire Models.

Figure 4 instead plots the measured level of internal separation versus the mileage of the tires. The results shown in Figure 4 suggest the internal separation of tires appears to correlate better to the mileage experienced by the tire than to the age of the tire. This is an intuitive observation, since the initiation and growth of internal cracks/separations are driven primarily by the cyclical deformation of the tire.

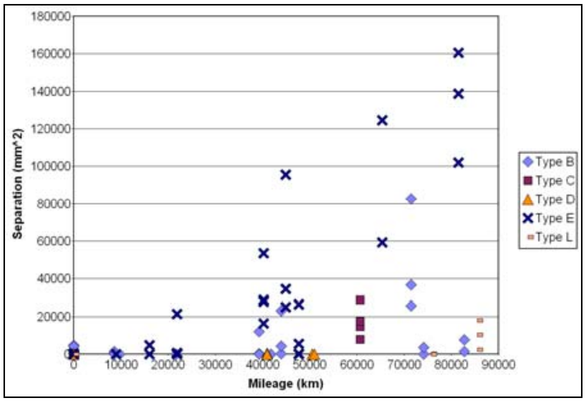

Figure 4. Bead to Bead Shearography Separation @ 50 mbar Vacuum vs. Mileage, Phoenix-Retrieved Non-Spare Tires, 5 Tire Models (Original Equipment Tires only).

Laboratory Roadwheel Testing

Evaluations of whole tire performance were conducted on new and Phoenix-retrieved tires using laboratory roadwheels. All roadwheel testing was completed at a single laboratory per the ASTM F 551 standard practice for testing tires on a 1.7 meter (67 inch) roadwheel. All Phoenix-retrieved tires underwent multiple pre-test visual inspections as well as shearographic inspection before testing. To not unfairly bias the results, only tires free from visible damage and repairs (patches, plugs, exposed belt edges, etc.) were subjected to roadwheel testing. Comprehensive pre and post-test inspections of the tires were completed with uniform coding of the results and photographic documentation.

Within the six tire models tested, 111 Phoenix-retrieved tires and 45 new tires were subjected to either a stepped-up speed to failure or stepped-up load to failure test on a laboratory roadwheel (See Table 7). The Stepped-Up Speed test (SUS) is intended to measure a tire's retention of prolonged maximum speed capability while under a typical loading condition. The Stepped-Up Load test (SUL) was intended to measure a tire's resistance to prolonged operation at a typical U.S. interstate highway speed while over-deflected (i.e. overloaded and/or underinflated). Both roadwheel tests are based on the pass/fail tests in the new FMVSS No. 139, "*New Pneumatic Radial Tires for Light Vehicles*". However, since the pass/fail test criteria in the new standard are based on a minimum performance level, the criteria are of marginal utility as a research tool. Instead, the versions of tests used in this program continued to step up the test speed or load until tire failure rather than stopping the test at the passing mark.

Table 7.
Phase 1 Roadwheel Tests Sample Size

Tire Position	Stepped-Up Speed Test	Stepped-Up Load Test	Total
New	21	24	45
On-road	38	65	103
Spare	6	2	8
Total	65	91	**156**

The results of the Phase 1 testing for the six Phoenix-retrieved tire models were compared to new, unused versions of themselves in the next section of this report. (As always, when examining indoor laboratory roadwheel results it is important to consider that a straight-line test, under static uniaxial loading conditions, on a curved steel roadwheel only approximates the real world operation of a tire under dynamic multi-axial handling and loading conditions on a flat roadway surface.)

Stepped-Up Speed Roadwheel Test Results - The Stepped-Up Speed (SUS) roadwheel test is based on the new FMVSS No. 139 High Speed tire test. Per the standard's High Speed test conditions, the tire is subjected to a two hour break-in on the roadwheel at 80 km/h (50 mph), then run continuously and uninterrupted for ninety minutes through three thirty-minute test stages at the following speeds: 140, 150, and 160 km/h (87, 93, and 99 mph). If the tire completes the roadwheel test intact (i.e. no catastrophic structural failures or significant loss of inflation pressure), the tire is stopped for a one-hour cool down period and inspected.

Unlike the pass/fail FMVSS No. 139 High Speed test, which ends after the 90-minute test period is complete, the tire was restarted and run through additional speed steps that increase 10 km/h every 30 minutes until the speed rating of the tire is reached. Once the speed steps reach the speed rating of the tire, the tire is run at that speed uninterrupted until a catastrophic failure occurs. Details of the test are listed in Table 11 in the Appendix.

The results of the Stepped-Up Speed (SUS) roadwheel test versus age for new and on-road (non-spare) tires can be seen in Figure 5. (Spare tire results will be analyzed in a separate section.) Since the "Type D" tire model had only one Phoenix-retrieved tire tested, no exponential trendline was plotted through its data. Figure 5 is organized by the speed rating of the tire and displays the results for new, original equipment, and replacement non-spare tires retrieved from Phoenix. The time to failure in minutes is plotted against the age of the tire at retrieval. (The time to failure plotted does not include the 120 minute pre-test break-in period.) New tires are denoted by a "0" age on the x-axis.

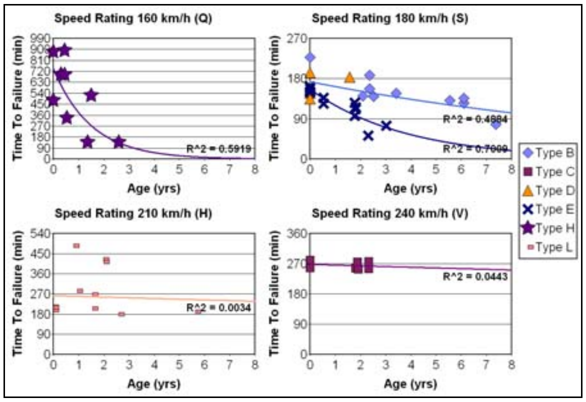

Figure 5. Stepped-Up Speed to Failure Test: Time to Failure vs. Age, Phoenix-Retrieved Non-Spare Tires, 6 Tire Models [Excludes 2 Hour Break-in Time].

To evaluate the SUS test results in context, it's necessary to look at the requirements of the FMVSS No. 139 High Speed test for new tires. This regulation requires new tires to complete a 2 hour low-speed break-in and three 30-minute steps of increasing speed to pass. All new tires tested in the SUS test easily exceeded the minimum requirements of the standard. The new "Type H" load range E light truck tires, which have a Q-speed rating of 160 km/h (99 mph), ran at that speed rating for hundreds of additional minutes beyond the passing mark. However, as displayed in Figure 5, this tire model exhibited a precipitous decline in time to failure with age. Two of the three S-speed rated tires did show a decline in time to failure with age, with some tires eventually dropping below the new tire requirements. Conversely, the two tire models with the highest speed ratings (H and V-speed rated) showed little change in the test with increasing age. For these two tire models the coefficients of determination (R^2) for the SUS test were very weak.

8% (3/38) of the on-road Phoenix-retrieved tires failed before reaching the requirement of the FMVSS No. 139 High Speed test for new tires (See Table 8). All three were S-speed rated (180 km/h [112 mph]) tires and failed during one of the last two speed steps.

Table 8.
On-road Phoenix-Retrieved Tires That Did Not Exceed FMVSS No. 139 High Speed Test Requirements for New Tires

Speed Step	Speed Step Duration (min)	Speed	Failed
Break-in	120	80 km/h (50 mph)	0
1	30	140 km/h (87 mph)	0
2	30	150 km/h (93 mph)	1
3	30	160 km/h (99 mph)	2
Failures			**3/38**

In Figure 6, the results of the SUS test are plotted against the mileage of the tires at removal date. Since only OE tires can be plotted against mileage, only the two tire models with OE tires tested in the SUS test are displayed. For the two tire models, the time to failure in the SUS test was observed to decrease with increasing mileage.

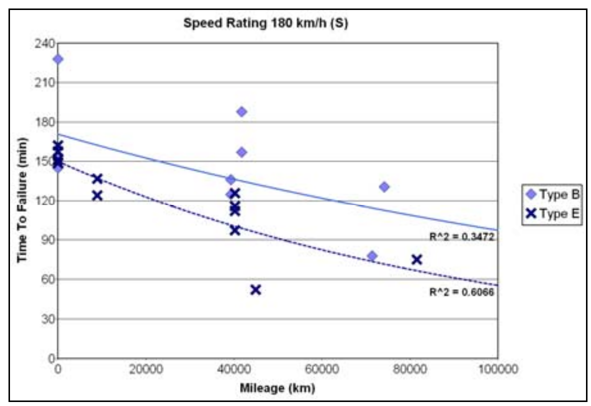

Figure 6. Stepped-Up Speed to Failure Test: Time to Failure vs. Mileage, Phoenix-Retrieved Non-Spare Tires, 2 Tire Models (Original Equipment Tires Only) [Excludes 2 Hour Break-in Time].

The overall results of the SUS test showed correlation to age and mileage for some tire models, but not for others. For the Q and S rated tire models the results of the SUS test suggest a reduction in prolonged maximum speed capability with age and mileage. Construction features for H and V rated tires such as overlays (e.g. cap-plies) may explain their better retention of prolonged maximum speed capability with age and mileage.

Stepped-Up Load Roadwheel Test Results - The Stepped-Up Load (SUL) roadwheel test is based on the new FMVSS No. 139 Endurance tire test. Per the Endurance test conditions there is no pre-test break-in. The tire is run continuously and uninterrupted at 120 km/h (75 mph) while overloaded/underinflated for four hours at 85% max load, six hours at 90% max load, and then twenty four hours at 100% max load. If the tire completes the roadwheel test intact (i.e. no catastrophic structural failures or significant loss of inflation pressure), the tire is stopped for a one-hour cool down period and inspected. Unlike the 34 hour pass/fail requirement of the FMVSS No. 139 Endurance test, the SUL test restarts tires and runs through additional load steps that increase by 10% of max load every four hours until catastrophic failure. The initial load and incremental loads are proportional to the maximum load rating for each tire. Details of the test are listed in Table 12 in the Appendix.

The results of the SUL test versus age for new tires and on-road (non-spare) tires can be seen in Figure 7. (Spare tire results will be analyzed in a separate section.) Figure 7 is organized by the speed rating of the tire and displays the results for new, original equipment, and replacement non-spare tires retrieved from Phoenix. The time to failure in hours is plotted against the age of the tires at removal date. New tires are denoted by a “0” age on the x-axis.

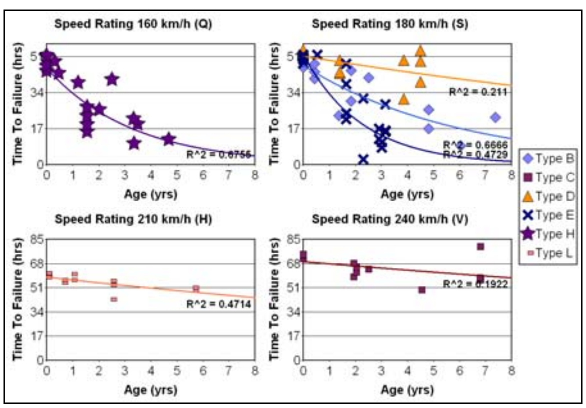

Figure 7. Stepped-Up Load to Failure: Time to Failure vs. Age, Phoenix-Retrieved Non-Spare Tires, 6 Tire Models.

As seen in Figure 7, new tires tended to last the longest in the SUL roadwheel testing, with time to failure decreasing with increasing age of the tire. All six tire models saw a decrease in time to failure with age. The rate of change in performance with age differed greatly between different tire models, with higher speed rated tires having less of a change in performance with age.

To evaluate the SUL test results in context, it is necessary to look at the requirements of the FMVSS No. 139 Endurance test for new tires. This regulation requires new tires to complete three steps of increasing load for a combined 34 hours to pass. All new tires tested easily exceeded the 34-hour requirement of the 139 Endurance test. For instance, new V-speed rated (240 km/h [149 mph]) tires repeatedly reached 230-240% of their maximum specified Tire and Rim Association (T&RA) load for the 180 kPa (26 psi) test pressure before failing. However, 43% (28/65) of on-road Phoenix-retrieved tires tested failed before reaching the 34-hour passing mark for new tires (See Table 9).

The shortest time to failure in the SUL dataset was 2.62 hours. For this tire, this represented 2.62 hours of continuous operation at 120 km/h (75 mph) under 98% of the maximum rated load for the tire inflation pressure used in the test (180 kPa [26 psi]). Three additional tires failed before the end of the second load step (≤10 hours), which depending on the tire size corresponded to 103 to 104% of the maximum T&RA rated load for the test pressure. Twenty four more tires failed before the end of the third and final load step (i.e. 34 hours), which corresponded to 115 to 123% of the maximum T&RA rated load for the test pressure. Unlike the improbable long durations at high speed represented by the SUS test, long periods of operation at 120 km/h (75 mph) while moderately overloaded / underinflated are realistic in the U.S.

Table 9.
On-road Phoenix-Retrieved Tires That Did Not Exceed FMVSS No. 139 Endurance Test Requirements

Speed Step	Load Step Duration (hours)	Max Sidewall Load (%)	Max Rated Load for Test Pressure (%)	Failed
1	4	85	98	1
2	6	90	103-104	3
3	24	100	115-123	24
Failures				**28/65**

The results of the SUL test are plotted against the mileage of the tire at removal date in Figure 8. As in prior plots against mileage, only OE tires are plotted. Similar trends to plotting against age were observed when plotting against mileage. Those were a general decrease in time to failure with increasing mileage, also a difference between the rates of degradation with age for brands that started out with similar new tire performance.

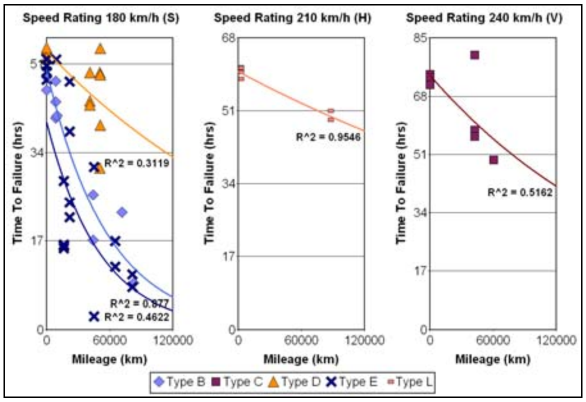

Figure 8. Stepped-Up Load to Failure: Time to Failure vs. Mileage, Phoenix-Retrieved Non-Spare Tires, 5 Tire Models (Original Equipment Tires Only).

Tires in the SUL test with higher speed ratings tended to lose less resistance to prolonged operation while overloaded / underinflated than lower speed rated tires. The coefficients of determination ("R^2") for the SUL test were better than expected given that these tires were taken off of random vehicles with varying service and operational histories.

The general conclusions from the SUL test results suggest that tires lose resistance to overloading / underinflation (i.e. resistance to the higher strain levels and temperatures that result from over-deflection) with increasing age and mileage. The next sections of the report provide examples of changes in the tire structure and tire component material properties measured that can be used to explain the observed changes in whole tire performance with increasing service life.

Destructive Inspection

<u>**Optical Microscopy**</u> - To conduct optical microscopy inspections, tires were cut into cross-sections at random locations, buffed, and examined under a microscope that utilized a high precision scale for measurement of distance. Over 50 quantitative or qualitative measures were recorded for each tire cross-section. An example of an internal crack measured using optical microscopy can be seen in Figure 9. Internal cracks, especially in the critical belt edge region are thought to have a negative impact on tire durability.

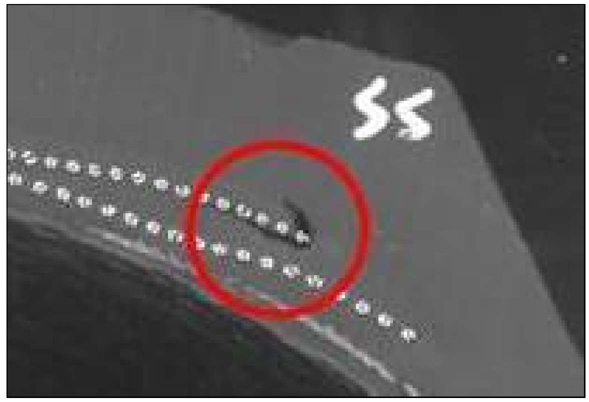

Figure 9. Example of Crack Observed in the Tire Shoulder at the Top ("#2") Belt Edge via Microscopy

Internal cracks in the tires were generally observed at the edge of the top (#2) steel belt, and progressing around the #2 belt edge inward between the two steel belts. The largest internal crack observed in the Phoenix tire cross-sections was 17.15 mm (0.675 in) in length. (The crack length data represent the largest cracks observed in the random section of the tire removed for microscopy only, not the largest crack in the whole tire.) The largest crack length measured per tire cross-section versus the age of the tire is displayed in Figure 10. For the six tire models studied, the largest crack length in the cross-section tended to increase with increasing tire age.

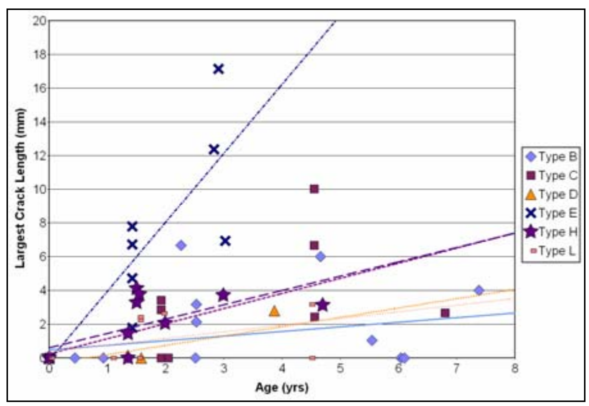

Figure 10. Largest Crack Length in the Tire Cross-Section vs. Age, Phoenix-Retrieved Non-Spare Tires, 6 Tire Models.

Figure 11 plots the largest crack length data against the mileage of the tire for original equipment tires. Largest crack length was observed to increase with increasing tire mileage.

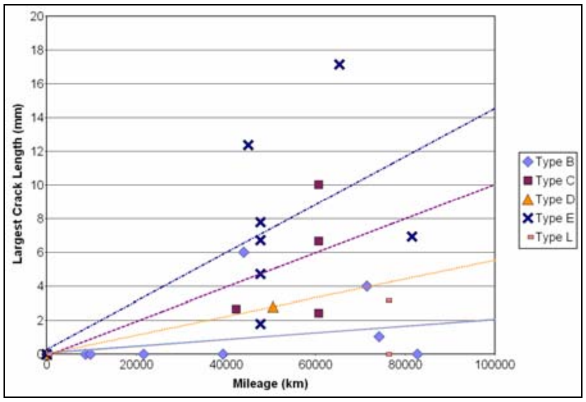

Figure 11. Largest Crack Length in the Tire Cross-Section vs. Mileage, Phoenix-Retrieved Non-Spare Tires, 5 Tire Models (Original Equipment Tires Only).

A logical question would be if the cracks and inter-laminar separations observed by shearography and microscopy were a product simply of stress-strain fatigue cycles from miles put on the tires, or if there were changes in the rubber compound themselves that made the tire components more likely to crack and delaminate as they experienced longer durations of service. To address this question, a comprehensive evaluation of tire material properties was conducted.

Material Properties

The material properties of individual rubber compounds and composite layers of the new and Phoenix-retrieved tires were tested in multiple areas of the tires (See Figure 12). The "Shoulder Region" and the "Bead Region" are critical areas of the tires that can experience high relative temperatures, strains, and forces. In particular, the "Wedge" rubber between the two belt edges in each shoulder of the tire and the inter-belt "Skim" rubber are critical to tire durability. These two components were the most thoroughly tested rubber components in Phase 1. (However the innermost tread and bead regions were also evaluated to serve as a baseline for development of an accelerated service life test. The goal was to develop a test that produced "field-like" material properties throughout the tire, not just in the skim and wedge compounds.)

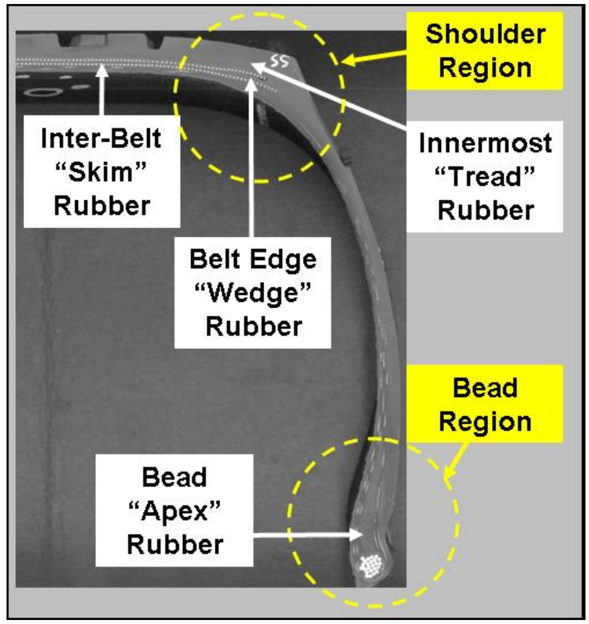

Figure 12. Regions of the Tires Where Material Properties Testing was Completed

Wedge Component Material Properties

Since virtually all the cracks and internal delaminations observed by shearography and microscopy in Phoenix-retrieved tires were at the belt edges of the tires, examples of select material properties of the wedge rubber component at the belt edge will be discussed in this section.

Tensile Properties - The tensile properties of the skim and wedge rubber compounds were tested per the ASTM D-412 standard test method. Five tensile test specimens (See Figure 13) from each side of the tire at two locations around the circumference of the tire were tested for both the skim and wedge rubber compounds.

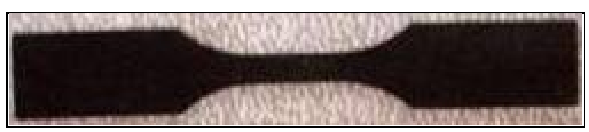

Figure 13. Tensile Test Specimen - Wedge Component Rubber Compound.

One tensile test measure, the modulus at a particular strain, is a measure of a material's tendency to deform (in this case elongate) when a force is applied to it. In Figure 14 the average per tire stress measured at 100% Strain (M100) for the wedge rubber compound was plotted against the age of the tire. As is evident from the figure, the rubber compound requires more force to stretch to the same length with the increasing age of the tire. If tested under compression instead of elongation, the compound would be “harder” than when it was new.

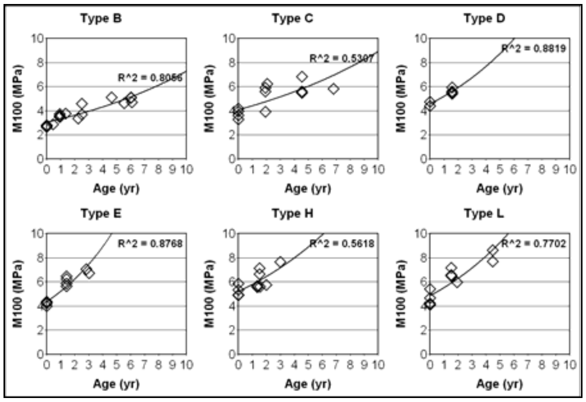

Figure 14. Per Tire Average Stress Measured at 100% Strain (M100) in the Wedge Rubber vs. Age, Phoenix-Retrieved Non-Spare Tires, 6 Tire Models.

In Figure 15, the stress measured at 100% Strain (M100) for the wedge rubber compound was plotted against the mileage of the OE tires. As with age, average per tire stress measured at 100% Strain (M100) increases with the increasing mileage of the tire.

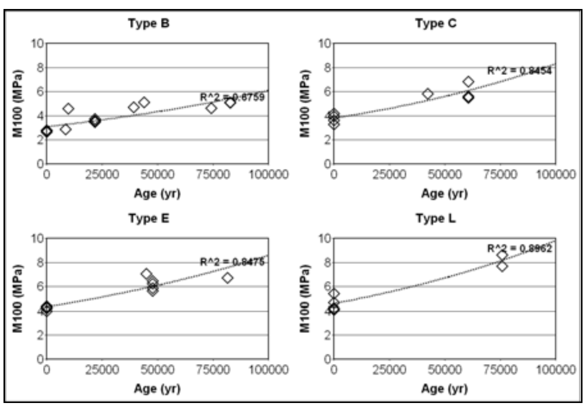

Figure 15. Per Tire Average Stress Measured at 100% Strain (M100) in the Wedge Rubber vs. Mileage, Phoenix-Retrieved Non-Spare Tires, 4 Tire Models (Original Equipment Tires Only).

Another tensile test measure is the ultimate elongation of a material. It represents the maximum length to which the rubber sample can be stretched before breaking. In Figure 16, the average per tire ultimate elongation for the wedge rubber compound was plotted against the age of the tire. The ultimate elongation was observed to decrease sharply with the increasing age of the tire.

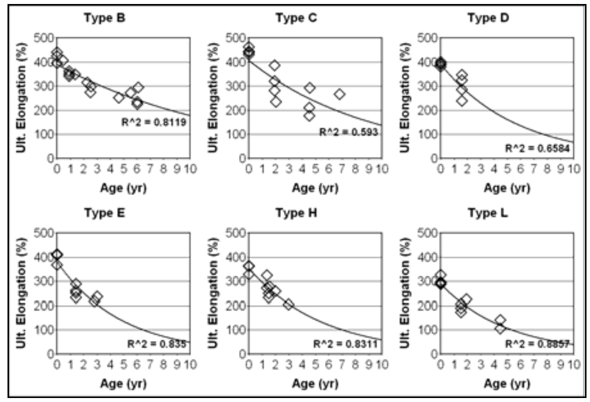

Figure 16. Per Tire Average Ultimate Elongation in the Wedge Rubber vs. Age, Phoenix-Retrieved Non-Spare Tires, 6 Tire Models.

In Figure 17, the average per tire ultimate elongation of the wedge rubber compounds are plotted against the mileage of the original equipment tires. As with age, the average per tire ultimate elongation decreases sharply with the increasing mileage of the tire.

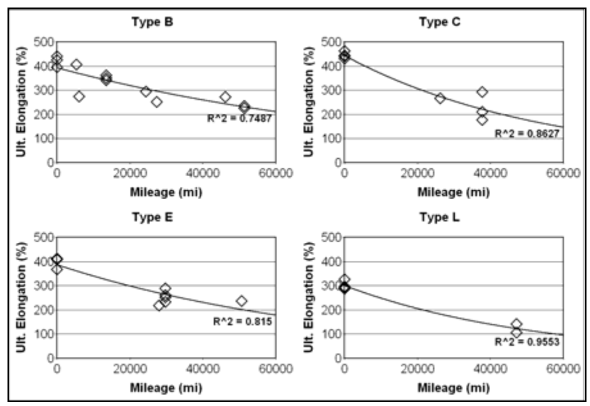

Figure 17. Per Tire Average Ultimate Elongation in the Wedge Rubber vs. Mileage, Phoenix-Retrieved Non-Spare Tires, 4 Tire Models (Original Equipment Tires Only).

Overall, the tensile properties of the wedge rubber compounds are increasing in modulus and decreasing in ultimate elongation with increasing service life. In other words, the compounds are getting harder, do not flex as much under a given load, and are losing their ability to stretch to a maximum length before breaking. These degradations in the wedge rubber material properties may contribute to the increased crack and delamination levels observed by shearography and microscopy in the wedge region with increasing service life.

The next question would be if there are not only changes in the material properties of the wedge compound but also the adhesion values between the steel belts in the wedge region with increasing service life. To test this hypothesis, inter-belt peel strength was measured.

Inter-Belt Peel Strength - The peak and average peel strength between the two steel belts in the tires were evaluated using the ASTM D 413 standard test method. Samples were taken from both sides of the tire at four locations around the circumference of the tire. Data were divided into results for the skim and the approximately 25.4 mm (1 inch) long wedge rubber regions at the edges of the steel belts separately (See Figure 18).

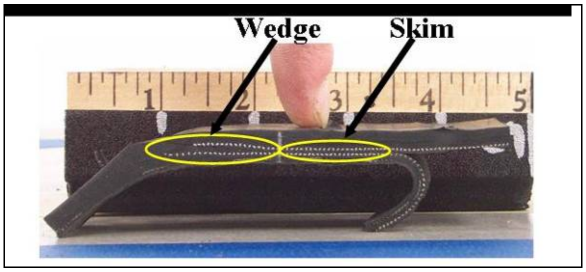

Figure 18. Peel Strength Test Specimen - Skim & Wedge Components.

In Figure 19, the average peel strength results in the wedge rubber region were averaged for eight test samples and displayed versus the age of the tire. The average peel strength in the wedge rubber region (i.e. adhesion level between the edges of the steel belts) was observed to decrease with the increasing age of the tire for all six tire models.

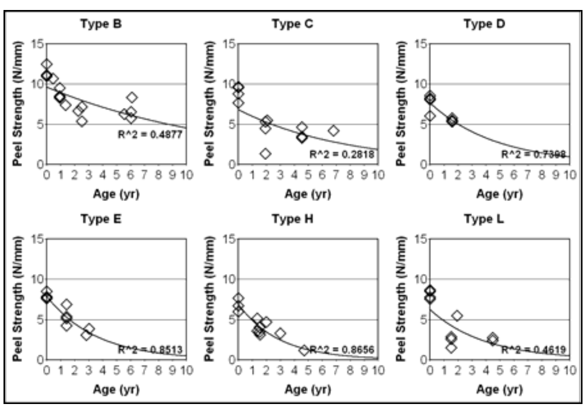

Figure 19. Per Tire Average Peel Strength in Wedge Rubber Region vs. Age, Phoenix-Retrieved Non-Spare Tires, 6 Tire Models

In Figure 20 the average peel strengths are plotted against the mileage of the original equipment tires. As with age, the average peel strength in the wedge rubber region between the belt edges was observed to decrease with the increasing mileage of the tire. The results of peel strength testing suggest that inter-belt adhesion in the wedge region of the belt package is decreasing with increasing service life.

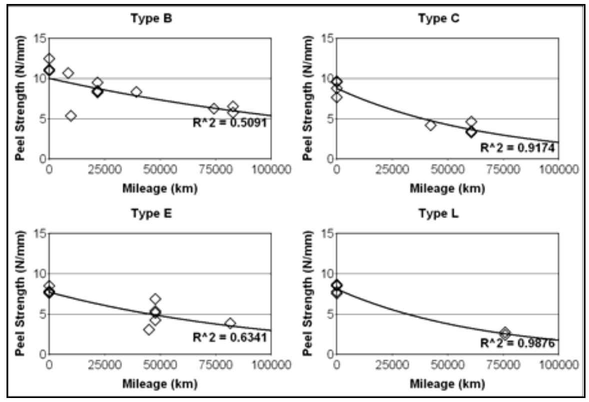

Figure 20. Per Tire Average Peel Strength in Wedge Rubber Region vs. Mileage, Phoenix-Retrieved Non-Spare Tires, 4 Tire Models (Original Equipment Tires Only).

Overall, the select material properties tests discussed in the section for the wedge rubber component suggest quantifiable changes in the compound that affect crack growth rate and inter-belt adhesion in that region. These changes can be explained by chemical changes in the wedge compound and adhesive system; however discussion of these measures is beyond the scope of this paper. The main point of including examples of material property testing was to emphasize that the changes in whole tire performance observed with age and mileage were partly a result of changes in tire compounds and interfaces, and not simply a result of cyclic fatigue.

Spare Tires

Figure 21 documents the inflation pressure of all tires retrieved from the spare tire location on the vehicle. This plot includes 29 tires of the 12 models collected in Phoenix and includes both zero-mileage spares and used tires stored at that location. The lowest pressure observed was 55 kPa (8 psi) for a 6.78 year old passenger vehicle tire. 31% (8/26) of passenger tires at the spare tire location had pressures below 180 kPa (26 psi) when retrieved. 33% (1/3) light truck tires retrieved at the spare tire location had an inflation pressure below 250 kPa (36 psi).

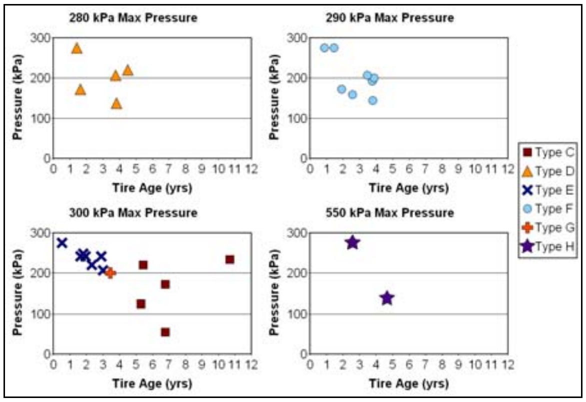

Figure 21. Inflation Pressure at Retrieval vs. Age, Phoenix-Retrieved Full-Size Spare Tires, All Tire Models.

Out of the 29 tires retrieved from the spare tire location, there were only 9 tires of the six tire models tested in Phase 1 that could be confirmed as only seeing service in Phoenix and having zero mileage. Since these confirmed spares did not see service, measurements such as tread depth, shearography, largest crack length are not informative.

A Ford Motor Company study of the material properties of 1500 tires retrieved from service in six cities in the U.S. concluded:

"On-road tires age roughly 1.25 times faster than (full-size) spare tires independent of property. That is, the ratio of the rates of crosslink density increase and peel strength loss are the same independent of whether or not the tire is a spare. This suggests that the difference in rate is due to the fact the on-road tires see a somewhat higher temperature history than spare tires due to a combination of sun load and tire heating during driving. It is important to note that on-road tires are typically driven around 5% of the time." [11]

"In every case, the spare tire data was statistically identical to the road tire data, meaning that mechanical fatiguing does not impact the aging process with regards to property change of the rubber." [12]

Ford's findings suggest full-size spare tires were experiencing material property degradation in a manner similar to on-road tires, but at a slower rate. The next logical step was to see if this material degradation also resulted in a change in performance of spare tires in roadwheel tests. In Phase 1, six full-size spare tires were subjected to the Stepped-Up Speed test and two tires to the Stepped-Up Load test.

The results for the six spare tires that were subjected to the SUS test are plotted against age in Figure 22. Though the dataset is limited in size, a small decrease in time to failure was observed for the five S-rated full-size spares with age but not for the single V-rated spare.

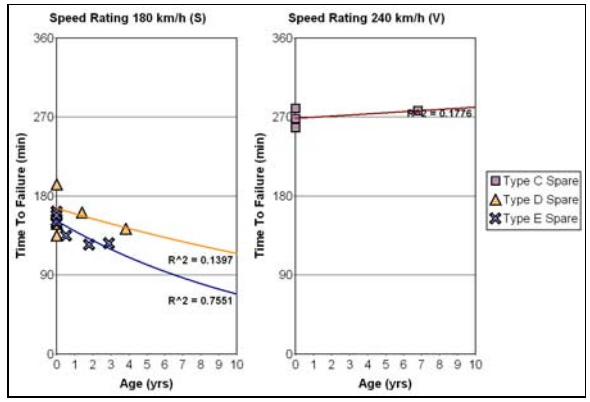

Figure 22. Stepped-Up Speed to Failure Test: Time to Failure vs. Age, Phoenix-Retrieved Full-Size Spare Tires, 2 Tire Models [Excludes 2 Hour Break-in Time].

The results for the two spare tires that were subjected to the SUL test are plotted against age in Figure 23. Again, though the dataset is limited, a small decrease in time to failure was observed for both models of spare tires regardless of speed rating.

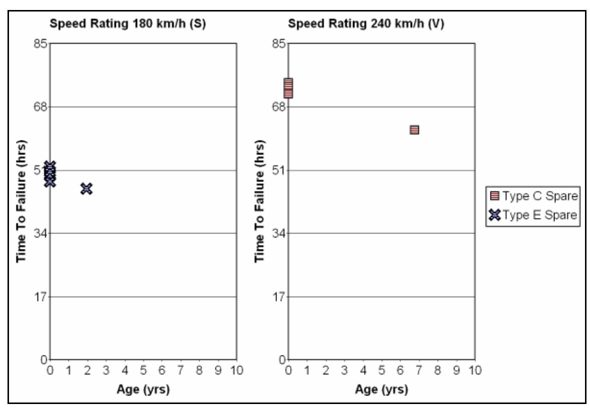

Figure 23. Stepped-Up Load to Failure: Time to Failure vs. Age, Phoenix-Retrieved Non-Spare Tires, 2 Tire Models.

The trends in the roadwheel tests were the same for on-road tires as spare tires. Namely the lower speed rated tire showed reductions in time to failure in both the SUS and SUL tests. The higher speed rated tires showed no significant change in time to failure in the SUS test but measurable changes in the SUL test.

While the reductions in the whole tire performance of the full-size spare tires in the two roadwheel tests were smaller in magnitude than for the on-road tires, and the dataset was extremely limited, the results support the hypothesis that spare tires could degrade while stored on the vehicle. This is a particular concern when coupled with the inflation pressures of full-size spare tires at retrieval. Over 30% of the passenger and light truck tires at the spare tire location had inflation pressures below the T&RA Load Table minimums. A recent study by the agency projected that more than 50% of passenger vehicles will still be on the road in the U.S. after 13 years of service, and more than 10% will still be on the road after 19 years. For light trucks, those figures go to 14 and 27 years respectively. [13] Since few consumers replace their full-size spare tires when replacing on-road sets of tires, full-size spare tires have the potential for very long service lives. This elicits the logical concern that older full-size spare tires with possible degradations in capability may see emergency use while significantly underinflated.

CONCLUSIONS

The goals of Phase 1 were to provide a better understanding of the effects of service life on tires and to serve as the “real-world” baseline for evaluating the effectiveness of accelerated laboratory tire-aging methods in subsequent phases of the project. For the tests detailed in this paper, the following trends were observed in the Phoenix-retrieved tires:

- While mean tire inflation levels of on-road tires did not deviate much with age, approximately 11% of passenger vehicle tires and 14% of light truck tires had retrieval pressures below the minimum pressures in the 2003 Tire & Rim Association Tire Load Limit Tables that were in place at the time of the tire collection.

- Results of bead-to-bead shearography of the tires indicated that internal separations in the tire tended to increase with increasing age and mileage, correlating better to mileage.

- In the Stepped-Up Speed roadwheel test, some tire models showed a decline in time to failure with age and mileage, while others did not. Results indicated a strong correlation to the speed rating of the tire, with the higher speed rated tires losing the least capability with increasing age and mileage.

- In the Stepped-Up Load roadwheel test, all tire models showed a decline in time to failure with age and mileage. Results indicated a strong correlation to the speed rating of the tire, with the higher speed rated tires losing the least capability with increasing age and mileage.

- Optical microscopy results indicated that the largest crack length measured in tire cross-sections examined tended to increase with increasing age and mileage.

- The tensile properties of wedge rubber compound between the two belt edges were observed to increase in modulus and decrease in ultimate elongation with increasing age and mileage.

- The average peel strength in the wedge rubber region between the two belt edges was observed to decrease with increasing age and mileage, indicating reduced adhesion between the steel belts.

- The changes in the physical material properties of the tire rubber compounds can be explained by chemical changes in the compounds and interfaces; however discussion of these measures was beyond the scope of this paper.

- Over 30% of the passenger and light truck tires at the spare tire location had inflation pressures below the 2003 T&RA Load Table minimums. Roadwheel tests of eight zero-mileage full size spare tires indicated possible reductions in performance with age.

ACKNOWLEDGEMENTS

The agency would like to thank its contractors at the Akron Rubber Development Laboratory, Inc., Smithers Scientific Services, Inc., Standards Testing Laboratories, Inc., and Transportation Research Center, Inc. for their contributions to the project. In addition, the agency has benefited from an extraordinary level of technical support, as well as access to internal test procedures and data from the Ford Motor Company, ExxonMobil Chemical Company, and ASTM F9.30 Task Group and its associated members. Finally, the researchers would like to acknowledge the contributions of Jan Cooper of TRC and NHTSA Contracting Officers Robin Esser and Shannon Reed for their significant contractual, logistics, and procurement support.

APPENDIX

Table 10.
Twelve Tire Models Collected In Maricopa County (Phoenix), Arizona

NHTSA Tire ID	Tires	Tire Manufacturer	Tire Model	Tire Size	Load Range	Speed Rating
A	34	Hankook	H406	P185/65R14	85	H
B	70	BFGoodrich	Touring T/A SR4	P195/65R15	89	S
C	31	Goodyear	Eagle GA	P205/65R15	92	V
D	39	Michelin	LTX M/S	P235/75R15XL	108	S
E	50	Firestone	Wilderness AT	P265/75R16	114	S
F	49	Goodyear	Wrangler HP	255/55R18	109	H
G	29	Kumho	ECSTA HP4	P205/60R15	90	H
H	49	Pathfinder	ATR A/S	LT245/75R16	120/116E	Q
I	22	Yokohama	Avid Touring	P205/70R15	95	S
J	45	Continental	Touring Contact A/S	P205/65R15	92	S
K	35	Pirelli	P6 FourSeasons	P235/45R17	94	V
L	40	General	Grabber ST	255/65R16	109	H
Total	**493**					

Table 11.
Stepped-Up Speed to Failure Test: Speed stepped-up through FMVSS No. 139 High Speed test conditions to the speed rating of tire and held to failure

Test Stage	Duration (hours)	Speed	
1	0.5	140 km/h	139
2	0.5	150 km/h	
3	0.5	160 km/h[1]	
Inspection	1	*	*
4	0.5	170 km/h	Until failure
5	0.5	180 km/h[2]	
6	0.5	190 km/h	
7	0.5	200 km/h	
8	0.5	210 km/h[3]	
9	0.5	220 km/h	
10	0.5	230 km/h	
11	0.5	240 km/h[4]	

1 Do not increment speed over 160 km/h for Q speed rated tire, hold at speed rating until tire failure.
2 Do not increment speed over 180 km/h for S speed rated tires, hold at speed rating until tire failure.
3 Do not increment speed over 210 km/h for H speed rated tires, hold at speed rating until tire failure.
4 Do not increment speed over 240 km/h for V speed rated tires, hold at speed rating until tire failure.

Table 12.
Stepped-Up Load to Failure Test: Load stepped-up through FMVSS No.139 Endurance test conditions and continued on to failure

Test Stage (#)	Duration (hours)	Percent Max Load	Speed (mph)	Test
1	4	85%	75	*FMVSS 139 Endurance*
2	6	90%	75	
3	24	100%	75	
Inspection	**1**	**-**	**-**	**-**
4	4	110%	75	*Stepped-Up Load to Catastrophic Failure*
5	4	120%	75	
Etc.	4	+10% every 4 hours	75	

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