Nitrogen Tire Inflation: When Does the Tire Really Need it?

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ABSTRACT: The paper will review the principle effect of nitrogen inflation on the oxygen permeation through a tire. The effect of oxygen permeation will be discussed with an emphasis on the temperature dependence of the rate of oxidation (i.e., aging) in the tire. The usefulness of nitrogen inflation will be discussed for passenger and light truck tires, snow tires, spare tires, and medium radial truck tires.

KEY WORDS: Nitrogen inflation, inflation pressure loss rate, nitrogen purity evolution, oxygen flow across a tire.

EXECUTIVE SUMMARY: Nitrogen tire inflation has been shown to provide a significant reduction in the total amount of oxygen that permeates through a tire over its lifetime. The result of oxygen permeation is generally considered to be oxidative degradation, or aging, of the rubber materials that make up the tire. Increased environmental temperature has been shown to increase the rate at which the oxidation reaction occurs regardless of the tire’s construction. It is shown that the permeation of oxygen accelerates with temperature more slowly than the oxidation reaction itself, consistent with a diffusion-limited oxidation characteristic. This principle is used, along with the mass of oxygen flowing through tires in simulation, to predict the oxygen concentration in the rubber of the tire. The effect of nitrogen inflation gas is shown to forestall the increase of oxygen concentration through the tire for about four years. These elements provide a decision matrix for the application of nitrogen inflation in tires used in different service environments. The potential use of nitrogen tire inflations is discussed for passenger and light truck tires in routine service, for snow tires, for spare tires, and for medium radial truck tires.

Introduction

Nitrogen tire inflation has been the subject of extensive study designed to determine the practical benefits of the approach. The vast majority of this work has been directed at passenger and light truck tires in routine service. Of the many benefit claims made for nitrogen tire inflation, a reduction in the inflation pressure loss rate and a reduction in the oxygen permeation through the tire over its lifetime have been established as factual. Tire manufacturers, however, do not uniformly support the use of nitrogen tire inflation, and the likely reason is that it is difficult to see that every tire has need of it, or that absence of nitrogen inflation could somehow be construed as a root cause of tire failure.
Tire oxidative aging and the associated tire expected lifetime have become significant topics in the past several years. Vehicle manufacturers generally recommend removal of tires six years after the date of manufacturing regardless of the wear. Tire manufacturers, on the other hand, seem to have established ten years as the threshold where a tire’s structural integrity due to oxidative degradation may be in doubt. Presumably, these are conservative lifetime estimates for passenger and light truck tires, and all life estimates assume proper tire maintenance.

This paper will discuss the rationale behind the use of nitrogen inflation as a means to reduce oxidative degradation (i.e., aging) in tires. The use of nitrogen tire inflation will be discussed relative to a number of tires in different types of service. A generalized decision matrix for the use of nitrogen tire inflation will be developed.

**Background**

Nitrogen inflation for on-road vehicle tires has been studied for decades, either as a method for the tire service industry to exploit or to develop insight into tire aging. Sperberg [1] discussed nitrogen inflation as a means of improving tire life (and retread potential) as early as 1967 and again in 1985 [2]. Sperberg indicated that the threshold for rubber degradation occurred when the oxygen concentration in the rubber was about 1% by weight. In his work, Sperberg use the ratio of oxygen to sulfur atoms in the rubber compounds, as measured by energy dispersion of x-rays. Tokita [3] discussed the use of an oxygen permeation and consumption model in conjunction with more rapid aging of tires for wheel tests. The model proposed in that paper accounted for the permeation of oxygen through the tire as well as for the reaction of oxygen with the rubber hydrocarbon. A mixture of 50% nitrogen and 50% oxygen was used in that study as a means of accelerating the oxidation of the tire’s rubber components (and the use of oxygen-rich inflation gas with oven aging continues to be widely used in the industry when studying tire durability). Tokita concluded that there was a correlation between the amount of oxygen absorbed by the tire and both the tire’s breaker rubber strength and the mileage to failure on a given wheel test. Specifically, Tokita found that “tear resistance fell and reached a critical value” at about 16cc of oxygen per gram of rubber hydrocarbon. This level works out to about 2% by weight of rubber polymer. However, since rubber polymer constitutes about 50% of tire rubber compounds, this is essentially the same level identified by Sperberg. More recently, Baldwin [4] showed the results of the influence of nitrogen
on belt skim stock properties. Karmarker and Herzlich [5] discussed the results of an investigation on the influence of nitrogen inflation on belt skim stock. MacIsaac [6], with the National Highway Traffic Safety Administration (NHTSA), has also studied the influence of nitrogen inflation on tire performance. In that study, NHTSA found that the inflation pressure loss rate (IPLR) of the tires studied did decrease with the purity of the nitrogen in the tire, and that the IPLR in dynamic testing was greater than in static tests. NHTSA also tested tires with 50% nitrogen, air, and 95% nitrogen by oven aging at 65 C, followed by Federal Motor Vehicle Safety Standard (FMVSS) Number 139 endurance tests, and found that some of the tires inflated with an oxygen-rich inflation gas failed the wheel test while all those inflated with air or 95% nitrogen passed. Napier and Waddell [7] studied nitrogen inflation using laboratory tests and vehicle studies and concluded that nitrogen affected neither the operating temperature nor the rolling resistance coefficient directly. Daws [8] studied the permeation of oxygen through passenger and light truck tires. In that study, the total amount of oxygen that permeated through the tire at 21 C for six years was shown to be reduced by about 50% when using nitrogen tire inflation instead of inflation with air.

Tire response to operating strain is generally described in the context of a Wohler curve, which relates strain to life. Figure 1 illustrates such a curve (such curves are generally shown with the cycles on a log scale, but a linear scale is used here for illustration purposes). The higher the operating strain, the fewer the number of cycles (in tire terminology, service miles) the tire will be able to endure. The lower the tire operating strain, the higher the ultimate number of tire cycles to failure. Figure 1 shows the tread life target as a vertical line at, say, 60,000 miles, and a constant operating strain. Obviously, many factors play into this operating strain, such as inflation pressure, vehicle load, and so on, but for this illustration, the strain is assumed to be constant. The objective of tire design is to deliver a tire that has an operating strain level and strength such that the intersection of the Wohler curve (the strength) and the strain level yields a significant safety margin, as shown. It is well known that oxidative degradation reduces the crack resistance of the rubber compounds in the tire, thereby resulting in an effective depression of the Wohler curve. The oxidative degradation is a function of the amount of oxygen that combines with the rubber polymer in the tire, and this process depends upon the environmental temperature and the duration of time that the tire has been in service. It therefore becomes possible that tires having low service
mileages but long service lifetimes may reach a point where the safety margin becomes negative (i.e., the tire cannot endure to the tread life target), especially in hot climates. Under normal circumstances, the tire’s construction and materials selection yield a product that’s new strength greatly exceeds the operational requirements. The effect of oxidative aging is to lower the Wohler curve. In extreme cases, the tire strength may be reduced sufficiently that the tire fails before the target tread life.

One can therefore make a certain number of statements about potential benefits of nitrogen inflation. First, the overall amount of oxygen passing through the tire (i.e., available for oxidative reactions) is reduced significantly, as stated above. Since reducing oxygen flow through a tire by using improved inner liner materials such as halobutyl has been shown to improve oven aged tire durability in wheel tests, and oven aging with oxygen-rich inflation gas has been shown to reduce tire durability in wheel tests, it is logical to propose that nitrogen tire inflation would result in a reduction in the rate of oxidative degradation, or aging, in tires. Sperberg [2] demonstrated this principle in testing, and further showed that high levels of combined oxygen in the rubber polymer was a characteristic of tire failure. Baldwin and Karmarker/Herzlich confirmed that nitrogen would reduce the rate of oxidative degradation, but indicated that they could not determine significant improvements above initial nitrogen tire gas purities of about 95%. Daws [8] showed that this was likely a result of the physics of the permeation of oxygen – when the nitrogen gas purity in the tire was very high (> 93% for a passenger tire), oxygen flowed from the outside of the tire to the inside,

The second important point is that the IPLR for the tire is reduced. Daws [8] showed that, when using nitrogen tire inflation, IPLR is reduced by about 30% over an air-inflated tire. That study also showed that, when the tire is topped off monthly with air, the IPLR improvement gradually decreases and essentially disappears after about six years. This phenomenon was also shown experimentally by MacIsaac.

**Nitrogen Tire Inflation**

A nitrogen purity evolution model was developed by Daws [8], following work done by Costemalle [9], on the permeability of tires to air. This model is based on a simple geometric model for the tire having one layer of material of a given thickness and filled with a mixture of
oxygen and nitrogen at a given initial pressure and temperature. Each of the gases obeys the following relationship independently of the other gas:

\[ (P(t) - P_A) = (P_0 - P_A) e^{-\left(\frac{Q}{G}\right) \frac{A}{V} R T t} \]  

[1]

where \( Q \) is the permeability coefficient of the materials to a given gas, \( A \) is the area of the permeated surface, \( G \) is the thickness of the material, \( P_0 \) is the initial partial pressure of the gas in the tire, \( P(t) \) is the partial pressure of the gas in the tire at some time \( t \), \( P_A \) is the partial pressure of the gas in the atmosphere, \( R \) is the ideal gas constant, \( T \) is the temperature, and the initial time has been assumed to be zero. The decrease or increase in partial pressure of either the oxygen or the nitrogen will be given by \( P_0 - P(t) \).

Daws developed a long-term model by assuming there must be some top-off gas added to replace the pressure loss that develops in the tire due to permeation of the inflation gas. Obviously, the top-off gas will have some purity of nitrogen that will be different than what is in the tire at the end of the time period \( t \). For the purpose of the analysis of the evolution of the nitrogen and oxygen purities in the tire, it is convenient to take the time period, \( t \), as 30 days. This period is consistent with tire industry recommendations that tire pressure be maintained on at least a monthly cycle.

In the case of the oxygen, this loss has special interest. The change in the partial pressure of the oxygen represents the mass of oxygen at the tire volume \( V \) and the tire temperature \( T \) that has crossed the tire material in the time period \( t \). That is, the mass of oxygen that has passed through the tire material during the time period \( t \) can be expressed as:

\[ M_{O2} = \frac{(P_0 - P(t))V}{RT} \]  

[2]

where \( M_{O2} \) is the mass of oxygen corresponding to the drop in partial pressure of oxygen during the tire period \( t \). Many studies have shown that limiting the oxygen flow (i.e., by using better inner liners), selecting rubber materials that are less reactive or integrating better antioxidants, and reducing tire operating temperature (i.e., designing lower rolling resistance tires) are all important to improving the long-term durability of the tire. It has also been shown that increasing oxygen
permeation by increasing the oxygen purity of the inflation gas will reduce the tire durability, even in short-term wheel testing.

Using the above analysis method, Figure 2 shows the oxygen flow by month across a P235/75R15 size tire at a constant 21 C for both an air-inflated tire and a nitrogen-inflated tire (using an initial nitrogen gas purity of 93%). The time span for this simulation is six years. Note that the nitrogen-inflated tire is assumed to have its pressure adjusted monthly with air, as is normal in the vehicle industry. The total amount of oxygen predicted to flow across the tire in six years is 79,022 mg. When the tire is initially inflated to 93% nitrogen and routinely topped off with air, the amount of oxygen predicted to flow across the tire in six years is 39,594 mg, or about 50% less than for the air-inflated tire. Figure 1 shows that the most significant benefits from nitrogen tire inflation in terms of the reduction in oxygen flow across the tire occur in the first years of the tire’s life. This is because, in the air-inflated tire, the percentage of nitrogen in the inflation gas slowly increases, while in the nitrogen-inflated tire, it slowly decreases due to the topping off of the tire with air. As time passes, the air-inflated and the nitrogen-inflated tires approach the same level of nitrogen purity in the inflation gas, and therefore wind up with about the same level of monthly oxygen permeation. Daws showed that this was characteristic of tires in general. This is also significant when considering tires that are demounted and remounted at some point in their lifetime, since the oxygen permeation curve restarts at the maximum level every time this occurs.

The IPLR is also reduced when using nitrogen tire inflation, at least initially. For the P235/75R15 SL tire analyzed, the expected reduction in IPLR would be about 30% with an initial nitrogen gas purity in the tire of 93%. Unfortunately, as the tire is topped off with air over its lifetime, the IPLR reduction advantage gradually disappears. If modern passenger radial tires lose about 2% of their inflation pressure in a month (Waddell [10] reported a range of 1.4% to 3% for tires in the United States) when inflated with air, then a 30% reduction means that the IPLR drops to about 1.4%. For a passenger tire with a recommended inflation pressure of 30 psi, the monthly pressure loss would drop from 0.6 psi to 0.42 psi. Therefore, while the 30% figure seems impressive, the difference of 0.18 psi over a month would not generally be noticeable by the average vehicle owner. It cannot replace regular pressure checks as part of normal vehicle maintenance by the owner. Daws [8] presented numerous simulations comparing oxygen and nitrogen tire inflation in this study, and
showed conclusively that optimal nitrogen tire inflation results can be obtained only when the tire is topped off with nitrogen rather than with air.

Daws [8] proposed the use of total oxygen flow across the tire as a means of analyzing the effectiveness of nitrogen tire inflation. It can be seen from the previous oxygen flow figures that nitrogen tire inflation resulted in a reduction of about 50% in the flow of oxygen across the tire. The significance of this reduction depends upon the amount of oxygen taken up by the tire in oxidative reactions versus the amount the flows completely through the tire.

**Temperature Effects**

Much of the previous work involving nitrogen tire inflation that was cited initially was targeted at the issue of rapid aging of tires (i.e., the development of an aged-tire test). Some of the initial work in this area was reported by Kaidou and Ahagon [11]. They found that the primary temperature driver in tire oxidative degradation was the environmental temperature rather than the operating temperature of the tire. This is likely due to the fact that, at least for passenger and light truck tires, the tire operation time is a small fraction of its overall lifetime. The rate of the oxidation reaction of the tire’s rubber hydrocarbon was described in terms of the standard Arhennius relationship:

\[
K = B e^{-\left(\frac{E}{RT}\right)} \tag{3}
\]

where \(K\) is the rate of the reaction, \(E\) is the activation energy for the material, \(R\) is the ideal gas constant, \(T\) is the absolute temperature, and \(B\) is a material constant. Kaidou and Ahagon found, for the belt skim materials in their experiments (passenger car tires), that the value of the activation energy, \(E\), was about 42 kJ/mole. Given a situation where a rubber sample is exposed to a certain temperature \(T_l\) in the laboratory, experiences a reaction at a rate \(K_l\). It can be shown that the same material exposed to a field service temperature, \(T_f\), would be expected to undergo the same reaction at a rate \(K_f\), given by:

\[
K_f = K_l e^{\left[\frac{E}{R} \left(\frac{1}{T_f} - \frac{1}{T_l}\right)\right]} \tag{4}
\]
If Equation 15 is evaluated using a laboratory (rapid aging) condition of 60 C, and 21 C is used as a field condition, it is easily shown that the rate of the oxidative reaction at 60 C is about 7.4 times the rate at 21 C. For the permeation process, the activation energies governing the permeation coefficients for oxygen and nitrogen are different, indicating that the permeation coefficients for oxygen and nitrogen will change at different rates with temperature. Santaler, et al. [12] gives the activation energies for permeation through natural rubber as about 37.8 kJ/mole for nitrogen and about 28.8 kJ/mole for oxygen. Using equation 4, it can be shown that the rate of the permeation reaction for oxygen at 60 C will be about 3.9 times faster that at 21 C. These values suggest that the permeation rates of the gases increase more slowly with temperature than do the oxidation reaction rates, resulting in what has been termed in the literature a “Diffusion Limited Oxidation”, or DLO. This indicates that as temperature climbs, the total oxidative reaction system in the rubber polymer is limited by the amount of oxygen that flows into the tire. This is consistent with improvements in tire inner liners causing improvements in long-term tire durability, and increases in oxygen content of the inflation gas causing a loss in durability. Equation 4 also holds for the relationship between the rates of a reaction at different temperatures.

For practical purposes, then, the environmental temperature in which the tire is immersed for its lifetime plays a significant role in how rapidly the oxidative degradation takes place. Oxidative degradation in an inflated tire takes place with time, not mileage. Equation 4 can therefore be used to compute an effective permeation time in the field from environmental data. If the average monthly temperatures for a few cities in the United States are plotted, using Detroit, MI, as a reference, the result is shown in Figure 3. Note that Detroit, MI, has the lowest average annual temperature at 47.8 F, while Miami, FL, has the highest at 74.3 F. In Figure 4, the potential permeation time for a tire in each city has been normalized to that computed for Detroit, MI. The reference time is one year at 21 C. Figure 4 shows that in one year in Phoenix, AZ, a tire would experience about 2.4 times the level of oxygen permeation as the same tire would in a year in Detroit, MI. This is the same as saying that the rate of potential oxidative degradation in Phoenix, AZ, is about 2.4 times higher than that experienced in Detroit, MI.

Figure 5 shows a similar analysis done using 30-year National Oceanic and Atmospheric Administration data for quarterly average temperatures for a larger number of cities in the continental United States. Again, the reference temperature was arbitrarily selected to be 21 C
A tire in Detroit, MI, would have about 0.64 years of oxygen permeation compared to the reference of one year at 21 C. Phoenix, Arizona, would have experienced 11% more oxygen permeation as does the reference tire at 21 C. Compared to Detroit, the tire in Phoenix experiences about 73% more oxygen permeation in a year. Figure 5 also shows two major east-west interstate routes, I-40 and I-80. These roadways divide the United States into approximate thirds north to south. It can be seen the north of I-80, all permeation times are generally 0.7 or lower. South of I-40, ratios are typically greater than 0.9 (note that the source for these data was quarterly average data, while the source for Figure 3 was monthly average data, which explains the slight differences in permeation levels). In between I-40 and I-80, the permeation times generally range between 0.7 and 0.9, with the notable exception of Las Vegas, NV, which had a permeation time of just over one year relative to the reference tire at 21 C. It follows that tires in service in areas south of I-40 in the United States would be more susceptible to oxidative degradation, while tires in service in areas north of I-80 are likely to be least affected by this process. This chart assumes that there is sufficient oxygen to support the oxidative reaction. However, the tire inflation gas composition changes with time, so the analysis is not as simple as these rate and time calculations might indicate.

Recall that Figure 2 showed a comparison of the oxygen flow across a P235/75R15 SL tire at a constant temperature. Using Equation 4, the permeability increase with temperature can be estimated for both oxygen and nitrogen. The same simulation can therefore be done for a given location using monthly temperature data. Figure 6 shows the results of such a simulation for the same P235/75R15 SL tire in Phoenix, AZ. Note that there is a seasonal progression from winter to summer in the oxygen curves like that shown for temperature in Figure 3. Since nitrogen and oxygen permeabilities do not change at the same rate with temperature, this simulation predicts that the air-inflated tire and the nitrogen-inflated tire actually end up with the same inflation gas nitrogen purity after six years. With the annual temperature variation, the simulation predicts 84,009 mg of oxygen flowing into the tire over the six-year period for the air-inflated tire, and 44,777 mg of oxygen for the same period for the nitrogen-inflated tire. Again, the effect of the nitrogen inflation is to reduce the amount of oxygen flowing into the tire by about 47% over the six year period.
Tire manufacturers formulate rubber compounds for use in tires and incorporate various ingredients called antioxidants. The function of these compounds is to react with oxygen molecules permeating through the rubber before the oxygen can react with the rubber itself. Unfortunately, there is a practical limit to the amount of antioxidant that can be put into a rubber compound and still be present after the vulcanization process. In addition, antioxidants can migrate from one rubber compound in the tire’s structure to another. In general, the amount of antioxidant incorporated is thought to be sufficient to deal with the “useful lifetime” of the tire. The problem for tire buyers is that the useful lifetime of a tire depends upon its tread life and the number of miles of service per year demanded. The longer the service lifetime, the more important the environmental oxidation rate becomes.

So, the question becomes one of the significance of the amount of oxygen that can permeate into the tire and still have the tire serve its function. The real question is how much oxygen is too much oxygen. As previously noted, Sperberg and Tokita independently arrived at about 1% by weight of rubber compound as the threshold at which oxidative degradation becomes “significant” to “catastrophic”. For the P235/75R15 SL tire discussed previously, the total tire weight would be around 13 kg. Sperberg [2] showed that the oxidation of the tire is focused on the casing components, since they are the closest to the source of the oxygen. A P235/75R15 SL tire has about 5 kg of tread rubber, leaving the casing with a weight of around 8 kg. If the weights of the beads, the polyester sidewall material, and the steel cords in the belts are subtracted, the weight of rubber compound would be about 7.5 kg. For an air-inflated tire over a period of six years at a constant 21 C, the simulation predicts about 78,881 mg of oxygen, or about 1.05% of the casing compound weight to permeate into the tire. Sperberg [2] also made measurements showing that the oxygen concentration as a function of distance from the inner liner surface into the tire was exponential in nature. If a simple exponential function for the distribution of oxygen concentration in the tire casing material is assumed as

\[ \eta = e^{-k\delta} \]

where \( \eta \) is the ratio of the concentration at some point in the thickness to the concentration at the inner liner surface (the maximum concentration), \( \delta \) is the ratio of the distance from the inner liner surface to the casing thickness, and \( k \) is a fitting parameter. The details of this simple model are
shown in Figure 7. Note that the average concentration, $\overline{C}$, is simply the integral of this concentration function divided by the casing thickness, $t$. From the permeation simulations described previously, the average concentration of oxygen in the casing can be computed as the amount of oxygen that moves into the casing divided by the mass of rubber compound in the casing. Figure 7 shows that for an average concentration $\overline{C}$, the maximum concentration at the inner liner can be computed as $C_m$. If the concentration at the extreme casing thickness is assumed to be 10% of the maximum oxygen concentration, then Figure 8 shows a distribution of oxygen for a casing thickness of 7 mm. The maximum of this distribution (2.5% at the inner liner surface) yields an average concentration of 1.05%, i.e., that predicted for the tire at 21°C for six years. This is a logical assumption since the oxidative reaction will be able to consume all the oxygen that can flow into the tire. Figure 7 shows that the innermost layers of the tire casing have exceeded an oxygen concentration of about 1%, but the steel belts, which begin between 2 mm and 3 mm from the inner liner surface, and outer sidewalls of the tire have not. Of course, this analysis ignores the effect of antioxidants built into the rubber polymers. If the antioxidants are sacrificial in nature, then the effect would be to delay the oxidative reaction by some period of time (until the antioxidants have been consumed). If the antioxidants serve as a dilutant, then the oxidative process is slowed proportionally. Either way, the analysis presented here ignores the effect of the antioxidants, and therefore represents an extremely conservative approach.

The simple model shown in Equation 8 can be used to evaluate the effect of temperature on the permeation of oxygen into the tire. Figure 9 shows the results of such an analysis for a P235/75R15 SL tire inflated with air, using the permeation ratios for various temperatures computed using Equation 4. Figure 9 includes curves for Detroit, Oklahoma City, and Phoenix. Clearly, the result of an increased temperature environment is to encourage the more rapid permeation of oxygen into the layers of the tire. Figure 9 shows that the oxygen content is at 1% to a depth greater than 3 mm if the tire is in Phoenix for six years, but the corresponding depth for the tire in Detroit for the same amount of time is slightly greater than 2 mm.

How does nitrogen tire inflation influence this picture? Figure 10 shows the results of the same model, except the levels have been chosen to match the average concentrations of oxygen predicted by the six-year model with an initial nitrogen tire purity of 93% and routine top-off being done with air. This clearly shows that the casing layers having oxygen concentrations greater than 1%
are limited to the body ply region even in Phoenix. Based on this analysis, nitrogen tire inflation has significant potential to improve the long-term durability of tires.

Another way to look at this type of data is to ask how long a period of time would need to pass before the oxygen concentration in the tire attained 1%, and then how would that progress through the tire’s layers. Following the model shown in Figure 8, an analysis was performed for both air inflation and nitrogen inflation of a P235/75R15 SL tire using the average oxygen concentrations predicted by the permeation model at the various city temperature distributions (Detroit, Oklahoma City, and Phoenix). The results for the air-inflated tire are shown in Figure 11. In this figure, it can be seen that an air-inflated tire reaches an oxygen concentration of 1% before the end of the second year of service life in Phoenix, and between 3 and 4 years of service in Detroit. The oxygen concentration of 1% reaches the bottom of the steel belts, located about 3 mm to 3.5 mm into the casing, during the fifth or sixth year of service life in Phoenix and about at the twelfth year of service in Detroit. These results are consistent with a conservative six-year service life recommendation for passenger and light truck tires using air inflation (recall that the effect of antioxidants has been ignored).

For nitrogen inflation, Figure 12 summarizes the results. With nitrogen tire inflation, the tire begins to see 1% oxygen concentration in the fourth to fifth year of service life in Phoenix, in the twelfth year of service life in Detroit. The oxygen concentration of 1% reaches the bottom of the steel belts (around 3 mm to 3.5 mm) between eight and ten years of service in Phoenix, and well beyond fifteen years in Detroit. This suggests that the effect of nitrogen tire inflation is to shift the development of critical oxygen concentration by about 3.5 years at the onset. The time to attain 1% oxygen concentration at 3 mm into the casing is also shifted by over three years in Phoenix when using nitrogen. This is consistent with a conservative ten-year service lifetime when using nitrogen-inflated passenger and light truck tires, even in the most severe climates in the United States. Again, the effect of antioxidants has been ignored.

The physics of nitrogen tire inflation for medium radial truck tires yield slightly different results from those of passenger and light truck tires for several reasons. First, since the inflation pressures of medium radial truck tires are typically in excess of 100 psi, attaining 95% nitrogen purity in the tire with a single inflation step using 98% purity inflation gas is straightforward. Second, tire
volumes are much larger than passenger and light truck tire volumes, and the tires are significantly thicker. This means that the IPLR for medium radial truck tires is significantly lower than for passenger and light truck tires. As an example, a set of simulations was performed, using the method described earlier, for a 315/80R22.5 tire inflated to 110 psi. This tire has an internal volume of about 144.8 liters (as compared to the 51.7 liter volume of a P235/75R15 tire) and an average sidewall thickness of around 18 mm. While the complete tire will weigh around 68.2 kg, the weight of the rubber compound in the casing and belt system, excluding the tread, will be about 32.2 kg. The percentage concentration of oxygen can therefore be estimated by assuming that all the oxygen that permeates into the tire is consumed in the casing rubber. Figure 13 shows a comparison of the oxygen concentration across the tire inflated with air and inflated with nitrogen initially at 95% purity, with the simulation being done at a constant 21°C. For a six-year lifetime, the simulation predicts 263,107 mg of oxygen permeation for the air-inflated tire and 71,569 mg oxygen permeation for the nitrogen-inflated tire, a reduction of about 73%. Since many of these tires are operated in high-mileage service, the comparison of the first year improvement is interesting. During the first twelve months of service, the model predicts about 54,379 mg of oxygen will permeate the air-inflated tire, while only 8,087 mg of oxygen will permeate the nitrogen-inflated tire, a reduction of 85%. That is to say that if the tire were worn out and retreaded annually, consistent use of nitrogen tire inflation would reduce the oxygen permeation through the tire to about 15% of its normal level in an air-inflated tire. This would dramatically reduce the potential oxidative degradation of the tire over its lifetime.

Using the simple oxygen concentration distribution model of Equation 5, Figures 14-17 show concentration distribution curves for a 315/80R22.5 medium radial truck tire. Figure 14 shows the distribution of oxygen concentration for the tire over six years with several geographic locations (again, Detroit, Oklahoma City, and Phoenix). Figure 15 shows the same information for the tire inflated initially with 95% purity nitrogen and then topped off routinely with air. In the case of the medium radial truck tire, the working belts (the second and third belts in a four-belt construction) begin at about 7 mm into the casing thickness. If the curves for Phoenix are compared, it can be seen that the air-filled tire will develop a 1% oxygen concentration at the 7 mm depth at slightly more than 6 years of continuously-inflated service. In the nitrogen-filled tire, the oxygen concentration does not reach the 1% level anywhere in the tire in this six-year period.
Figure 16 shows the casing depth to an oxygen concentration of 1% by years of service life for the 315/80R225 tire initially inflated with air. As before, the tire in Phoenix will reach an oxygen concentration of 1% at 7 mm depth into the casing in about 6.5 years. This simulation is for a tire that is continuously inflated. If the tire were demounted and re-inflated annually (after being retreaded due to high mileage accumulation service, for example) the oxygen level in the casing after six years would be about 22% higher. Figure 17 shows the same simulation results for the 315/80R22.5 tire initially inflated to 95% nitrogen purity and topped off with air. Note that the 1% oxygen concentration level does not reach the depth of 7 mm until well beyond fifteen years of service. The simulation also predicts that if the tire is demounted and re-inflated with nitrogen annually (again, retreading of high mileage accumulation fleets), the oxygen level would be about 30% lower.

Applications of Nitrogen Tire Inflation

In general, nitrogen tire inflation is an extra-cost option when purchasing tires. This cost is normally either about equal to or slightly greater than tire balancing for passenger car tires, so it is not an insignificant percentage of the total cost of tires. The question for a consumer is clearly “Does the tire really need nitrogen inflation?” This clearly depends on a number of factors involving service life, environment, and potentially other issues. The following discussion examines several types of tires and service.

Passenger and Light Truck tires

In-service passenger and light truck tires represent a significant market for nitrogen tire inflation. Such tires are marketed with different levels of expected tread life (the warranty mileage). The use of the tire can lead to very different service lifetimes, however. For example, if a consumer who averages about 10,000 mi/yr purchases a 60,000 mile tire, the expected service lifetime of that tire would be six years. If the consumer averages 20,000 mi/yr, the expected service lifetime would only be three years. Hence, annual mileage accumulation per tire dramatically influences service life (this is true for all tires).

Vehicle manufacturers have, by and large, started recommending that tires be removed from service after six years. This includes spare tires which may never have been placed into service.
Figure 6 and Figure 9 would generally be in accord with this principle, since tires in areas having the highest permeation ratios can be expected to start attaining oxygen concentrations approaching 1% in the steel belt areas by the end of six years. Clearly, this is an extremely conservative recommendation, since the effects of antioxidants have been ignored in this analysis and service in the highest temperature environments are assumed. This suggests that when tire service life is maintained at less than six years, tires generally will not suffer extensive oxidative damage even without considering built-in internal protection in the form of antioxidants and inner liner material and thickness. Obviously, if the service life of the tires is anticipated to be significantly less than six years, then the use of nitrogen tire inflation to reduce the oxidative age of the tire in service becomes less beneficial. Tires that are expected to wear out in three to four years likely will obtain no oxidative benefit from nitrogen tire inflation.

If, however, the consumer purchases tires that will likely last six years or more, and lives south of I-80 in the United States, then nitrogen tire inflation would improve the likelihood that the tires would not suffer excessive oxidative degradation. Recall that nitrogen tire inflation with subsequent air top-off reduces the lifetime permeation of oxygen through the tire by about 50% at the six year point. The effect of nitrogen inflation is to shift the oxidation curve by about four years. Since all tires are not created equal in areas like antioxidants and inner liner thickness and material composition, however, even tires in service north of I-40 in the United States may benefit from nitrogen tire inflation. As time goes on, however, this advantage is decreased, since the air-inflated tire and the nitrogen inflated tire both converge on concentrations of nitrogen and oxygen in the inflation gas of about 88% and 12%, respectively, by the end of six years. Therefore, as consumers try to extend tire service life beyond ten years, the initial nitrogen tire inflation nets them no incremental benefit. This is why Daws [8] recommended either topping off with nitrogen or periodic recharging of the tire nitrogen during the life of the tire for long-life situations.

Consumers who live north of I-80 in the United States are not likely to obtain oxidative benefits from nitrogen tire inflation unless the service life of the tires in question exceeds twelve to thirteen years. Other benefits like inflation with a dry gas, oxidative protection for the tire in the event of structural damage (i.e., punctures), and so on may still make nitrogen inflation an attractive option for those consumers.
This idea can be further refined by stating that, for consumers who live south of I-40 in the United States, nitrogen tire inflation for tires that have expected service lifetimes exceeding six years can be considered important. The higher the value shown in Figure 5 for a given locale, the more important this purchase is likely to be. Also, the longer the service lifetime, the more important nitrogen tire inflation becomes. Nitrogen tire inflation should be highly recommended for passenger and light truck tires in these areas. When the consumer lives between I-40 and I-80 in the United States, then the usefulness of nitrogen tire inflation essentially requires longer tire service lifetimes, and the service could be recommended. When the consumer lives north of I-80 in the United States, it is not clear that nitrogen tire inflation will provide a noticeable benefit in reducing oxidative degradation in the tires unless the tires will have an exceptionally long service life (greater than thirteen years). As mentioned previously, not all tires are created with the same levels of inner liner permeability, oxidative resistance, and so on, so consumers should consider the worst-case scenarios.

Spare Tires

Spare tires are rarely used unless they are full-sized spares, in which case they may be pressed into road service after a number of years because the vehicle owner decides to purchase three new tires and employ the as-yet unused spare tire. However, the service life of the tire begins when it is mounted and inflated, regardless of whether or not it is used. Space-saver spares spend their lives in the storage area of the vehicle (where the temperatures may be significantly higher than those in the outdoor environment) and are hardly ever used. Vehicle manufacturers’ recommendations to dispose of any tire over six years old apply to spare tires, but these recommendations are not rigorously being followed in the field.

Spare tires, then, are at risk for long lifetimes even with little or no mileage (the annual mileage accumulation is zero or nearly zero in most cases). In addition, the environment surrounding spare tires may be considerably different in terms of temperature from that experienced by the in-service tires on the vehicle. Therefore, spare tires likely to experience additional risk due to increased temperature exposure and consequently higher permeation ratio. The risk here is that an unused, but heavily oxidized, spare tire will have little visual evidence of even extreme oxidative damage because it has not been strained (i.e., loaded and run). It is the strain of being loaded and operated
that generates the cracks that are normally held to be evidence of oxidative aging. The use of nitrogen inflation in any spare tire would therefore be recommended, regardless of the type of tire or the geographic location of the vehicle.

\textit{Snow Tires}

Snow tires fall into a slightly different category than passenger and light truck tires discussed above. Snow tire consumers generally live in areas where the permeation rate may be lower, but not necessarily (example: very little snow falls in Phoenix, AZ, but snow tires are sold in the area because ski resorts are within driving distance). However, snow tires are used in two predominate ways: continuously mounted, and demounted/remounted each season. When the snow tires are mounted continuously on wheels specially purchased for this task, then the oxidative process follows that described in detail above for the P235/75R15 SL tire. When the tires are demounted at the end of a season, the oxygen permeation process is stopped. When they are remounted for the next season, the oxygen permeation process begins anew but at its maximum level because the tire gets a fresh charge of air (recall Figure 1). However, since the snow tires are in use in the winter months when the permeation rates are lowest, the amount of oxygen being pushed into the tire will be essentially at a minimum. For example, in the case of the P235/75R15 SL tire, the amount of oxygen expected to enter the air-inflated tire over a six year period in Phoenix would be 84,843 mg, as noted previously. For the same tire inflated with nitrogen would be expected to see 45,250 mg. If the same tire is demounted every spring and remounted in the fall (six full months of service per year), the amount of oxygen expected to enter the air-inflated tire would be 48,338 mg, or essentially the same level as if the tire were inflated with nitrogen. This holds true for any location, although the effect in Detroit is not quite as impressive (57,230 mg for air-inflated tire, 20,431 mg for nitrogen-inflated tire, and 27,279 mg for the air-inflated snow tire mounted only in winter). Therefore, if the snow tire is to be demounted/remounted annually, the tire will not obtain significant benefits from nitrogen inflation unless the service life is expected to be extremely long. If the snow tire is mounted on its own rim on a permanent basis, then the same logic outlined above for passenger and light truck tires applies.

It is clear from the discussion that the value proposition for nitrogen tire inflation in passenger and light truck tires is one of making sure that the tire will have sufficient durability so that the
consumer can take advantage of the entire tread life of the tire. This also has significant societal benefits, including vehicle safety and reduced environmental burden from prematurely scrapped tires.

*Medium Radial Truck Tires*

Medium radial truck tires generally have utilizations that are very different from those found in passenger and light truck tires. In addition to accumulating significant mileage every year, these tires can see service in all parts of the country. They also generally can be retreaded, and may go through that process several times during their lifetimes. Vehicle owners generally fall into two camps with regard to tire retreading: those that own their own casings, and those that exchange casings when the tire wears out. Owners who exchange casings will generally not be interested in the benefits of nitrogen tire inflation related to oxidation reduction because they would bear the cost of the process but not stand to reap the long-term benefits. Probably the largest field study of nitrogen tire inflation in fleets was reported by Transport Canada [13]. This study comprised about 110,000,000 tire miles and involved 1,988 tire wheel positions. Both fuel and tire savings were considered, but the study details suggest that these comparisons were made against a tire pressure maintenance cycle that was coincident with oil changes. Obviously, the longer the period between tire pressure checks, the larger the difference likely to be found between air-inflated and nitrogen-inflated tires. In addition, the gas used in routine pressure maintenance (air or nitrogen) was not specified.

Consider high-mileage fleets that own their own casings, and assume that each tire sees 100,000 miles per year. Since the retread cycle would be on the order of one to two years, and the owner would accrue the benefits of significant oxidative reduction over the tire’s life (on the order of 85%). Since the number of retreads possible tends to be limited by the casing condition (up to some service lifetime defined by the owner), savings could be obtained by permitting additional retread lives, provided that nitrogen tire inflation in this service can be done economically. However, this is likely to be an issue, since each nitrogen inflation for a tire of this size would require about 43.4 standard cubic feet of nitrogen gas (at 98% purity). Suppose that nitrogen tire inflation would permit one additional retread life on every casing (some sources have suggested two to four additional retread lives might be possible). If a fleet is averaging three retread lives for
every casing, then the use of nitrogen tire inflation would potentially yield four. To be practical in this case, the cost of five nitrogen tire inflation cycles (the original new tire inflation plus four retread inflations) would need to be significantly less than the value of the additional mileage on the fourth retread. This value presumably would be the reduced number of new tires being purchased on an annual basis. However, if the tires are being worn out in a one year period, there is a serious risk that the casing will suffer significant mechanical fatigue with the total accumulated mileage (first life at 150,000 miles plus four retread lives at 100,000 miles yields 550,000 miles on the casing). That is, the mechanical fatigue durability of the casing, and not the potential oxidative degradation, likely controls the service life of the tire (see the Wohler curve in Figure 1). This area will require field testing to resolve. In the interim, for tires that have their maximum service mileages exhausted in about six years, the benefits of nitrogen tire inflation would be related to IPLR reduction.

In contrast, consider the case of a regional or local delivery fleet where each tire sees about 25,000 miles per year. In this case, the retread cycle would be on the order of six years for the first life and four years thereafter. Total accumulated mileage per tire would not be a significant issue for casing mechanical durability, but oxidative degradation would, especially in environments where temperatures are high. The air-inflated tire would reach a 1% oxygen concentration in about six years, or during the life of the original tread. Retreading the tire would result in continually-increasing oxygen concentrations and an increasing possibility of tire failure. In this type of utilization, nitrogen tire inflation would reduce the oxygen permeation through the tire by about 75%, making the possibility of achieving a second retread life more realistic, even in high temperature regions. In this case, only two nitrogen tire inflation cycles would have been consumed to get the second retread life (extending the tire’s service lifetime to fourteen years), making the economics of the transaction more palatable.

The IPLR reduction available on medium radial truck tires is predicted to be about 30%, as was found for passenger and light truck tires. The IPLR for an air-inflated tire would be about 0.67% monthly and about 0.47% for the nitrogen-inflated tire. This means that, with an inflation pressure of 110 psi, an air-inflated tire would lose about 0.7 psi per month versus about 0.5 psi for a nitrogen-inflated tire. Again, the difference is likely not noticeable over a short period. However, in the Transport Canada study fuel savings were found to be 4% compared to air-inflation and
third-party tire pressure maintenance, and an impressive 6% over air-inflation with driver tire pressure maintenance. This study indicated that some tire pressure checks were only being done at oil change intervals, suggesting that the improvement in pressure maintenance has more significance when the time between pressure checks becomes very long. Also, the gas being used for pressure maintenance was not specified. These results suggest that nitrogen tire inflation has significant cost savings potential in general fleet use, especially if nitrogen is used in pressure maintenance as well as in initial inflation. In addition, Transport Canada indicated that the improved pressure retention may have resulted in improved tire wear mileage.

The temperature effects discussed for passenger and light truck tires apply to medium radial truck tires as well. For tires used with a local geographical area, the oxidative acceleration due to temperature can be reasonably predicted. Regional fleets with low annual mileage accumulation per tire and operating in the southern United States likely have the best opportunity to benefit from nitrogen tire inflation from the standpoint of extended tire durability. However, for tires used in long-haul applications having high annual mileage accumulations per tire, ultimate casing durability may govern the end of use life of the tire rather than effective oxidative age.

Clearly, the value proposition for medium radial truck tires exists when the casings belong to the vehicle owner, and involve the possibility of additional retreading steps on those casings, along with fuel savings and improved tire mileage. The benefits associated with fuel savings and improved tire wear life ultimately depend upon the IPLR improvement from nitrogen tire inflation being sufficient over extended periods to generate them. The Transport Canada study was based on very long periods between tire pressure maintenance, and likely would not be representative of what would occur if a fleet was performing tire pressure maintenance, even using air as the top-off gas, on a more routine schedule. The possibility of additional retread lives for a casing has not been documented in published, large-scale testing.

**When Does the Tire Need Nitrogen?**

Obviously, nitrogen tire inflation is an option that has the potential to provide benefits related to wear, fuel economy, and so on. These benefits are related to the reduction in IPLR that is obtained. The magnitude and duration of this reduction over an air-inflated tire will be larger if tire pressure
maintenance is not currently being done, or is only being done in a haphazard fashion. If the tire is inflated with nitrogen, and then routine pressure maintenance is performed using air as the fill gas, the IPLR reduction and its associated benefits gradually disappear. When routine tire pressure maintenance is performed using nitrogen as the fill gas, Daws [8] showed that it is possible to reduce oxygen permeation into the tire to nearly zero. Nitrogen’s ability to reduce the total oxygen that permeates into a tire has the potential to improve the long-term durability of the tire. Even when the pressure maintenance is performed with air, significant improvements are shown. The issue, then, is when is the durability of the tire possibly at issue?

Figure 18 shows a flow chart that encompasses, in broad strokes, the lessons from the present analysis. This chart takes into account the environment by breaking the United States into three geographic areas using the major east-west interstate routes I-40 and I-80. Obviously, areas like Las Vegas should be included in the southern third of the country. As such, Figure 5 represents a “first” approach, and should be further refined for wide use. Based on the analyses presented, tire used in areas north of I-80 in the United States likely do not need nitrogen tire inflation. Also, Figure 18 incorporates the anticipated service life of the tire. Any passenger car tire, for example, with an anticipated service life of less than five years likely does not need nitrogen tire inflation.

On Figure 18, it is recommended that spare tires be inflated with nitrogen, due primarily to the uncertainty associated with the temperature exposure and the service life. For medium radial truck tires, mileage accumulation rate is the primary determinant.

Figure 18 is designed to reflect when a tire needs to have nitrogen inflation for oxidative durability reasons. The present study has assumed that any nitrogen tire inflation is done with nitrogen inflation gas having at least 98% purity, and that only one inflate cycle to the tire’s maximum inflation pressure, is done. Daws [8] showed that this is sufficient to yield 93% nitrogen purity in passenger car tires and 95% purity in medium radial truck tires.

Obviously, a consumer may want to purchase nitrogen tire inflation in order to reap other associated benefits. For example, since nitrogen is a dry gas, nitrogen inflation will help to mitigate the effect of water vapor in the tire in cold climates, resulting in lower pressure drops overnight. The use of nitrogen inflation will presumably also provide additional protection for the tire in the event of damage to the tire’s structure by minimizing the oxidative component associated
with increased intra-carcass pressurization. On Figure 18, then, the “Nitrogen Optional” reflects that the tire, in that environment and utilization, does not need the oxidative improvements available from nitrogen tire inflation, but the IPLR reduction and other protection afforded by the procedure may still be attractive to the customer.
Conclusions

1. The IPLR reduction available from nitrogen tire inflation, while large in percentage, is small enough that it is not likely to be noticed by the vehicle owner/user. This assumes that the comparable air-inflated tire does not have water vapor, which can result in much larger pressure swings especially in cold climates. The IPLR reduction from nitrogen tire inflation is maximized when the tire is initially inflated, and it gradually gets smaller over time.

2. Nitrogen tire inflation has the potential to reduce the effective oxidative aging of the tire over its lifetime. For passenger and light truck tires, the oxygen permeation process could be reduced by a factor of 50% over six years. For medium radial truck tires, this figure is on the order of 73%.

3. Passenger and light truck tires operated over long service lives where the environmental temperatures are high will have the most oxidative benefit from nitrogen tire inflation. Tires anticipated to last more than 6 years and operated south of I-40 in the United States should be inflated with nitrogen for this reason. Tires anticipated to last more than ten years and operated south of I-80 in the United States should routinely be inflated with nitrogen, again for the oxidative benefit.

4. Spare tires, due to their potentially long service lives and potential for exposure to temperatures higher than the surrounding environment should be inflated with nitrogen.

5. From an oxygen permeation viewpoint, there is little difference between leaving snow tires mounted all year and inflated with nitrogen and demounting/remounting them each season, especially if the service life of the tire is likely to extend beyond six years. Snow tires anticipated to last over ten years and operated south of I-80 in the United States should either be inflated with nitrogen or demounted/remounted each season.

6. Medium radial truck tires represent a significant opportunity for nitrogen tire inflation in terms of reduced oxidative degradation. Nitrogen tire inflation on long haul tires that exhaust their tread lives in one to two years would reduce the oxygen permeation through those tires by around 85% over air inflation, but mechanical fatigue may be more significant than oxidative degradation in this type of service. In regional haul service where annual mileage accumulation is lower, the oxidative degradation of the casing likely overwhelms its mechanical fatigue properties. In that case, nitrogen tire inflation may have
oxidative benefits in terms of the number of retread operations attainable, although this has not been proven in field trials.

7. For passenger car and light truck tires, the need for nitrogen tire inflation is associated with permitting the use of the tread wear life built into the tire. This appears to be reasonable based on known response of tires to both higher and lower levels of oxygen permeation. Improvements associated with IPLR reduction are likely to be within the normal variation of tire pressure for owners who properly maintain tire pressure (compared to an air-inflated tire with dry air). While desirable, many buyers will not be able to perceive the improvement. For medium radial truck tires, the value proposition for nitrogen tire inflation involves the potential for additional retread lives obtained by improving the long-term casing durability. Again, benefits associated with IPLR may result, but this will depend upon a given fleet’s current tire pressure maintenance practices and what type of maintenance gas is used.
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FIGURE 1. Illustration of the effect of Oxidative Degradation on the Wohler curve for Tire Durability.
FIGURE 4. *Relative Permeation Ratios for Passenger Tires in Several US Cities (Detroit = 1.0)*.
FIGURE 5. Relative Permeation Times for Cities Across the United States. Reference is 21 C for one Year.
Assumed $O_2$ Concentration Profile

\[ \eta = \frac{C}{C_m} \quad \delta = \frac{x}{t} \]

Average $O_2$ Concentration = $\bar{C}$

\[ \eta = e^{-k\delta} \]

Now: $\eta = \frac{C_i}{C_m}$ where $\delta = 1$, so $k = -\ln\left(\frac{C_i}{C_m}\right)$

\[ C_m = \frac{\bar{C}k}{1-e^{-k}} \]

For a critical concentration $C_i$

\[ x_i = \frac{t}{k} \ln\left(\frac{C_i}{C_m}\right) \]

FIGURE 7. Oxygen Concentration Model Assuming Profiles Demonstrated by Sperberg.
FIGURE 8. Oxygen Concentration Distribution in P235/75R15 SL Tire after 6 Years at 21 C. Casing Thickness Set at 7 mm.
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