

Automotive Fire Apparatus Tire Replacement

Final Report

Prepared by:

Sreenivasan Ranganathan

Minchao Yin

Fire Protection Research Foundation

Quincy, Massachusetts USA

© March 2015 Fire Protection Research Foundation



THE
FIRE PROTECTION
RESEARCH FOUNDATION

FIRE RESEARCH

THE FIRE PROTECTION RESEARCH FOUNDATION
ONE BATTERYMARCH PARK
QUINCY, MASSACHUSETTS, U.S.A. 02169-7471
E-MAIL: Foundation@NFPA.org
WEB: www.nfpa.org/Foundation

(This page left intentionally blank)

FOREWORD

An automotive Fire Apparatus fleet must be maintained in the highest state of readiness in order to immediately respond to an emergency. The provision of a reliable firefighting apparatus is one of the most important capital assets of a local government. The Technical Committee on Fire Department Apparatus has required that **“tires shall be replaced at least every seven (7) years or more frequently...”** This requirement was incorporated in a complete rewrite of the 2007 edition of NFPA 1911, and lacks supporting scientific documentation. Due to high capital costs, the decision for replacing fire apparatus tires should be based on an objective decision making process. The required replacement of tires after seven (7) years is placing an undue financial burden on departments and agencies trying to comply with the 1911 requirements. In addition, the waste of natural resources and the need for proper disposal or reprocessing of the tire have an unfavorable effect on the environment.

The goal of this project is to determine if there is evidence that supports a mandatory seven (7) years replacement schedule for Fire Department Apparatus tires, develop guidance for Fire Departments regarding the replacement of apparatus tires, and provide recommendations for future revisions of this requirement in NFPA 1911.

The Research Foundation expresses gratitude to the report authors Sreenivasan Ranganathan and Minchao Yin of the Fire Protection Research Foundation. Thanks are also expressed to the National Fire Protection Association (NFPA) for providing the project funding through the NFPA Annual Code Fund.

The content, opinions and conclusions contained in this report are solely those of the authors.

About the Fire Protection Research Foundation

The [Fire Protection Research Foundation](#) plans, manages, and communicates research on a broad range of fire safety issues in collaboration with scientists and laboratories around the world. The Foundation is an affiliate of NFPA.

About the National Fire Protection Association (NFPA)

NFPA is a worldwide leader in fire, electrical, building, and life safety. The mission of the international nonprofit organization founded in 1896 is to reduce the worldwide burden of fire and other hazards on the quality of life by providing and advocating consensus codes and standards, research, training, and education. NFPA develops more than 300 codes and standards to minimize the possibility and effects of fire and other hazards. All NFPA codes and standards can be viewed at no cost at www.nfpa.org/freeaccess.

Keywords: NFPA 1911, tire replacement, fire apparatus, automotive, inspection, testing, maintenance

(This page left intentionally blank)

PROJECT TECHNICAL PANEL

Ryan Depew, NFPA

Don Frazier, Los Angeles Fire Department

Mike Stankus, North West Fire Mechanics

Doug Jones, Michelin

PROJECT SPONSORS

National Fire Protection Association

(This page left intentionally blank)

Executive Summary

The Technical Committee on Fire Department Apparatus has required that “**tires shall be replaced at least every seven (7) years or more frequently...**” This requirement lacks supporting scientific documentation. The goal of this project is to determine if there is evidence that supports a mandatory seven (7) years tire replacement schedule for Fire Department Apparatus. Additionally, this project aims to develop guidance for Fire Departments regarding the maintenance and replacement of apparatus tires, providing recommendations for future revisions of this requirement in NFPA 1911.

The above mentioned objectives are carried out through the following specific tasks:

- 1) **Task 1: Review of Literature and Data Collection.** A comprehensive review of the literature and available data to determine if the seven year replacement requirement is supported by any existing research.
- 2) **Task 2: Identification of Tire Aging Issues.** A comprehensive analysis on the factors affecting the tire aging process. One commonly held belief is that tire failures are mainly due to poor maintenance or extreme condition. However, tire aging is a distinctly different phenomenon from the maintenance and inflation issues. Aging is affected by the heat generated in tires and the degradation that occurs due to the chemical reaction within the rubber components due to oxidation.
- 3) **Task 3: Identification of Tire Maintenance issues.** Identification of the factors which could result in tire failures or decreasing the tire lifetime. Comprehensive research with a primary focus on how to maintain the fire apparatus tire at the highest state of readiness within the years of service, and how to extend the tire lifetime through proper maintenance methods.
- 4) **Task 4: Tire Lifetime Assessment Technology.** Introduction of the existing technologies that can be used to test the tire usage and condition stage and how these technologies can be used to evaluate the fire apparatus tire condition which usually have a low mileage.
- 5) **Task 5: Final Report.**

From the present research, it is found that no literature convincingly supports a seven year tire replacement criteria. Further, it is realized that the wear and tear of the tire are due more importance while considering a tire replacement. As mentioned in the rubber manufacturer’s association statement, since service and storage conditions vary widely, accurately predicting the actual serviceable life of any specific tire based on simple calendar age is not possible. A tire should be removed from service for multiple reasons: tread wear to minimum tread depth, tire damage like cuts, cracks, bulges etc., improper inflation pressure and storage conditions. A specific inspection and maintenance of fire apparatus tire is recommended.

Table of Contents

| | |
|---|------|
| Executive Summary..... | viii |
| 1. Introduction and Background | 1 |
| 2. Identification of Tire Aging Issues..... | 3 |
| How to improve tire aging? | 4 |
| 3. Identification of Tire Maintenance issues..... | 5 |
| Tire Pressure | 5 |
| Under Inflated Tire..... | 5 |
| Over Inflated Tire | 5 |
| Routine Tire Pressure Check | 6 |
| Tire Tread Wear | 6 |
| Toe wear | 6 |
| Camber wear..... | 7 |
| Cupped wear..... | 7 |
| Diagonal wear | 7 |
| Tread depth..... | 7 |
| Sidewall Weathering | 7 |
| Wheel Alignment | 8 |
| Toe | 8 |
| Camber..... | 9 |
| Caster | 9 |
| Thrust Angle | 9 |
| Recommendations for Fire Apparatus Wheel Alignment..... | 9 |
| Tire Balance..... | 9 |
| Tire Rotation | 10 |
| Tire load rating..... | 11 |
| Spare tires | 12 |
| 4. Tire Life Assessment Technology | 13 |
| Non-destructive Inspection..... | 13 |
| Tread Depth | 13 |
| Shore Hardness of Tread..... | 13 |
| Shearographic Interferometry | 13 |
| Tire Pressure Monitoring System (TPMS) | 14 |

| | |
|-------------------------------------|----|
| Destructive Inspection | 14 |
| High Speed Free Rotation | 14 |
| Optical Microscopy | 15 |
| Recapping/Retreading of Tires | 15 |
| Summary & Recommendations | 16 |

Table of Figures

| | |
|--|----|
| Figure 1 - Anatomy of radial tire | 1 |
| Figure 2 - Tire wear patterns | 6 |
| Figure 3 - Adjustable alignment angles..... | 8 |
| Figure 4 - Traditional tire rotation patterns..... | 11 |
| Figure 5 - Flowchart of retreading process | 16 |

Table of Tables

| | |
|--|---|
| Table 1 - Vehicle Manufacturers Recommend Replacement at 6 Years | 2 |
| Table 2 - Tire Manufacturers' Warranties Expire at 6 Years | 2 |

1. Introduction and Background

An automotive Fire Apparatus fleet must be maintained in the highest state of readiness in order to immediately respond to an emergency. The provision of a reliable firefighting apparatus is one of the most important capital assets of a local government. The Technical Committee on Fire Department Apparatus has required that “tires shall be replaced at least every seven (7) years or more frequently...” This requirement was incorporated in a complete rewrite of the 2007 edition of NFPA 1911, and lacks supporting scientific documentation. Due to high capital costs, the decision for replacing fire apparatus tires should be based on an objective decision making process. The required replacement of tires after seven (7) years is placing an undue financial burden on departments and agencies trying to comply with the 1911 requirements. In addition, the waste of natural resources and the need for proper disposal or reprocessing of the tire have an unfavorable effect on the environment.

While manufacturing tires, rubber, consisting of mostly diene-based elastomers, is bonded to fabric plies and steel cords. Figure 1 depicts the anatomy of tire.³ During this manufacturing process, anti-aging ingredients are mixed with rubber compounds to slow down the process of tire wear out. But still, some tires age even before their treads wear out. Hence, a question which is constantly asked is, how long will it take for the tire to age out? Unfortunately, it is impossible to predict this based solely on calendar age. Further, wear out may not be assessed by external indications, hence it is difficult to understand the extent of deterioration based on the inspection by a tire expert. It is realized that there are a lot of other parameters affecting this process. **The U.S. National Highway Traffic Safety Administration (NHTSA)** and tire manufacturers are currently studying the many variables associated with tire aging like - exposure to sunlight and various atmospheric conditions, regularity or frequency of use and maintenance, and the quality of care and storage (maintaining proper inflation pressure, wheel alignment, poor storage, etc.).¹ A survey by NHTSA indicates that about 9% of the total vehicle crashes are due to tire-related issues, such as tread separations, blowouts, under inflation, etc.²

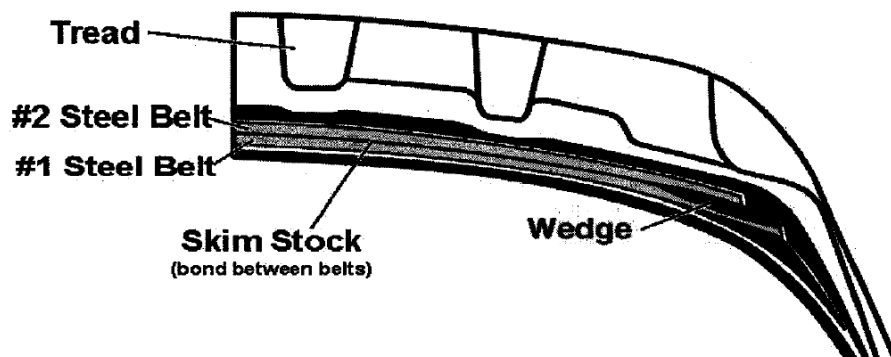


Figure 1 - Anatomy of radial tire³

¹ “Tire Aging – Part #1.” Tire Tech Information/General Tire Information, Tire Rack. Web: <http://www.tirerack.com/tires/tiretech/techpage.jsp?techid=138>

² “Tire-related factors in the pre-crash phase”, DOTHS811617, US Dept. of Transportation, National Highway Traffic Safety Administration, April 2012. Web: <http://www-nrd.nhtsa.dot.gov/Pubs/811617.pdf>

³ J. M. Baldwin & D. R. Bauer., “Rubber Oxidation and Tire Aging – A Review”, *Rubber Chemistry and Technology*: May 2008, Vol. 81, No. 2, pp. 338-358.

Earlier, in June 2001, the **British Rubber Manufacturers Association (BRMA)** recommended a practice to replace all tires ten (10) years from the date of manufacture and that the unused tires should not be used if they are over six (6) years old.¹ In May 2005, the **Japan Automobile Tire Manufacturers Association (JATMA)** recommended the inspection of a tire (including spare tires) after five (5) years of use for its usability and replacement of tires which are made ten (10) years ago. Several **European vehicle manufacturers** prohibit the usage of tires that are older than six (6) years. It is worth noting that these recommendations are based on the driving conditions different from those of America.¹

It is observed that heavily loaded tires on vehicles stored outdoors in sunny, scorching hot climates and only driven occasionally, face some of the most severe service conditions and potentially have the shortest calendar life span.⁴ The fire apparatus fleet would fall into this category of vehicles.

Listed below in Table 1 is the recommended time for tire replacement by different vehicle manufacturers.

Table 2 shows the warranty provided by different tire manufacturers. Both indicate six (6) years as the limiting time.

Table 1 - Vehicle Manufacturers Recommend Replacement at 6 Years⁵

| Vehicle Manufacturer | Recommended Tire Replacement at |
|-----------------------------|--|
| Audi | 6 year |
| BMW | 6 year |
| Ford | 6 year |
| Jeep | 6 year |
| Mercedes-Benz | 6 year |
| Toyota | 6 year |
| Volkswagen | 6 year |

Table 2 - Tire Manufacturers' Warranties Expire at 6 Years⁵

| Tire Manufacturer | Tire Manufacturers' Warranties Expire at |
|--------------------------|---|
| BF Goodrich | 6 year |
| Bridgestone | 6 year |
| Firestone | 6 year |
| Goodyear | 6 year |
| Hankook | 6 year |
| Michelin | 6 year |
| Yokohama | 6 year |

The report from NHTSA on tire aging indicates that the average tire service life in United States has been increasing over years.⁵ Data shows that, the average tire service life of a passenger car tire in 1973 was around 2.4 years where this increased to 3.6 years in 2004. Presently, as we see from the above tables,

⁴ "Tire Aging – Part #2." Tire Tech Information/General Tire Information, Tire Rack. Web. <http://www.tirerack.com/tires/tiretech/techpage.jsp?techid=183>

the tire tread warranties provided are around six (6) years from the date of manufacture or five (5) years from the date of purchase.⁵

2. Identification of Tire Aging Issues

According to NHTSA, “Tire aging” is defined as a phenomenon involving the degradation of the material properties of a tire which, over time, can compromise its structural integrity and jeopardize its performance.⁵ Since this happens irrespective of whether the tire is used or not, this is a concern for spare tires as well. When aging occurs, tires are more prone to failure, which could cause an inconvenience or lead to a motor vehicle crash. Other than tire aging, tire failures can be caused by a number of factors such as under- or over-inflation of the tire, overloading of vehicles, road hazards, improper maintenance, structural defects, improper installation, and tire aging. One common belief is that poor maintenance is the primary reason for failure in cases where the aging of the tires leads to tire failures.⁵

It is observed that a “chemical” process can also result in tire aging.⁵ A chemical reaction of oxidation within the rubber components with oxygen and heat is different from inadequate inflation and other poor maintenance issues. This chemical degradation of tire material is of greater concern in the warmer geographical locations. A NHTSA report indicates that the tire failures were higher in Arizona, New Mexico, Texas, Florida, and Southern California, whereas they were low in Northern states of USA.⁵ Further, this indicates the effect of higher average ambient temperature on faster tire degradation. It is also noted that the crack growth rates increase tremendously with oxidation of rubber.³ Previously, it was observed that most vehicle manufacturers recommend that tires be replaced every six (6) years regardless of use and a number of tire manufacturers recommend ten (10) years as the maximum service life for a tire as aging can affect the performance of the tires even if they have adequate tread and proper inflation.

Tire failures caused by both mechanical as well as chemical degradation can lead to motor vehicle crashes. From 1995 to 2006, NHTSA estimates that approximately 386 fatalities annually may be attributed to tire failures of all types. It is difficult to estimate how many crashes are caused specifically by tire aging. The data for 2005-07 from sources like National Motor Vehicle Crash Causation Survey (NMVCCS), General Estimates System (GES), and Crashworthiness Data System (CDS) indicate that around 90 fatalities and over 3,200 injuries that occurred as a result of crashes were likely caused by tire aging or with tire aging as a significant factor.⁶

There are essentially four major factors that contribute to tire aging:

- **The Inner Liner:** The inner liner of any tire is a specialized butyl rubber compound that is designed to be impermeable to air so as to keep the air inside the tire where it belongs. No inner liner is completely impermeable, so some air will always leak slowly through the liner due to osmosis. The quality of the inner liner determines just how much air leaks through and, therefore, how fast the inner structure of the tire is exposed to oxygen.
- **Oxygen Concentration:** The oxygen concentration is mainly controlled by its consumption rate for oxidation as well as the permeability of oxygen.³ Oxidation rates will increase when oxygen

⁵ “NHTSA Tire Aging Test Development Project – Phase 1”, DOTHS 811201. US Dept. of Transportation, National Highway Traffic Administration, October 2009.

⁶ “Tire Aging – A summary of NHTSA’s work” Web:

http://www.sae.org/events/gim/presentations/2013/medri_marison.pdf

concentration is higher. This means that a tire that is mounted and filled with compressed air will age much faster than a tire that is simply being stored, because the air pressure is orders of magnitude higher in a filled tire, and more oxygen will permeate through the liner.

- **Heat:** Oxidation of rubber occurs much faster under high heat than low heat. In essence, heat increases both the permeability and reactivity of oxygen, making it both easier for oxygen to get through the inner liner and easier for it to react with the rubber inside the tire. As mentioned earlier, NHTSA research shows that especially in the warmer parts of the United States, there appears to be a relationship between the age of the tire and the propensity of the tire to fail.⁵ This is also influenced more during summer months, during the day, and when vehicles are driven at high speed.⁶
- **Usage:** When a tire is driven, the pressure and flexing motion circulate the internal oils through the rubber. These oils lubricate the internal rubber and keep it from drying and stiffening. So tires that are used less are often more vulnerable to aging effects.

Usually, the end of tire life is judged based on tire tread wear. The factor of tire aging is often not taken into consideration. The above sections clarifies that aging of tire has direct effect on its structural integrity. Since this is not visibly detected, as an aged tire would still show a good tread, more attention is required to consider tire aging as a factor for tire replacement.

How to improve tire aging?

A few methods to improve the tire aging are identified here:

- One common way to improve tire aging is by adding anti-oxidants into rubber. Typical anti-oxidants include substituted phenols, diphenylamine-acetone reaction products, and tris (nonyl phenyl) phosphite.⁷
- Another interesting method is to fill the tires with nitrogen rather than air. This is mainly because, the oxygen needed for permeation and further oxidation is available within the tire itself. This practice has been proved worthwhile in applications such as aerospace, racing, and over-the-road trucks.³ Looking from the perspective of chemistry, nitrogen has a lesser permeation rate than oxygen, thus the tire pressure retention would be improved. This is evident from the NHTSA's report on nitrogen inflation of tires.⁸
- Literature shows that by improving the characteristics of the inner liner of the tire, its thickness and composition, a reduction in the permeation rate of air is achieved.³
- Exterior degradation of tires can be slowed down by applying protective waxes, oils, and exterior surface treatments.³

Tire fires or self-ignition of tires due to overheating in truck tires are greatly reduced recently due to the increased usage of tubeless radial tires. This reduces the internal friction or rubbing which occurs mainly when the tire is underinflated or overloaded.⁹

⁷ "The use of anti-ozonants in rubber compounding", Technical Publication, Hall Star. Web. <http://www.hallstar.com/techdocs/ANTIOZO.pdf>

⁸ "The effects of varying levels of nitrogen in the inflation gas of tires on laboratory test performance", DOTHS 811094. US Dept. of Transportation, National Highway Traffic Administration, March 2009.

⁹ Web. http://www.goodyeartrucktires.com/pdf/resources/service-manual/retread_s5_v.pdf

3. Identification of Tire Maintenance issues

Tire maintenance has a significant effect on the life span of the tire. Tire maintenance is the most important factor affecting the mechanical aging of tires. In order to properly maintain a tire, several factors like tire pressure, tire tread wear, sidewall weathering, wheel alignment, tire balance, tire rotation, tire load rating, and spare tires that will dramatically affect the tire condition, safety, and replacement plan have to be taken into account.¹⁰

Tire Pressure

Tire inflation pressure is the pressure at which the tire should be inflated with air and it is usually measured in pounds per square inch (psi) or Kilopascals (kPa). Manufacturers of passenger vehicles and light trucks determine this number based on the vehicle's design load limit, that is, the greatest amount of weight a vehicle can safely carry, and the vehicle's tire size.¹⁰ Though NFPA 1901, *Standard for Automotive Fire Apparatus*, does not mention anything regarding the inflation tire pressure for the fire apparatus, it is applicable only for fire apparatus with gross vehicle weight rating (GVWR) of 10000 lb (4500 kg) or greater.¹¹ As there can be different types of fire apparatuses available, the inflation tire pressure requirements would also differ accordingly.

As mentioned before, the inflation pressure is usually related to the load carrying capacity of the vehicle. Usual truck tire inflation pressures vary between 70-125 psi depending on the type of loading it is expected to carry. A proper load-inflation table provided by the manufacturer has to be used to inflate the tire to the proper pressure according to the loads. A sample load-inflation table can be found in the Goodyear truck tire specifications.¹²

Under Inflated Tire

A tire with its pressure below the recommended inflation pressure is an under inflated tire. When an under inflated tire is driven, it becomes flatter than intended and thus high heat is generated. This in turn can cause rapid tire wear, tire blowout, and loss of vehicle control.¹³ Even if the tire is underinflated by 6 psi, which is approximately 20% of the tire's recommended pressure of 30-35 psi for a passenger vehicle, the tread life could be reduced by 25%, leading to a faster tire failure.¹⁴ A tire that is under inflated shows more wear on the inside of the tread than around the edges. This will also result in the bending of tires.¹⁴

Over Inflated Tire

Over inflation of a tire above its recommended pressure results in lesser contact with the road. This also results in increased probability of tire damage from the objects on the road and potholes.¹⁴ Since it is difficult to identify an over inflated tire visually, a frequent pressure check is necessary.

¹⁰ "Everything Rides On It Tire Safety." NHTSA. Web.

<http://www.nhtsa.gov/cars/rules/tiresafety/ridesonit/images/brochure.pdf>.

¹¹ "1.3.1 (1). Application" NFPA 1901: Standard for Automotive Fire Apparatus, NFPA. 2009 edition.

¹² "Load and pressure adjustments." Web.

http://www.goodyeartrucktires.com/pdf/resources/publications/2010_loadinflation.pdf

¹³ "Tire Pressure Maintenance - A Statistical Investigation" National Highway Traffic Safety Administration, April 2009. Web. <http://www-nrd.nhtsa.dot.gov/Pubs/811086.pdf>

¹⁴ "Air Pressure – Correct, Underinflated and Overinflated." *Tire Tech Information/Air Pressure - Tire Inflation*, Tire Rack. Web. <http://www.tirerack.com/tires/tiretech/techpage.jsp?techid=1>

Routine Tire Pressure Check

Checking and refilling tire air is as important as refilling fuel. This is because tires lose pressure every day through the process of permeation. This will again depend on the weather conditions. A tire will typically lose one (1) or two (2) pounds of air per month during cool weather, whereas the rate of tire air pressure loss is even higher during warm conditions. Tires are also often subjected to flexing and impacts that can diminish air pressure as well. Adjustments have to be made for some vehicles that require different tire pressures on the front and rear axle. Also, it is equally important to have the pressure in the spare tire checked.¹⁵

Tire Tread Wear

Tire treads are important as they provide the gripping action and traction that prevent the vehicle from slipping or sliding, especially when the road is wet or icy. Tires have built-in tread wear indicators that let you know when it is time to replace the tires. These indicators are raised sections spaced intermittently in the bottom of the tread grooves.¹⁰

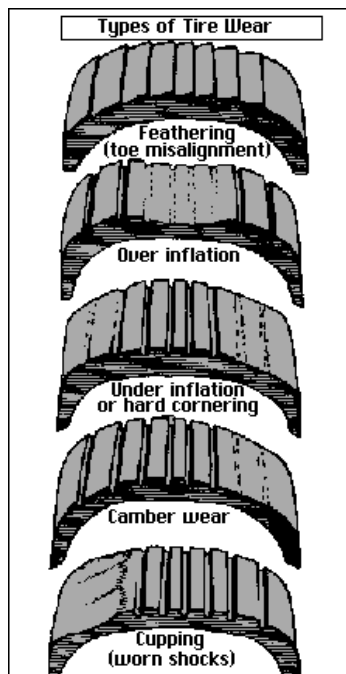


Figure 2 - Tire wear patterns^{16 17}

Toe wear

A feathered wear pattern, and/or inner shoulder wear, is produced on both front tires as a result of toe wear. The main reason identified for this is worn tie rod ends. Toe wear is usually accompanied by steering looseness or steering pull.¹⁶

¹⁵ "Air Pressure." *The Reinolt-Thomas Corporation*, Discount Tire. Web. <http://www.discounttire.com/dtcs/infoAirPressure.do>.

¹⁶ "Tire Wear." *Automotive Diagnostic & Repair Help*, AA1Car.com. Web. http://www.aa1car.com/library/tire_wear.htm.

Camber wear

Camber misalignment leads to leaning of tires. This results in the uneven wear on one side of a tire. This is caused by defective control arm bushings, ball joints, or a bent spindle which could have occurred due to a factory misassembly or severe corrosion damage.¹⁶

Cupped wear

Tire cupping or scalloped dips appear usually around the edge of the tread as a result of badly worn shocks or struts, or wheel and tire imbalance.^{16,17} The worn tire should be balanced and possibly moved to a different location.

Diagonal wear

Diagonal wear is an uneven wear that occurs at an angle across the tread or along the edge of the tread on the rear tires caused by rear toe misalignment, worn rear control arm bushings, excessive flexing of the rear suspension or not rotating the tires often. The uneven tread wear produced by diagonal wear or heel-and-toe wear makes the surface of the tire rough.¹⁶

Tread depth

Tread depth is a vertical measurement between the top of the tread rubber to the bottom of the tire's deepest grooves.¹⁸ It is best measured with a tire tread depth gauge. The use of a U.S. Lincoln penny is common to confirm the tire's tread depth. If Lincoln's entire head is visible, it is considered to be worn out. When the tire is worn to approximately 2/32 of an inch, it is considered legally worn out in most states.¹⁸ The tread depths of snow/winter tires and trucks are deeper than the normal passenger vehicle with all season or summer tires. Tire tread constantly channels rain, snow, and other debris out of the way so that the rubber tire face can meet the road surface. On commercial motor vehicles (vehicles more than 26,001 pounds-i.e., ideally the case of most fire trucks), the front steering tires must not have treads less than 4/32 of an inch and on any non-steering axle, tires must not have treads less than 2/32 of an inch. This is as stipulated in section 6.3.1 (4) of NFPA 1911, 2012 edition.

Studies show that tires will lose much of their effectiveness when tread depths reach less than 5/32 of an inch. If the tread depth is less than 5/32 of an inch, vehicles will hydroplane at a slower speed than vehicles with deeper treads. Apart from this, the other adverse effect include increase in the stopping distances. Considering that most emergency vehicles are to operate under extremely inclement road conditions, it is important to keep critical tire tread depth as a tire replacement criterion.¹⁹

Sidewall Weathering

Sidewall weathering is a naturally occurring condition mainly due to exposure to heat and sunlight. Sidewall weathering appears as a crazing and/or cracking in the flex area of the sidewall. According to NFPA 1911, section 6.3.1 (3), tires having cuts in the sidewall that penetrate to the cord should be taken

¹⁷ "How to read tire wear". Web.

<http://www.procarcare.com/includes/content/resourcecenter/encyclopedia/ch25/25readtirewear.html>

¹⁸ "Tire Specs Explained: Tread Depth." Web. <http://www.tirerack.com/tires/tiretech/techpage.jsp?techid=197>

¹⁹ "Avoiding Tire-Related Vehicle Crashes." Chris Daly., Web.

http://www.fireengineering.com/content/dam/fe/online-articles/documents/FEU/FEU_2_09.pdf

out of service. As per the tire replacement guidelines and report on sidewall weathering by tire manufacturer Goodyear, the probable causes of sidewall weathering are:²⁰

- Long periods of inactivity or storage, this will have significant effect on spare tires
- Direct exposure to air and sunlight
- Exposure to high levels of ozone (smog, electrical generators)
- Excessive washing or dressing using alcohol or petroleum based cleaners

Thus a more frequent usage and rotation of tires will reduce the sidewall weathering. For any fire apparatus, as explained in section 6.3.2 of NFPA 1911, a qualified technician shall conduct an out-of-service evaluation of tire deficiencies and make a written report, including recommendations to the authority having jurisdiction (AHJ).²¹

Wheel Alignment

Wheel alignment refers to the position of the wheels relative to the vehicle. A wheel misalignment or out-of-alignment can lead to their resistance to follow the steering commands, eventually causing an early wear out of tires. A few alignment angles are taken into consideration during the wheel alignment.²² The most common adjustable angles are discussed below, non-adjustable angles would require replacement.

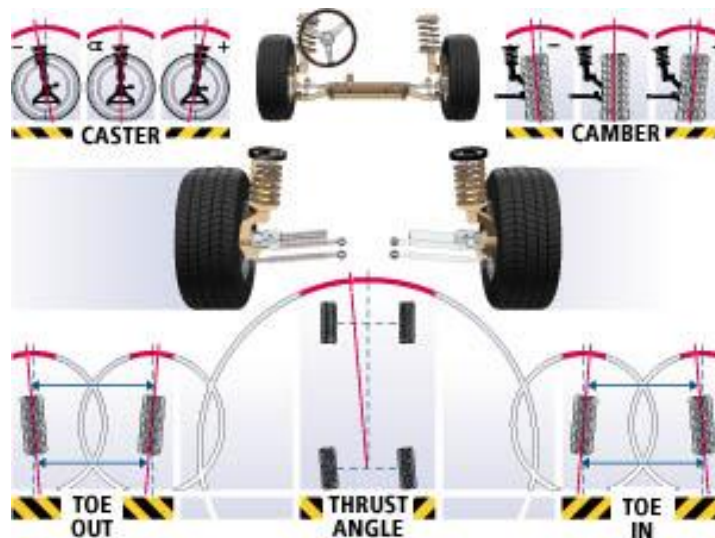


Figure 3 - Adjustable alignment angles²²

Toe

Toe angle is defined as the exact direction the tires are pointed compared to the centerline of the vehicle when viewed from the top. It is expressed in either degrees or fractions-of-an-inch. The tires may toe-in

²⁰ "Tire Replacement Guidelines and Sidewall Weathering." The Goodyear Tire & Rubber Company, 2011. Web. <http://www.goodyearvtires.com/tire-replacement-guidelines.aspx>.

²¹ Section 6.3.2, NFPA 1911: Standard for the Inspection, Maintenance, Testing, and Retirement of In-Service Automotive Fire Apparatus, NFPA. 2012 edition.

²² "Wheel Alignment." M&M Car Care Center, 2014. Web. <http://mmcarcarecenter.com/wheel-alignment.php>.

or toe-out depending on whether they point towards one another or away from each other respectively.²³ This is one of the most critical angles in wheel alignment because even a minor toe angle misalignment can result in a huge wear. In terms of numbers, even if the toe setting is just 1/16-inch off of its appropriate setting, each tire on that axle will scrub almost seven (7) feet sideways for every mile driven. This will result in a shortening of the tire life.²³

Camber

Camber angle is defined as the tilt or slant of the wheel from vertical when viewed from the front or back of the vehicle. Camber angle can be positive or negative depending on whether the tilt is away or towards the center of the vehicle respectively.^{22 23} Appropriate camber settings can provide better corner performance.²²

Caster

Caster angle refers to the angle of the steering axis in relation to an imaginary vertical line through the center of the wheel when viewed from the side.²² This can be positive as well as negative depending on whether the vertical line is tilted backward (positive) or forward (negative). Proper caster angle settings are required for the vehicle to balance steering effort, high speed stability, and front end cornering effectiveness.²³

Thrust Angle

Thrust Angle refers to the relationship of all four wheels to each other, as well as their relationship to an imaginary center line that runs to the rear axle centerline.²³ An out of position axle or incorrect toe setting, can result in an incorrect thrust angle. The preferred thrust angle is always zero. If the vehicle has a non-adjustable suspension, thrust angle is compensated for by aligning the front wheels to the rear wheels.²²

Recommendations for Fire Apparatus Wheel Alignment

An accurate wheel alignment is critical to balance the tread wear and tire performance. Hence, regular wheel alignments should be considered as preventative maintenance. The manufacturers also provide the acceptable "minimum" and "maximum" angles for each specification, for the same reason, the technician should be encouraged to align the vehicle to the preferred settings and not just within the range.

For automotive fire apparatus, since it is expected to drive hard through the corners and expressway ramps, a performance alignment consisting of the vehicle manufacturer's range of alignment specifications to maximize the tires' performance is recommended with manufacturer's maximum negative camber, maximum positive caster, and preferred toe settings.²³

Tire Balance

Tire balance may be defined as the uniform distribution of mass about an axis of rotation, where the center of gravity is in the same location as the center of rotation, i.e., a balanced tire is when the mass of the tire, when mounted on its wheel and the car's axle, is uniformly distributed around the axle.²⁴ When tires aren't balanced, certain areas of the tire tend to take on greater stress, which can result in more vibrations. However, an even greater problem is the extra wear on parts of the tire that might not normally

²³ "Alignment." Tire Tech Information/General Tire Information, Tire Rack. Web.

<http://www.tirerack.com/tires/tiretech/techpage.jsp?techid=4>.

²⁴ "Mounting and Balancing" Tire Tech Information/General Tire Information, Tire Rack. Web.

<http://www.tirerack.com/tires/tiretech/techpage.jsp?techid=20>

receive a lot of road contact.²⁵ An out of balance tire can adversely affect ride quality, shorten the life of the tires, bearings, shocks, and other suspension components.

Tire Rotation

The goal of rotating your tires is to ensure that the entire set wears at the same rate, resulting in an overall safer set of tires that don't require the replacement of tires out of sync with each other. However, tire rotation cannot correct wear problems due to worn mechanical parts or incorrect inflation pressures. The frequency for rotating tires and the pattern of rotation for the vehicle can be obtained from the manual. Any minor 1/32-inch to 2/32-inch differences in front-to-rear tread depth between tires that might be encountered immediately after periodic tire rotations at 3,000-5,000 mile intervals won't upset the vehicle's hydroplaning balance and should not preclude rotating tires.²⁶ Figure 4 shows the typical tire rotation patterns identified by the Tire and Rim association for four, six, and eight tired vehicles.²⁷

²⁵ Leichter, Jim. "Problems Caused By Unbalanced Tires." Biggers Chevrolet, 27 June 2013. Web. <http://www.biggerschevy.com/problems-caused-by-unbalanced-tires/>.

²⁶ "Tire Rotation Instructions." Tire Tech Information/General Tire Information, Tire Rack. Web. <http://www.tirerack.com/tires/tiretech/techpage.jsp?techid=43>.

²⁷ "Rotation." Web. <http://www.discounttiredirect.com/direct/infoTireRotation.do>

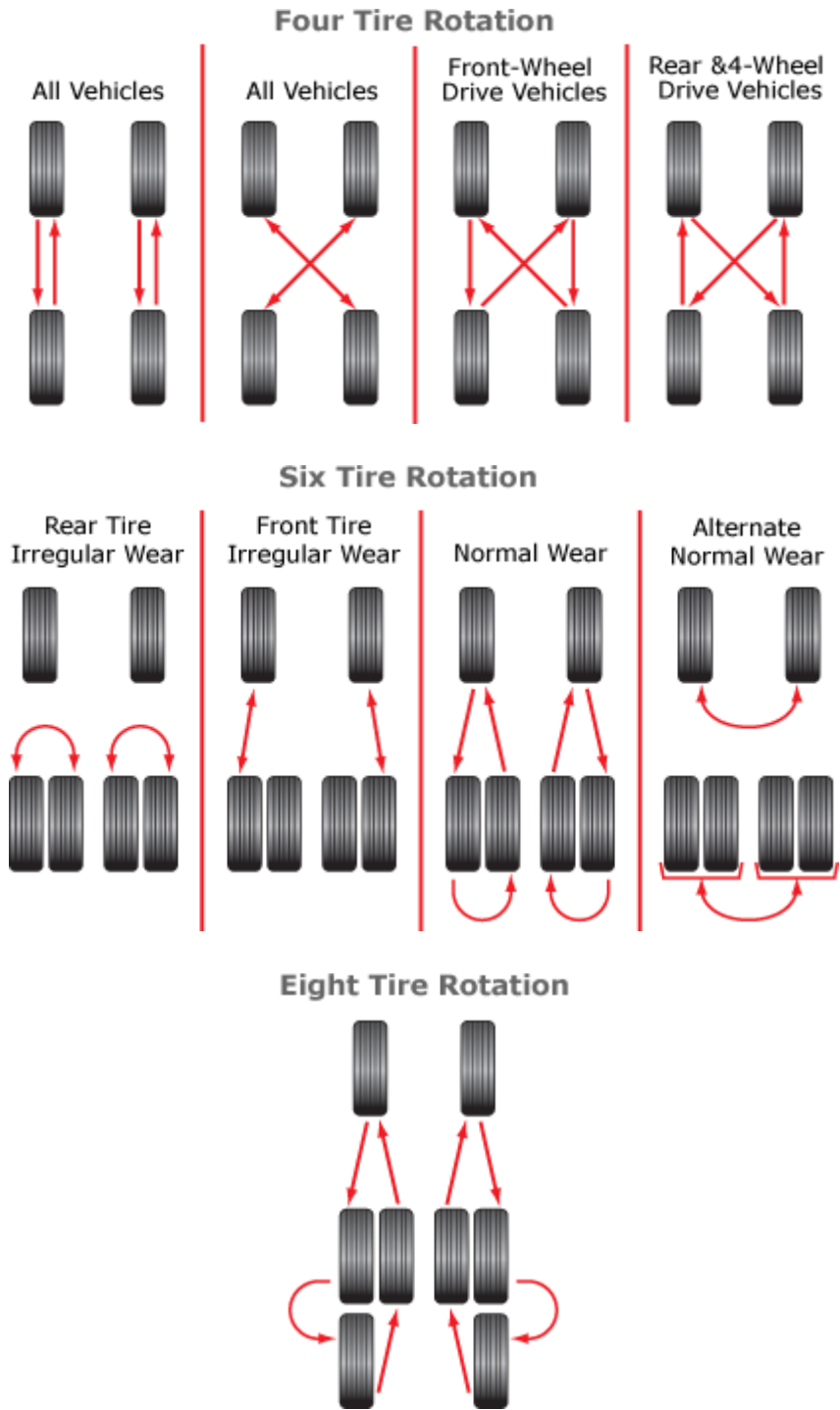


Figure 4 - Traditional tire rotation patterns²⁷

Tire load rating

Tires must be able to safely support a given amount of vehicle weight. If the tire's load rating is insufficient, it can result in over heating of the tire and hence aggravation of the associated wear and tear. A rough

estimate of the load carrying capacity of each tire can be obtained by dividing the vehicle's gross weight by the number of tires.²⁸

In general, the best and safest way to drive with heavy loads is by driving at slower speeds, but unfortunately this is frequently not possible with fire apparatus. Fire apparatus are typically heavily loaded and driven at higher speeds due to the emergency requirements. If a vehicle is travelling at a speed greater than the top speed of the vehicle, the tire inflation pressure has to be increased. By doing this the load carrying capability of the vehicle will decrease at higher speed. The load rating of a vehicle and inflation pressure are related.²⁹

Spare tires

It has been mentioned that stored spare tires are also equally susceptible to degradation and aging as those which are driven. Since the spare tires are not used, the mechanical wear and tear is considerably less, whereas the environmental effects such as sunlight, high heat, ozone, and other conditions have a great impact on them. Ozone cracking can be caused by direct exposure to sunlight and heat as well as from electric motors, welding equipment, or other ozone generating sources.³⁰ This can have serious consequences if it extends to the tire casing cords/pplies. Those tires should be removed from service.

A few recommendations that should be taken into consideration while storing tires are listed here:³⁰

- Area used to store tires should be clean, dry, and well ventilated with temperate ambient conditions, but with a minimum of circulating air.
- Tires should be stored on a surface raised off the floor to minimize exposure to moisture or damage.
- Avoid contact with petroleum-based products and/or other volatile solvents or substances.
- Keep tires away from electric motors, battery chargers, generators, welding equipment, or other ozone generating sources.
- Though indoor storage of tires is recommended, when storing tires outdoors protect them with an opaque, waterproof covering with some type of vent openings to avoid creating a "heat box" or "steam bath" effect.

For the tires which are mounted on a stored vehicle, it is recommended to minimize or remove all weight from the tires. Further, the tire pressures have to be frequently checked, including that of spare tires. The surface where the vehicle is parked should be firm, reasonably level, well drained, and clean. In order to change the tire flex area, the vehicle should be moved every three (3) months.³⁰

The NHTSA tire aging field study revealed that 30% of spare tires observed were significantly underinflated when first checked. Putting underinflated spare tires into service before being properly inflated would greatly increase their risk of catastrophic tire failure.⁴ Thus, before returning the spare tire to use, a proper examination should be conducted. A tire service professional should conduct a visual and tactile

²⁸ "How to determine tire load ratings?" Web. <http://www.worktruckonline.com/article/story/2007/07/how-to-determine-tire-load-ratings.aspx>

²⁹ "How high the psi when you are barely going by?" Technically speaking. Web. http://www.bridgestonetrucktires.com/us_eng/real/magazines/98v3issue4/v3i4Tech.asp

inspection to be sure each tire is clean, dry, free of foreign objects, and/or does not show signs of damage. More importantly, it should be inflated to the recommended inflation pressure.³⁰

4. Tire Life Assessment Technology

According to the NHTSA report,³¹ two kinds of tire life inspection technologies can be utilized: non-destructive and destructive. As the name suggests, the destructive testing destroys the product.

- Non-destructive inspection consists of Tread Depth inspection, Shore Hardness of Tread inspection, and Shearographic Interferometry inspection.
- Destructive inspection involves different tests to check the Ultimate Strength of tires and the use of Optical Microscopic inspection.

Non-destructive Inspection

Tread Depth

NHTSA regulations mandate tire tread testing and specification labeling on tire sidewalls. Tire tread depths are measured by a single laboratory per the ASTM F 421-00 standard test method in each groove of the tire at a minimum of six locations around the circumference of the tire and then averaged.³⁹ Data indicates that around 10-30% of tire replacement is caused due to the normal wear of tire depth from original depth of 9/32 inch to the minimum depth of 2/32 inch.³² Measuring the depth of steel and fiber ply cords or belting in all types of rubber tires and total wall thickness as well is very important.³³ An inappropriate cord positioning can result in more severe failures, especially in the case of heavy trucks. Olympus explains some sonic measurements/sound attenuation methods to measure these parameters accurately.³³

Shore Hardness of Tread

A material's resistance to permanent indentation is defined as Hardness. The use of a durometer is one way of measuring the hardness of a material, typically of elastomers, polymers, and rubbers.³⁴ A durometer measures the depth of an indentation in the material created by a given force. The output is a non-dimensional quantity ranging between 0-100, where 100 corresponds to when the indenter cannot penetrate at all into the material. The usual durometer value for an automotive tire tread is around 70.³⁴

Shearographic Interferometry

Shearography is a non-destructive testing method that identifies and measures the internal separations present between layers of a tire. These are separations like cracks, voids, disbondings, etc. in the composite structure which 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 again under vacuum conditions. The resulting difference between mapping images of the two surfaces is used to identify and measure the total internal separations within a tire.³¹ Shearography offers unique and

³⁰ "Storing Tires." Cooper Tire & Rubber Company, 2014. Web. <http://us.coopertire.com/Tire-Safety/Tire-Safety-Tips/Storing-Tires.aspx>.

³¹ "NHTSA Tire Aging Test Development Project – Phase 1", DOTHS 811201. US Dept. of Transportation, National Highway Traffic Administration, October 2009.

³² "Assessment of Tire Technologies and Practices for Potential Waste and Energy Use Reductions". UCD-ITS-RR-06-11, Institute of Transportation Studies, University of California, Davis, 2006.

³³ "Measuring Thickness of Rubber Tires." Application Notes, Olympus Corporation. Web. <http://www.olympus-ims.com/en/applications/measuring-thickness-rubber-tires/>.

³⁴ http://en.wikipedia.org/wiki/Shore_durometer

proven defect detection capabilities. The object under inspection is stressed by a minor load far below the load in real conditions.³⁵ Shearography images show changes in surface slope in response to a change in applied load. Laser Shearography is very sensitive to slight changes in surface strain due to subsurface flaws. Hence it is able to detect imperfections and defects such as belt-edge separations, bead blisters, liner separation, and broken cord and ply construction.³⁶ Apart from this, it is also able to detect the carcass abnormality and deterioration.³⁶ More explanation on the principles of working with shearography can be found in the reference.³⁵

Tire Pressure Monitoring System (TPMS)

The importance of proper tire inflation pressure has been previously discussed. If the inflation pressure is not maintained properly, the tire tread wear rate increases. According to tire manufacturer Goodyear, for every one (1) psi below the required inflation pressure, a 1.78% reduction in tire tread life is reported.³² Thus, Tire Pressure Monitoring Systems (TPMS) have become a mandatory requirement as they mainly serve to increase the awareness concerning the tire maintenance.³² TPMS can be direct or indirect. Direct TPMS uses a sensor within the wheel to directly measure pressure and transfer them to a receiver. Indirect TPMS uses wheel speed sensors and infers inflation levels from the difference in their rotational speed.³² More information on the working of these types of TPMS can be obtained from reference.³² For brevity, they are not repeated here.

Destructive Inspection

A tire consists of many components which undergo different manufacturing processes and are assembled together. Hence, in order to maintain the performance of tire, inspections involving destructive testing are done as well. As mentioned earlier, destructive testing destroys the tire or component being tested. Hence, these tests represent some of the extreme, unusual, overload conditions that may be applied to a tire. Tseng et al. explains them as they are used to determine how far above normal service conditions one might take a tire before it reaches its ultimate strength.³⁷ The three most commonly performed destructive tire tests to check this are: burst pressure, high speed free rotation, and DOT plunger energy.³⁷ Further, it should be noted that the destructive tests are done mainly on new tires. Since the production of tires happens constantly and the raw materials and components change frequently, these tests are conducted on a daily basis.³⁸ Numerical simulations are also done to predict the results from these tests.³⁷

High Speed Free Rotation

Tires are mounted on wheels and spun against giant drums, hour after hour, mile after mile, to determine heat-withstanding capabilities of casings and overall bead durability.³⁸

³⁵ Laser Shearography Technology. Laser Technology Inc. Web. <http://www.laserndt.com/technology/shearography.htm>.

³⁶ "Retreading." Desser Tire & Rubber. Web. <http://www.desser.com/retreading.php>.

³⁷ N. T. Tseng, R. G. Pelle, J. P. Chang, and T. C. Warholic; "Finite Element Simulation of Destructive Tire Testing". Tire Science and Technology, Vol. 19, No. 1, pp. 2-22, January 1991. doi: <http://dx.doi.org/10.2346/1.2141706>.

³⁸ "Is that all there is?" Real Questions Real Answers, Special edition three, Bridgestone. Web. http://www.bridgestonetrucktires.com/us_eng/real/magazines/bestof3/ra_special_edition_3_pdf_downloads/RA_30_quality_control_RA_Sp_Edition_3.pdf

Optical Microscopy

Optical microscopy is a precise microscopic examination of different cross-sections of tires at random locations. It utilizes a highly precise scale for measurement of distance.³⁹

Tires are also deliberately punctured by large hydraulic rams to determine their resistance to that kind of damage and to confirm load capacity ratings. Apart from all of these tests, a complete evaluation of tire material properties is required to identify the issues involving the rubber compounds and raw materials.

Recapping/Retreading of Tires

Tire maintenance cover a major part of the operating budget of fleets. The process of re-manufacturing tires by replacing the treads on worn tires is called Retreading or Recapping of tires.⁴⁰ It cuts cost both for the manufacturer and the customer. It is understood that retreading saves up to 80% of the tire material cost and are sold for 30-50% lower prices than the new ones.⁴¹ In general, it is believed that the retreaded tires are less safe than new tires and they are susceptible to faster wear and tear. But there are manufacturing standards governing retread quality and this has significantly improved the manufacturing quality of retread tires in recent years.⁴² The NHTSA report⁴² states that, “the Tire Retread and Repair Information Bureau (TRIB) and Technology and Maintenance Council (TMC) of the American Trucking Associations (ATA) contend that retreads are just as safe as new tires and that tire failures occur mostly due to lack of maintenance of the tire...”. Figure 5 shows the flow chart of tire retreading process. Tire retreading process start with an inspection, during which tires and casings are selected or discarded before further processing.⁴⁰ The casing should be in a good condition for a retreading process. Mold cure and Pre-cure are the two common types of retreading processes. Mold cure process requires temperature in the range of 300 °F as raw rubber is placed on the tire casing and the tread is produced by placing them on a mold. Whereas in pre-cure, previously prepared tread strip is applied to tire casing with adhesives.⁴⁰ Once the recapping process is done, the tire is finally inspected for its quality to meet the standards and performance requirement. The maintenance required for a retreaded tire is same as a new tire. When compared to the new tires, retreaded tires are given a limited warranty. All major tire retreaders offer some form of warranty,⁴³ like prorated, on the tread and casing down to varying tread depths. It is to be noted that the warranty periods vary for different retreaders. For example, at Service Tire Truck Centre (STTC), a warranty is offered until a remaining tread depth of 4/32 of an inch or a period of two years from the purchase of retread tire.⁴⁴

³⁹ J. D. MacIssac Jr. and S. Feve., “NHTSA tire aging Test Development Project: Phase 1 – Phoenix, Arizona Tire Study, Paper Number: 07-0496. Web. <http://www-nrd.nhtsa.dot.gov/pdf/esv/esv20/07-0496-W.pdf>

⁴⁰ Wikipedia, Web. <http://en.wikipedia.org/wiki/Retread>

⁴¹ S. D. P. Flapper, J. A. E. van Nunen, L. N. van Wassenhove, (2005). “Managing closed-loop supply chains”, Web. <http://books.google.com/books?id=XspQ0PUNjvkC&pg=PA119#v=onepage&q&f=true>

⁴² “Commercial Medium Tire Debris Study – Final Report”, DOT HS 811 060, US Dept. of Transportation, National Highway Traffic Safety Administration (NHTSA), December 2008.

⁴³ “Why should you retread your tires?”, Web. <http://www.truckinginfo.com/article/story/2013/05/why-should-you-retread-your-tires.aspx>

⁴⁴ STTC Michelin® Retread Limited Warranty, Web. <http://www.sttc.com/retreading/warranty>

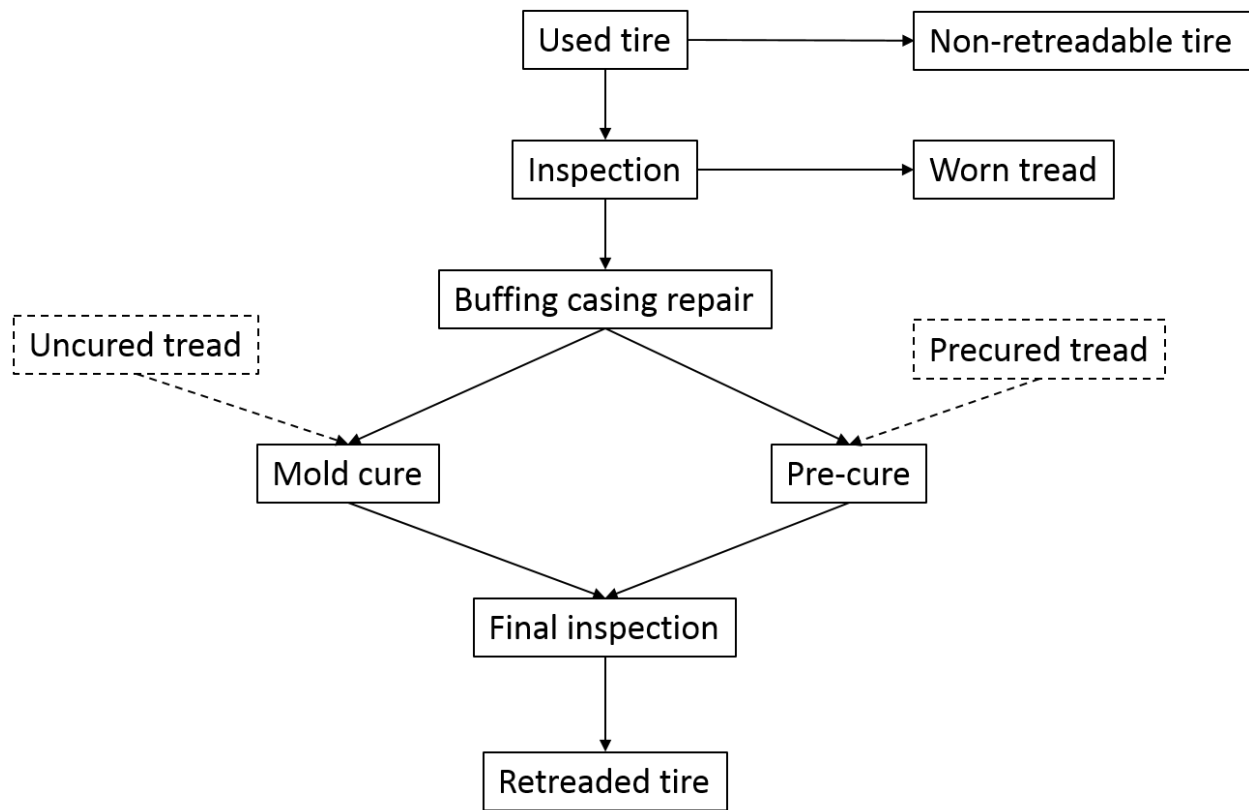


Figure 5 - Flowchart of retreading process⁴¹

Retreading also reduces the number of scrap tires and hence it beneficial to the environment (section 11.6⁴¹). Scrap tires are difficult to discard and it is also realized that scrap tire piles can also be a fire hazard which in-case of fire is difficult to extinguish. Hence tire retreading has to be given due importance and considered in the tire replacement criteria for fire apparatus.

Summary & Recommendations

This project is focused on the review of literature and collected data to determine if the seven year tire replacement schedule is supported by any scientific documentation. Further, issues related to tire aging and the tire maintenance practices are discussed.

From the present research it is realized that no literature convincingly argues a seven year tire replacement. It is observed that the wear and tear of the tire is of greater importance while considering tire replacement. As mentioned in the rubber manufacturer's association statement,⁴⁵ since service and storage conditions of tires varies widely, accurately predicting the actual serviceable life of any specific tire based on the simple calendar age is not possible. A tire should be removed from service for multiple reasons: tread wear to minimum tread depth, tire damage like cuts, cracks, bulges etc., improper inflation

⁴⁵ "Tire service life for passenger car and light truck tires." Web.
http://www.rma.org/download/tire_service/TSL_Statement_092014.pdf

pressure and storage conditions. As far as the inspection and maintenance of a tire is concerned, a specific schedule for tire maintenance should be addressed. Presently, the complete inspection and check of fire apparatus is done as per the manufacturer's recommendation or once per year, whichever comes first.⁴⁶ A more frequent inspection and diagnostic check of the fire apparatus is recommended. Another recommendation from this study is to consider tire retreading for fire apparatus tires. This is not currently addressed in NFPA 1911. The aspects such as cost saving and reduction in the number of scrap tires adding to the environmental benefits provides a solid support to this argument. Further research will be required to understand the performance characteristics of retreaded tires in fire apparatus. Full-scale performance based testing replicating the use and applied weight experienced in the operation of a fire apparatus, including conventional and recapped or retreaded tires, is also recommended to further understand and assess the actual wear of fire apparatus tires.

⁴⁶ Section 4.5.5, 4.5.6. NFPA 1911, Standard for the inspection, maintenance, testing, and retirement of in-service automotive fire apparatus, 2012 edition.