Practical Aspects of Nitrogen Tire Inflation

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ABSTRACT: Nitrogen as an inflation gas for passenger car and light truck tires use is widely available commercially. Consumers are confronted with a bewildering selection of offerings, and suppliers tout the purity of their nitrogen generation systems and effectiveness of using the gas in place of air. This paper summarizes some of the touted benefits to a consumer of nitrogen inflation and focuses on those that have technical merit. The costs and other issues facing the nitrogen supply industry are discussed. The paper discusses the physics of gas permeation as applied to a nitrogen-inflated tire and how it differs from an air-inflated tire, and applies this analysis to the cost-benefit issues in the nitrogen inflation industry.

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

Nomenclature

A	inner liner surface area of tire
AR	tire aspect ratio
D_R	tire rim diameter
G	gauge (thickness) of tire
M_{O2}	mass of oxygen corresponding to a loss in partial pressure
N	number of inflation steps
P	absolute inflation partial pressure of a gas in the tire
P_A	absolute partial pressure of a gas in the atmosphere
P_0	initial internal absolute partial pressure of a gas in the tire
Q	permeability coefficient for an ideal gas
R	ideal gas constant
R_c	compression ratio at maximum tire inflation pressure
S_N	tire section width
t	time
T	absolute temperature
V	tire internal volume
V_N	volume of nitrogen gas consumed in filling a tire
η	nitrogen purity of an ideal gas mixture

Introduction

Passenger car and light truck tire inflation using nitrogen gas is widely offered in the tire service industry. Nitrogen inflation has not been adopted by any vehicle manufacturers, nor has it been promoted by the tire manufacturers. Nonetheless, nitrogen inflation for passenger car and light truck tires is widely promoted in the tire service industry. Many claims are made by supporters of nitrogen inflation: lower inflation pressure loss rates (IPLRs), lower rolling resistance, higher fuel economy, lower running temperature, improved wear, and reduced age-related degradation, to name a few. The normal reasoning presented is that the tire materials are significantly more permeable to oxygen than to nitrogen (some promotional documents even infer that nitrogen will not leak out of the tire at all), while omitting the information that the partial pressure of nitrogen inside the tire is several times higher than that of oxygen. Claims of lower rolling resistance, lower running temperature, and improved wear have been linked to the improvement in the IPLR, since these tire characteristics are controlled by the mechanical deformation of the tire’s hysteretic materials. The issues are complicated by the fact that tire service providers offering nitrogen do not all offer the same level of nitrogen inflation gas purity and the maintenance of the inflation pressure in the tire falls to the vehicle owner who may follow any number of inflation maintenance strategies.

This paper will examine a number of the issues that are key to nitrogen inflation. Nitrogen inflation, as typically practiced in the service industry, involves replacing the air in the tire with some initial purity of nitrogen gas, usually by successively inflating and purging the tire with an inflation gas of some purity. The first issue is that of the benefits that accrue to the consumer – which of the touted benefits are real? The second issue is the level of nitrogen purity required in the tire to obtain these benefits. The third issue is that of the costs involved in supplying nitrogen inflation in a way that guarantees the consumer the benefits being purchased. This discussion will cover the difference between a nitrogen-inflated tire and an air-inflated tire over an extended time period so that the benefits issues can be fully explored.

Background

The spread of nitrogen inflation in the tire service industry has led to the availability of many different sources, and different purities, of the nitrogen inflation gas itself. The most common form of nitrogen supply system depends on the use of a membrane to extract the nitrogen from a compressed air stream. One of the characteristics of these membranes is that the level of nitrogen purity in the output gas is directly dependent upon the flow rate of the gas output. On some systems, there is even a dial that allows the provider to select any purity between 95% and 98%. These systems also depend upon proper maintenance of filters in front of the membrane, with the filters being designed to extract water vapor and oils from the compressed air stream prior to entering the membrane. Any degradation of these filters due to lack of maintenance has the potential to compromise the purity of the nitrogen being generated. These types of nitrogen generation systems have significant capital costs that depend upon their output rate. A second type of nitrogen supply is welding nitrogen supplied in standard tanks. While the capital outlay is significantly less, the cost per standard cubic foot of nitrogen gas is typically much higher. However, the purity is guaranteed to be greater than 99.9% (100% will be used for this source in all subsequent analyses). There are also safety issues in handling high-pressure tanks routinely in a tire shop. The combination of cost and handling issues mean that tank-supplied nitrogen is not widely used in the tire service industry.

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. Tokita [2] 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. 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. More recently, Baldwin [3] showed the results of the influence of nitrogen on belt skim stock properties. Of particular interest was that there was no apparent benefit beyond about 96% initial nitrogen purity in the tire. Karmarker [4] discussed the results of an investigation on the influence of nitrogen inflation on belt skim stock. Karmarker noted that “it has been shown that property changes with greater than 95% purity in a tire are within the error limits inherent in tire variations”. MacIsaac [5], 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 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 concluded that there was no direct effect of nitrogen purity on rolling resistance. As an aside, NHTSA found that the nitrogen purity actually increased in air-inflated tires over time. NHTSA also tested tires with 50% nitrogen, air, and 95% nitrogen by oven aging at 65C, followed by Federal Motor Vehicle Safety Standard (FMVSS) Number 139 endurance tests, and found that some of the tires inflated with 50% nitrogen failed the wheel test while all those inflated with air or 95% nitrogen passed. Most recently, Napier and Waddell [6] studied nitrogen inflation using laboratory tests and vehicle studies and concluded that nitrogen affected neither the operating temperature nor the rolling resistance coefficient directly.

With the results of the studies outlined above in hand, one can make a certain number of statements about potential benefits of nitrogen inflation. The first, and usually most important claim made about nitrogen inflation, is that the IPLR for the tire is reduced. While the reason for this is often incorrectly given as nitrogen molecules will not permeate the tire casing, the fact is that nitrogen inflation has been shown conclusively to reduce the IPLR in tires. This benefit will be discussed in depth later in this paper. Claims that nitrogen inflation improves fuel efficiency and lower rolling resistance have been shown to be false insofar as the influence of the gas itself. Obviously, if the tire’s internal pressure is better maintained, these performances will also be better maintained. Claims that the tire’s internal operating temperature is lower with nitrogen inflation have been shown to be false. Claims that tire wear and blowouts are reduced by nitrogen inflation have not been studied, but do not seem to have a scientific basis. The fundamental benefits that would accrue to a consumer who purchases nitrogen inflation therefore appear to be the improvement of the tire’s IPLR and a reduction in the oxidative degradation of the rubber materials in the tire (less rapid aging).

Initial Gas Discussion

Nitrogen, oxygen, and the rest of the components of air are considered ideal gases at pressures and temperatures found in tires. For the purposes of the analyses in this paper, air is considered to be 78.1% nitrogen and 21.9% oxygen, as the trace gases are generally found to comprise less than about one percent of the total. Following Dalton's Law (i.e., the pressure of a mixture of ideal gases equals the sum of the pressures of its constituents if each existed alone at the temperature and volume of the mixture) for air at 1 Bar (14.7 psia), the partial pressure of nitrogen is about 79.3 kPa (11.5 psia), and the partial pressure of oxygen is about 22.1 kPa (3.2 psia). Each of these gases is deemed to behave independently in the tire. Since the tire pressure is higher than that of the atmosphere, and the partial pressures of nitrogen and oxygen in the tire depend upon nitrogen purity in the tire, these gases will permeate through the tire materials at a rate that is dependent upon the permeability coefficient of the tire materials to each gas and the pressure difference between the partial pressures of each gas inside and outside the tire.

If one of the objectives of nitrogen inflation is to minimize the permeation of oxygen through the tire, it follows that for every tire inflation pressure, there is a purity of nitrogen where the partial pressure of the oxygen inside the tire is equal to the partial pressure of oxygen in the atmosphere. Figure 1, found in Daws [7], shows this relationship in graphical form. Each type of tire (P-Metric standard load, Load Range C, D, and E Light Truck, and a Medium-Duty Truck tire) has a partial pressure of oxygen at any nitrogen purity in the tire. The partial pressure of the oxygen in the atmosphere is shown as a horizontal line at 22.1 kPa (3.2 psi). It follows that if the nitrogen purity is such that the oxygen partial pressure inside the tire is less than that of the atmosphere, then oxygen will flow into the tire, and if the oxygen partial pressure inside the tire is greater than that of the atmosphere, oxygen will flow out of the tire. From the standpoint of oxygen flow, it would appear that oxygen flow into the tire would have the same effect on the tire materials as oxygen flow out of the tire. The oxygen-rubber chemical reactions depend upon the temperature of the tire and the presence of oxygen. The rate at which oxygen (and nitrogen, for that matter) permeates through the tire also depends upon temperature, which explains why dynamic testing results in higher IPLR than static testing.

Initial Tire Nitrogen Purity

The initial nitrogen purity in a tire can be increased by successive inflations and purges of the tire with a nitrogen-rich inflation gas. This is because the tire, after a bead seating cycle, contains air at one atmosphere if the valve stem is left open. When the tire is filled to its maximum inflation pressure with an inflation gas having nitrogen purity η_I, the gas in the tire will be a combination of the air that was in the tire initially and the nitrogen inflation gas that was added. If the tire is deflated, the gas in the tire retains the purity of the combination that was present at the highest pressure attained. Following Daws [7], if the compression ratio, R_c, is defined as the ratio of the maximum inflation pressure of the tire and the atmospheric pressure of air (both in absolute units), then the percentage purity of the nitrogen in the tire after N inflation steps is given by the following general relation:

$$\eta_N = \frac{\eta_A}{{R_c}^N} + \eta_I \left(1 - \frac{1}{{R_c}^N}\right) \qquad [1]$$

where η_N is the nitrogen purity at the end of the *N*th inflation step and η_A is the nitrogen purity of the atmosphere (~ 78.1%). This clearly shows that the nitrogen purity in a tire depends upon the inflation gas purity as well as the maximum inflation pressure of the tire. Since the volume of nitrogen being consumed in this process represents a cost to the service supplier, minimizing the value of *N* is important. Equation 1 also clearly shows that the nitrogen purity in a tire cannot exceed the purity of the inflation gas, regardless of the number of inflation steps used. In addition, the higher the value of R_c (the maximum inflation pressure of the tire) the faster the nitrogen purity in the tire increases. Figure 2 shows the evolution of nitrogen purity with one and two inflation steps for different types of passenger and light truck tires when the inflation gas has different nitrogen purities. This chart shows the effect of increasing inflation gas purity as well as the effect of increasing maximum inflation pressure on the nitrogen purity in the tire.

Economic Issues

While the primary thrust of this paper is the long-term effect of nitrogen in tires, the inflation of tires using nitrogen ultimately is constrained by economic realities. Economic analysis of nitrogen tire inflation has many variables, which can generally be broken down into three categories:

- the cost of the nitrogen gas itself,
- the labor costs associated with nitrogen inflation, and
- miscellaneous costs.

The cost of the nitrogen gas itself has a rather large number of variables. As mentioned previously, there are several means of generating nitrogen supplies of various purities, or high-purity nitrogen can be purchased directly. Most nitrogen generation systems are based on membrane extraction of the nitrogen using compressed air, and generally, the higher the flow rate of the nitrogen, the lower the purity of the nitrogen generated. These systems also require filtering of the compressed air stream to avoid contaminants and moisture entering the membrane. Such systems have a reasonably high capital cost, and are available in various nitrogen generation rate capacities, so some knowledge of the demand for nitrogen inflation at a given location is needed. The volume of nitrogen consumed, V_N, depends upon the tire size and the number of inflation steps used, and can be conservatively estimated as:

$$V_N = N(R_c - 1)\pi AR\left(S_N{}^2\right)\left(D_R + AR(S_N)\right) \qquad [2]$$

where S_N is the tire's section width, AR is the aspect ratio, D_R is the rim diameter, and N is the number of inflation steps. For example, a P235/75R15 Standard Load tire using two inflation steps would require about 12.2 ft^3 of nitrogen inflation gas, while a LT245/75R16 LRE light truck tire with the same two inflation steps would require about 32.1 ft^3 of nitrogen inflation gas. Following Equation 1, if the inflation gas had 96% purity nitrogen, then the P235/75R15 SL tire would have an inflated purity of about 94.5%, while the LT245/75R16 LRE tire would have an inflated purity of about 95.6%. Higher purity inflation gas would yield higher nitrogen purity in the tire, albeit at the same volume. Whatever the nitrogen source selected, the volume of nitrogen that would be consumed in a given period must be available from the equipment installed. Most generating systems provide a storage tank that allows the nitrogen generation to proceed at a constant, albeit slower, pace than the utilization. From a cost standpoint, the depreciation on the equipment must be amortized over the number of tires treated for any comparison of alternatives to be valid.

Labor costs associated with nitrogen inflation are directly related to the equipment available. There are systems available that treat multiple tires at one time in an automatic fashion. That is, direct labor is involved in hooking up the system to the tires on the vehicle, setting the maximum inflation pressure and the number of inflation cycles, and letting the system do the work. For maximum benefit (nitrogen purity in the tire), these systems should be set to inflate the tire to its maximum inflation pressure during the nitrogen fill process, and then adjusted to the vehicle placard pressure after the nitrogen inflation is complete. “Wand” type nitrogen sources, where a person has to be present during the entire process for each tire and each tire must be done in series with the other tires on the vehicle, obviously require more direct labor for each vehicle treated. Other labor costs associated with nitrogen service would include the servicing of the nitrogen generation equipment.

Miscellaneous costs involved in nitrogen inflation include green valve caps, literature, and the like, associated with the marketing of nitrogen. Electrical power for air compression, while a real cost, is not likely to be significant, although additional compressor maintenance might be. In addition, filters and other consumables for the nitrogen supply equipment can become a significant cost which must be borne to guarantee correct system performance. Consumable costs may be difficult to get from system vendors prior to equipment installation, so special efforts must be applied here to generate a fair comparison between different systems.

Lifetime Nitrogen Purity Evolution Model

A nitrogen purity evolution model was developed by Daws [7] following work done by Costemalle [8] 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:

$$(P(t) - P_A) = (P_0 - P_A)e^{-\left(\frac{Q}{G}\right)\left(\frac{A}{V}\right)RTt} \qquad [3]$$

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, t is time, 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 $P_0 - P(t)$.

The permeability coefficient, Q, depends upon the gas, the rubber material, and the temperature. In the earlier referenced work by Costemalle, the tire was considered to be layers of rubber having different permeability coefficients relative to air. In that analysis, an overall permeability for the tire was developed by considering the tire as being made up of several layers acting in series, with each layer having a (Q/G) value. In this analysis, the permeability coefficients for both nitrogen and oxygen are required. Since Daws' model was concerned with permeation rather than tire construction, the tire was considered as a single material. Units of Q are normally given in barrers, where one barrer unit is:

$$1\ barrer = 10^{-10}\left(\frac{cm \times cm^3}{s \times cm^2 \times cmHg}\right) \qquad [4]$$

The permeability coefficients reported for typical rubber materials in tires in barrer units are about 10 for oxygen and about 3 for nitrogen at around 25C. Limited data suggests that when the temperature rises from 25C, where the vast majority of this type of data is presented, to 65C where some additional data has been taken, the permeability coefficients increase by about a factor of around three. This explains why dynamic testing shows higher inflation pressure loss rates than static testing. However, for passenger car and light truck analyses, using 25C as the analysis temperature for IPLR and gas purity evolution will produce generally appropriate results, since these tires are estimated to be in service only about 10% of their lifetimes.

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:

$$M_{O2} = \frac{(P_0 - P(t))V}{RT} \qquad [4]$$

where M_{O2} is the mass of oxygen corresponding to the drop in partial pressure of oxygen during the tire period *t*. Daws proposed that oxidation is known to be the process by which the tire is aged, so estimating the amount of oxygen that passes through the tire can help in the evaluation of the benefit of different nitrogen inflation strategies. Obviously, there is a difference between the amount of oxygen that passes through the tire and the amount that reacts with the tire’s rubber hydrocarbons. Tokita estimated the reacted amount of oxygen by using oxygen-rubber kinetics. That study, as well as many others, have shown that limiting the oxygen flow (i.e., by using better inner liners), selecting rubber materials that are less reactive, and reducing tire operating temperature (i.e., designing lower rolling resistance tires) are all important to improving the long-term durability of the tire.

Lifetime (6-year) Simulation and Results

The formulation presented above was used to develop a set of simulations. The process for each simulation was to assume that the initial nitrogen purity in the tire was set to a given value, as described previously (Equation 1). Then, Equation 3 was used to compute a change in the nitrogen and oxygen partial pressures over a time period equal to 30 days. The total inflation pressure loss was found as the sum of the two partial pressure losses. The pressure in the tire was assumed to be reset to the starting pressure by using an inflation gas of a given purity nitrogen. This resulted in a new nitrogen and oxygen purity in the tire, and the process was repeated. For the purposes of this analysis, the “lifetime” of the tire was arbitrarily taken to be six years, as this would effectively demonstrate how the nitrogen and oxygen purities evolved over an extended period of time. Then, Equation 4 was used to compute the mass of oxygen that passed through the tire during the period based on the oxygen partial pressure losses. Obviously, this analysis assumes that the tire is receiving monthly maintenance as recommended by the tire industry. Further, the parameters used in this phase of analysis were for a temperature of 25C. To simplify the number of variables, a P235/75R15 tire was chosen as the tire size for the passenger car analysis, and a LT245/75R16 size tire was chosen for the light truck analysis.

Air Inflation with Air Top-off

For a P235/75R15 SL tire that is initially inflated with air, and then topped off monthly with air, Figure 3 shows the evolution in the partial pressure losses in nitrogen and oxygen from the tire, along with the total pressure loss each month. It is clear that the inflation pressure loss rate determined by the total pressure loss starts out at 2.61% and evolves to a lower value (in this case, 2.08%) over the simulated lifetime of the tire. Figure 4 shows the gas purity evolution for both nitrogen and oxygen in the tire during the same time. As was noted by NHTSA, the nitrogen purity in an air-inflated tire evolves, and in this case it evolves from 78.1% to about 87.6%. The initial partial pressure losses in Figure 3 for the nitrogen and oxygen were nearly equal, with the monthly oxygen flow across the tire falling over the lifetime of the tire as the nitrogen purity in the tire increased. This reflects the fact that, while the tire is over three times more permeable to oxygen than nitrogen, the initial partial pressure of the nitrogen is over three times higher than the initial partial pressure of the oxygen. Figure 5 shows the mass of oxygen flowing across the tire on a monthly basis as a result of permeation. Integration of this curve results in an estimate of 78,881 mg of oxygen crossing the tire during its simulation lifetime of six years. This establishes a baseline for comparison of the various nitrogen inflation strategies that are being proposed in the tire service industry,

Nitrogen Inflation with Air Top-off

In order to present simulation results in a consistent manner, nitrogen inflation will be considered based on the initial nitrogen purity in the tire. The inflation process has been explored previously, and there are generally several approaches to attaining an initial tire nitrogen purity depending upon the purity of the inflation gas, the tire’s maximum inflation pressure, and the number of inflation steps to be used. When the top-off gas is air, the only variable is therefore the tire initial nitrogen purity. Air top-off probably represents the norm in the tire service industry, since providers typically charge for the initial inflation, and consumers are essentially on their own for the routine maintenance of the tire's inflation pressure.

Figure 6 shows the partial pressure change for a P235/75R15 Standard Load tire having an initial nitrogen purity of 96%. It can be seen that the initial pressure loss for nitrogen and oxygen are very different, reflecting the initial tire nitrogen purity. In fact, it can be seen that oxygen actually flows into the tire, as expected, for several months while the oxygen partial pressure inside the tire is less than that found in the atmosphere. The initial IPLR for this case is 1.61%, a reduction of 57% over an air-inflated tire. However, in contrast to the air inflation case, the IPLR *increases* rather than decreases over time. At the end of the simulation life, the IPLR for the tire with a 96% initial nitrogen purity and monthly air top-off is 2.05%, which is nearly what the air-inflated tire has at that point. Figure 7 shows the corresponding purity evolution curves for oxygen and nitrogen in the tire. Note that the oxygen loss curve, instead of having a downward trend as for the air-inflated tire, has a consistent upward trend. This reflects the fact that the top-off gas is air (with 78.1% nitrogen purity). Figure 8 shows the oxygen permeation curve for the nitrogen inflation case. As air is added to top off the tire, the oxygen permeation from the exterior decreases as the oxygen partial pressure nears equilibrium, and then increases as more oxygen is pumped into the tire. The total amount of oxygen crossing the tire in this case was estimated to be 39,466 mg, which is a significant reduction (about 50%) compared to the air-inflated tire.

Further increase in the tire initial nitrogen purity in passenger car tires leads to decreasing returns, as will be shown in the summary section. Additional nitrogen purity in the tire results in a faster permeation of oxygen into the tire initially followed by a gradual transition to permeation of the oxygen out of the tire. Since oxygen flow affects the tire rubber regardless of the direction of the flow, the total amount of oxygen crossing the tire over the simulated lifetime does not continue to decrease monotonically. Figure 9 shows the initial IPLR as a function of the tire's initial nitrogen purity. The IPLR is simply the sum of the partial pressure losses or gains for nitrogen and oxygen, each derived independently using equation 3. The higher the initial nitrogen purity, the better the IPLR performance with respect to the air-inflated tire will be. It can easily be shown that this relationship is linear with nitrogen purity at any time, and that the slope of the line depends upon the tire parameters, the permeability coefficients for the tire materials, and the temperature of the tire. As was shown, the nitrogen and oxygen purities in the tire evolve over the simulated lifetime of the tire. In the case where the top-off gas is air, the IPLR at the end of the tire life is not significantly different than that of air-inflated tires at initial nitrogen purities being offered by the tire service industry. The significance of this fact is critical to the benefits espoused by advocates of nitrogen tire inflation – *the IPLR benefit cannot be maintained throughout the tire's lifetime without some other measures being taken to reestablish the nitrogen purity in the tire*. One approach simulated by Daws was to provide monthly top-off service using nitrogen rather than air. This approach has been shown to yield significant oxygen flow benefits in the tire while maintaining the IPLR benefit for the consumer. Another approach suggested by Daws was to recommend that the nitrogen inflation procedure be repeated every two to three years, essentially resetting the initial level of nitrogen purity in the tire and restoring the IPLR benefit for the consumer. This approach also has significant oxygen flow benefits for the tire. Either approach to the maintenance of the nitrogen purity in the tire would require changes in the way in which nitrogen is marketed and supplied.

Discussion

Obviously, an analysis of the type discussed above can be performed for any initial nitrogen purity and for many different tire sizes and types. For the purpose of this discussion, the analysis is repeated for P235/75R15 tires having maximum inflation pressures of 35 psi, 42 psi, and 44 psi, and for LT245/75R16 light truck tires having maximum inflation pressures of 50 psi, 65 psi, and 80 psi. These analyses were repeated for initial nitrogen tire purities ranging from 78% to 100%. The total six-year oxygen flow for each case, as a percentage of the air-inflated tire of the same size and inflation pressure, is shown in Figure 10. It is clear from Figure 10 that, as initial nitrogen purity increases from 78% (essentially air), the oxygen flow over the tire lifetime drops steadily until the initial nitrogen purity reaches about 93% for the passenger car tire and about 96% for the light truck tire. Recall from Figure 2 that these nitrogen purities were where oxygen partial pressure equilibrium was established for these tire types. Beyond these initial nitrogen purity levels for tires that are routinely topped off with air, there is a decrease in the incremental benefit in oxidation reduction. This "flattening" of the oxygen reduction (benefit) curves suggests that the benefits delivered to the consumer in terms of oxidation reduction (i.e., reduction in aging degradation) would be nearly the same across a wide range of initial nitrogen purities.

Initial nitrogen purity is a function of the purity of the inflation gas and the number of inflation steps. The number of inflation steps has a direct effect on the amount of nitrogen consumed and therefore on the cost of the service. In fact, if a target improvement of, for example, 50% reduction in total oxygen flow is sought, then these curves can be used to determine the initial nitrogen purity to establish in the tire to deliver this result. For the P235/75R15 size passenger car tire, a 50% reduction would require an initial nitrogen purity of about 93% or better, which could be attained by using many different combinations of inflation steps and inflation gas nitrogen purity. The difference among these approaches is a matter of cost, since the benefit curves are essentially flat. As was discussed previously, inflation gas nitrogen purity can be used along with these benefit targets to develop minimum cost nitrogen inflation processes for practically any type of tire and equipment.

Since the IPLR benefit is a function of the nitrogen purity and its evolution, consider the P235/75R15 SL tire previously discussed. If the tire is inflated to a nitrogen purity of 93%, it will initially have a partial pressure of oxygen nearly equal to that of the atmosphere. This 93% level can be obtained, as previously discussed, in many ways. If this tire is then topped off monthly with air, the resulting evolution in IPLR will follow the curve shown in Figure 11. If this tire were instead topped off with the 98% nitrogen, its IPLR would evolve according to the corresponding curve in Figure 11. Note that the IPLR for the tire gradually decreases over the life of the tire similar to the air-inflated tire but in direct contrast to the nitrogen-inflated tire being topped off with air. The initial benefit of a lower IPLR is maintained throughout the tire’s life, but the top-off process imposes a substantial on-going burden on the provider. If, instead of topping off the tire monthly with nitrogen, the top-off is allowed to proceed using air, but the tire nitrogen inflation is periodically renewed, then the IPLR follows the corresponding curve in Figure 11. In this simulation, the tire was assumed to be reinflated with nitrogen every two years, using a single step process with a 98% purity inflation gas. As expected, the curve generally follows the same trend as the tire topped off with nitrogen, but with a “sawtooth” shape corresponding to the tire topped off with air. The IPLR, on average, would be equivalent to the tire topped off with nitrogen, but the number of services would be dramatically reduced.

However, the values attained in simulations reported here depend upon only two tire sizes and absolutely regular pressure maintenance. It is very likely that, if these simulations were extended across many different tire sizes, and allowance was made for variation in the lifetime pressure maintenance, it would be difficult to determine significant differences in the overall results (IPLR and lifetime oxygen flow) across small variations in initial nitrogen purity. This suggests that the nitrogen supply industry should consider standardizing the methodology used when offering nitrogen inflation to customers. Also, in order to maintain the IPLR benefit, the nitrogen supply industry should develop a consistent approach to maintaining the nitrogen purity in the tires. This could be done by recommending a repeat of the nitrogen inflation process every two to three years, or providing nitrogen top-off gas for customer use as part of their services.

Conclusions

1. The fact that a tire is about three times more permeable to oxygen than nitrogen is offset by the fact that the partial pressure of the nitrogen is over three times higher than the oxygen. This means that the initial permeation of gas out of an air-filled tire is almost half nitrogen and half oxygen.
2. The equilibrium partial pressure of oxygen is different for different maximum inflation pressures in different tire types. Higher purities of nitrogen may be obtained in fewer inflation steps with lower purity gas sources if the maximum inflation pressure for the tire is high. Standard Load passenger car tires marked with 240kPa (35psi) represent the most difficult tires in which to attain high initial nitrogen purity since they have the lowest maximum inflation pressure.
3. The partial pressure of both the nitrogen and the oxygen in the tire evolves over the life of the tire. For a tire inflated with air, the purity of nitrogen in the tire increases monotonically over the tire life as the tire’s pressure is topped off with additional air.
4. Initial inflation of a tire with nitrogen at some purity level results in a reduction in inflation pressure loss rate compared to an air-inflated tire. However, the IPLR approaches that of an air-inflated tire over time if the tire is topped off with air. The IPLR at any point in the tire’s life is linearly related to the level of nitrogen purity in the tire at that time, so the IPLR established at the initial inflation with nitrogen degrades over the life of the tire.

5. Initial inflation of a tire with nitrogen at some purity above 93% and topping it off with air results in a reduction in the total oxygen flowing across the tire during a simulated lifetime of six years of about half that experienced by an air-inflated tire. The bulk of this reduction occurs in the first half of the simulated life, so extending the lifetime beyond the six-year life studied will reduce the percentage reduction in oxygen flow.
6. The reduction in oxygen flow across the tire using nitrogen inflation will likely be substantially the same regardless of the purity of the nitrogen inflation source or the number of inflation steps used as long as the tire is topped off with air when considering many tire sizes and varying maintenance intervals.
7. Maintenance of IPLR requires maintenance of the nitrogen purity in the tire. This could be accomplished by repeating the nitrogen inflation every two to three years or by providing nitrogen as a top-off gas.

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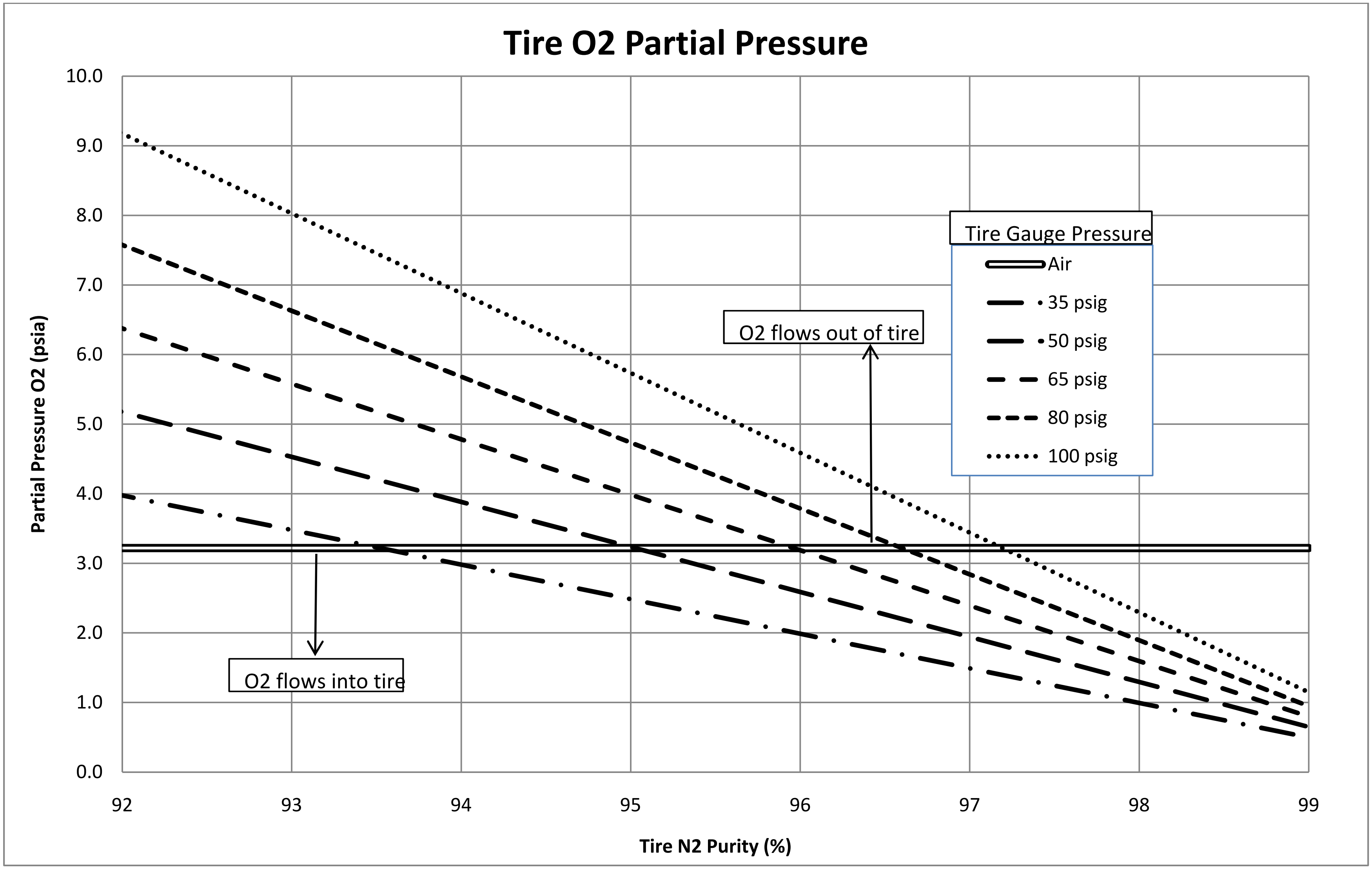


FIGURE 1. *Oxygen Partial Pressure as a Function of Tire Maximum Pressure and Nitrogen Purity.*

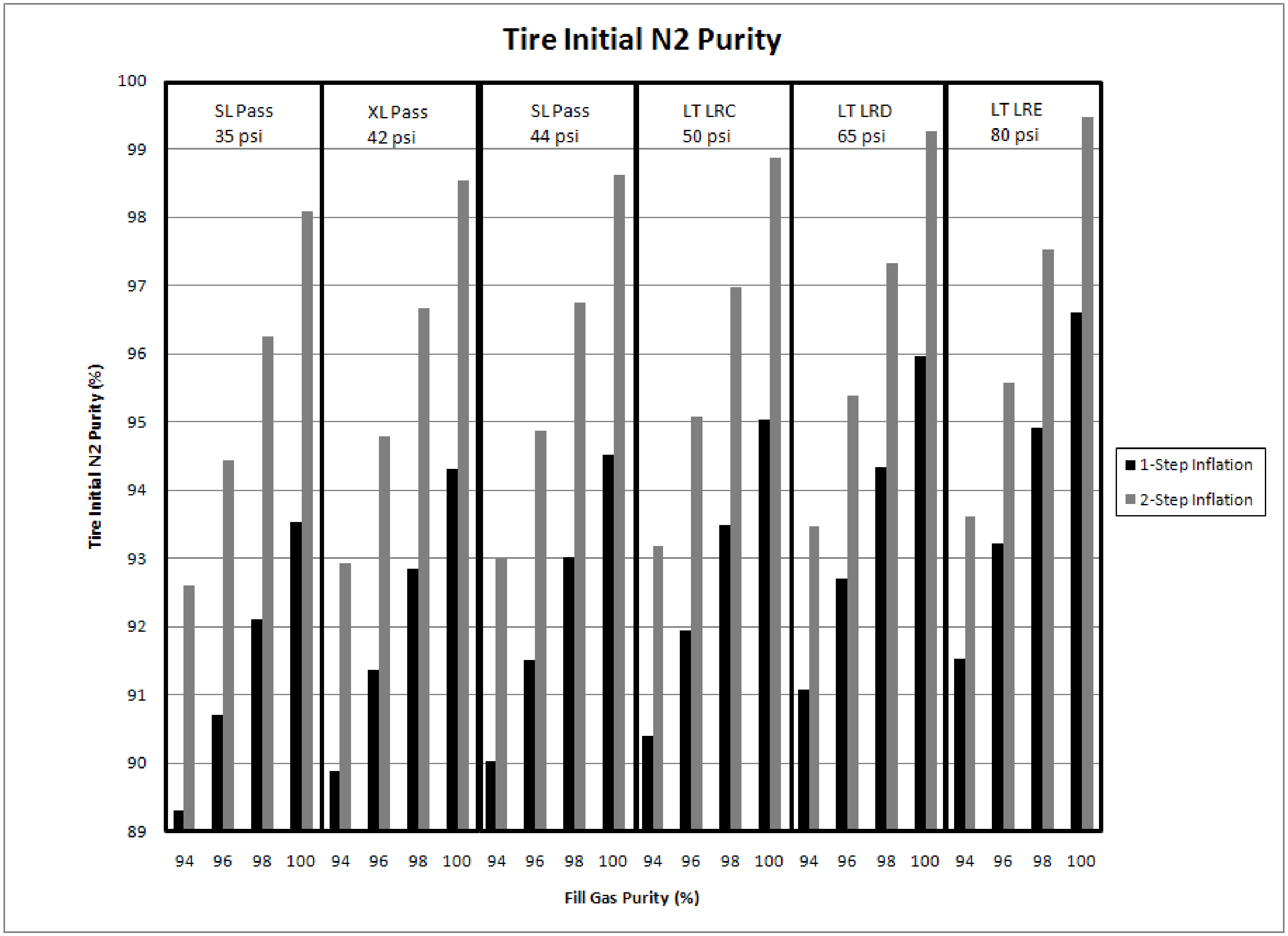


FIGURE 2. *Tire Initial Nitrogen Purity for Various Tire Types and Fill Gas Nitrogen Purities.*

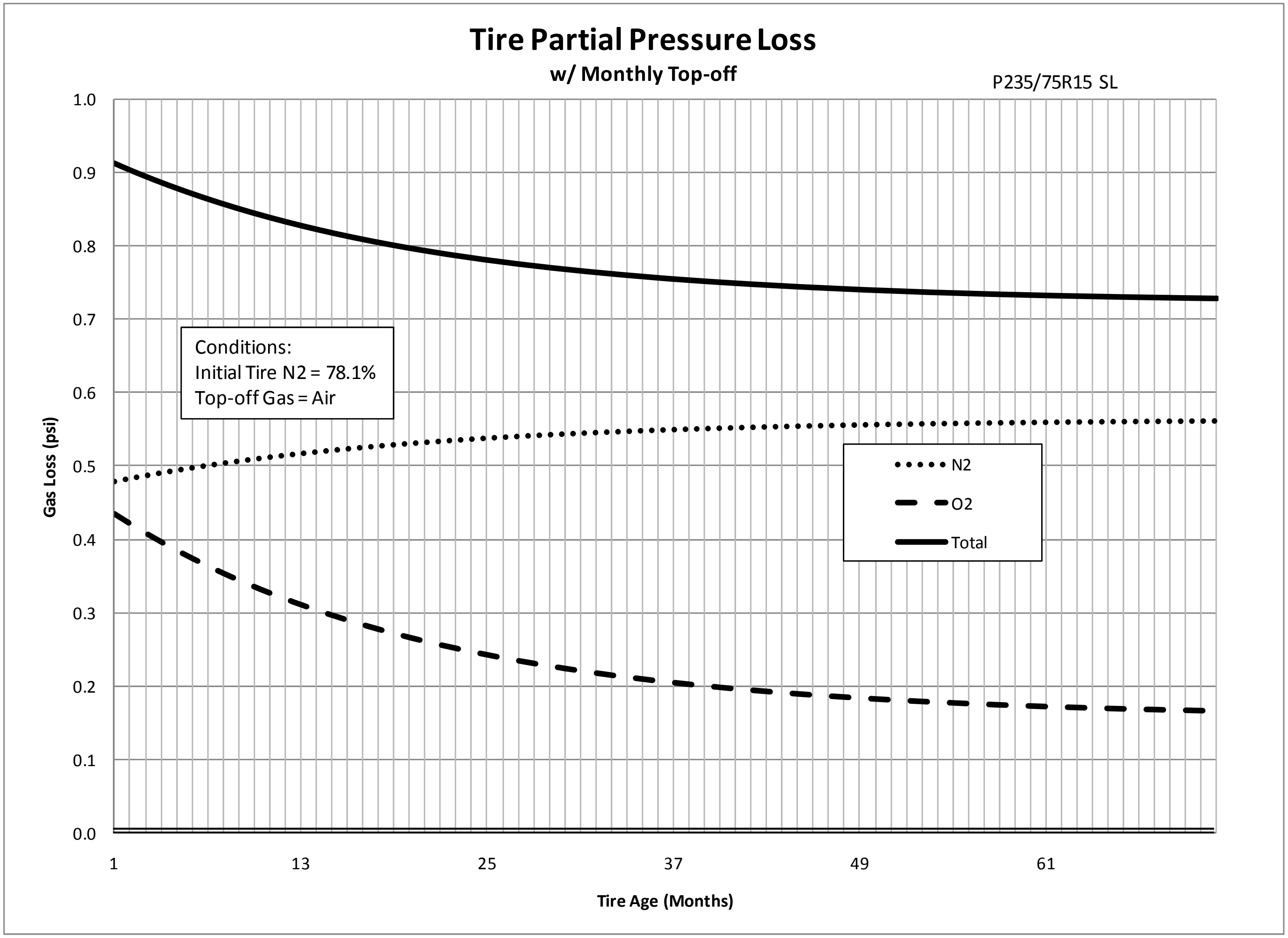


FIGURE 3. *Partial Pressure Evolution over Service Life for P235/75R15 SL Tire Inflated with Air and Topped Off With Air.*

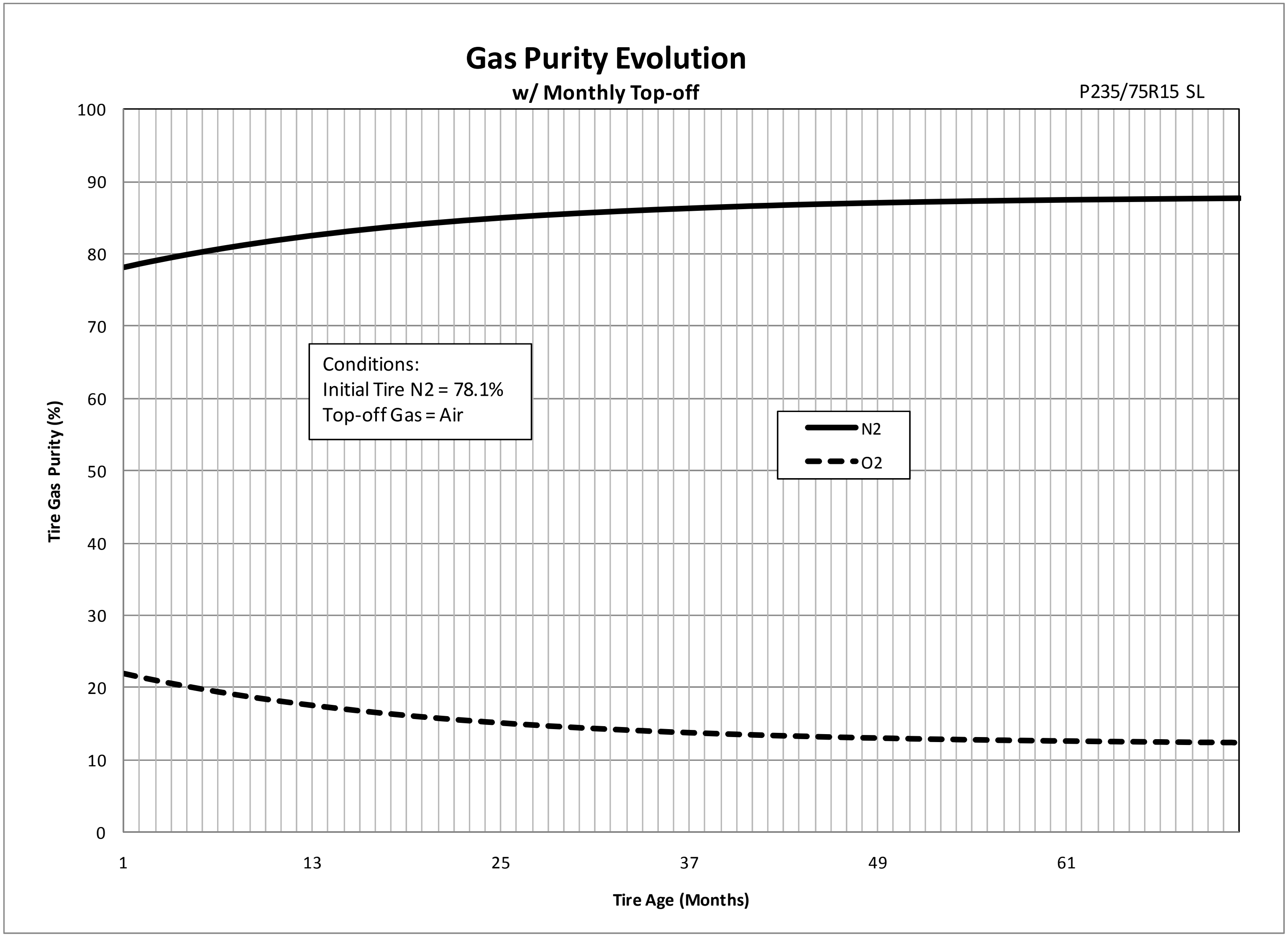


FIGURE 4. *Gas Purity Evolution over Service Life for P235/75R15 SL Tire Inflated with Air and Topped Off With Air.*

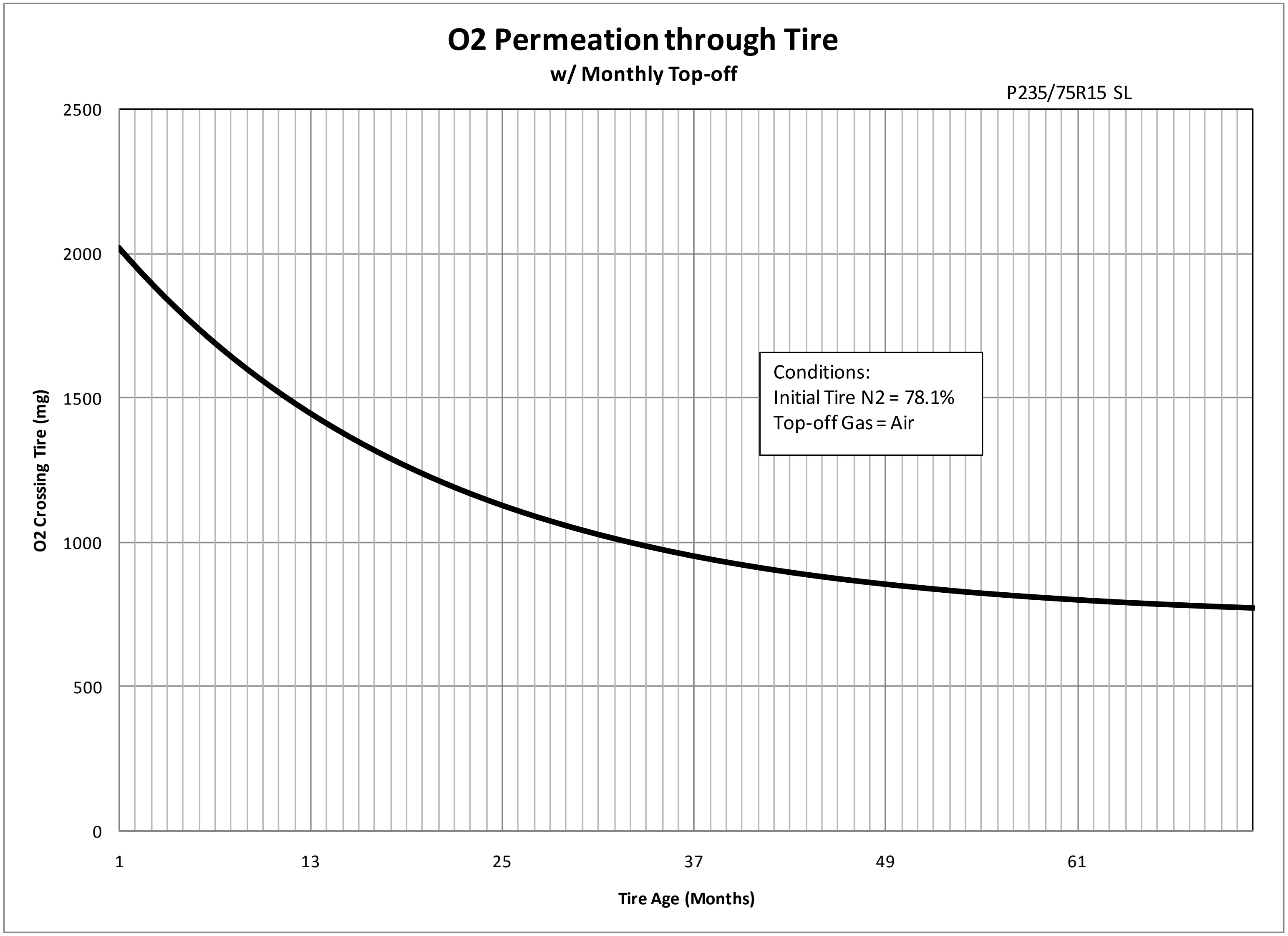


FIGURE 5. *Oxygen Permeation over Service Life for P235/75R15 SL Tire Inflated with Air and Topped Off With Air.*

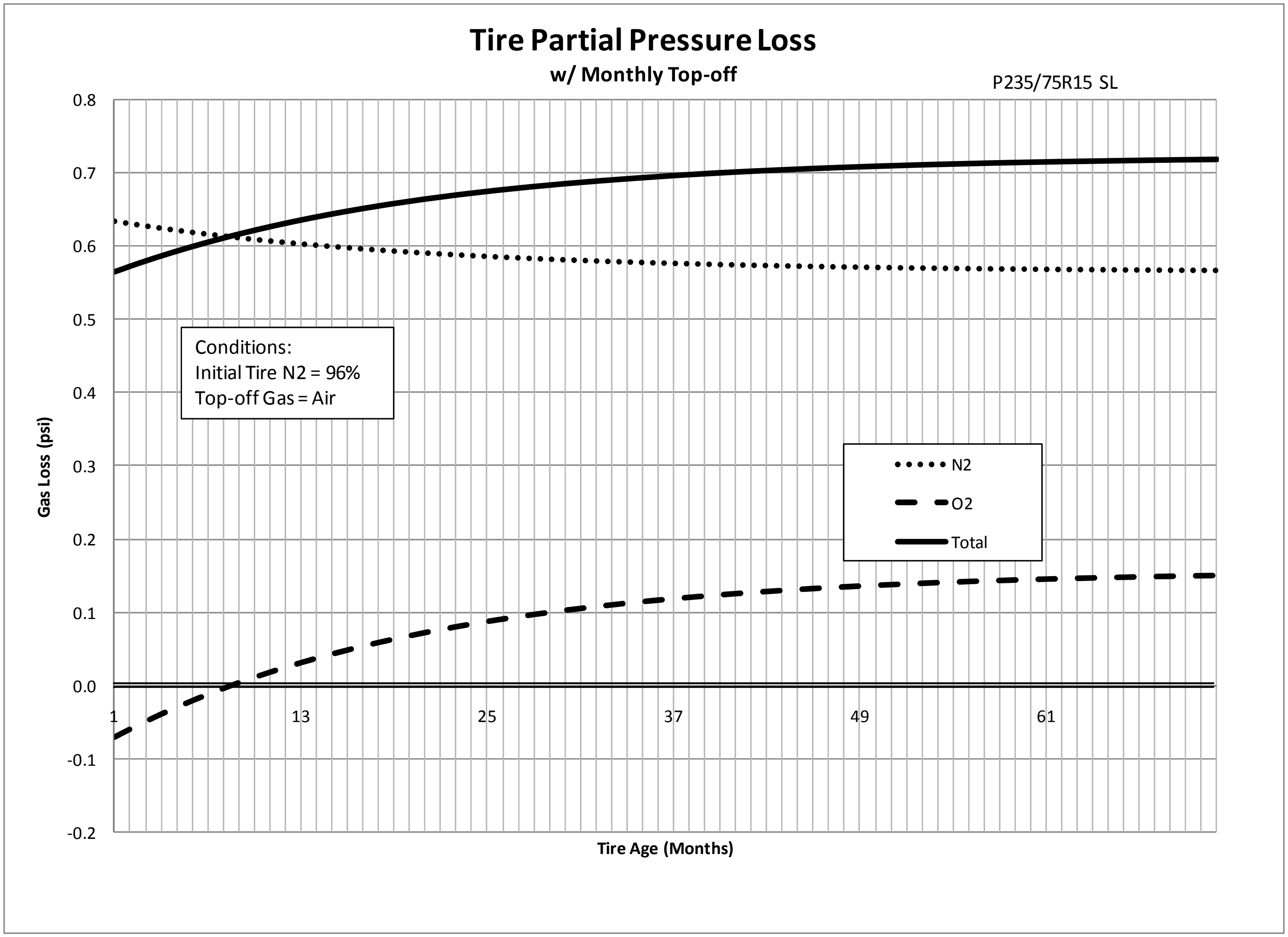


FIGURE 6. *Partial Pressure Evolution over Service Life for P235/75R15 SL Tire Inflated with 96% Nitrogen and Topped Off With Air.*

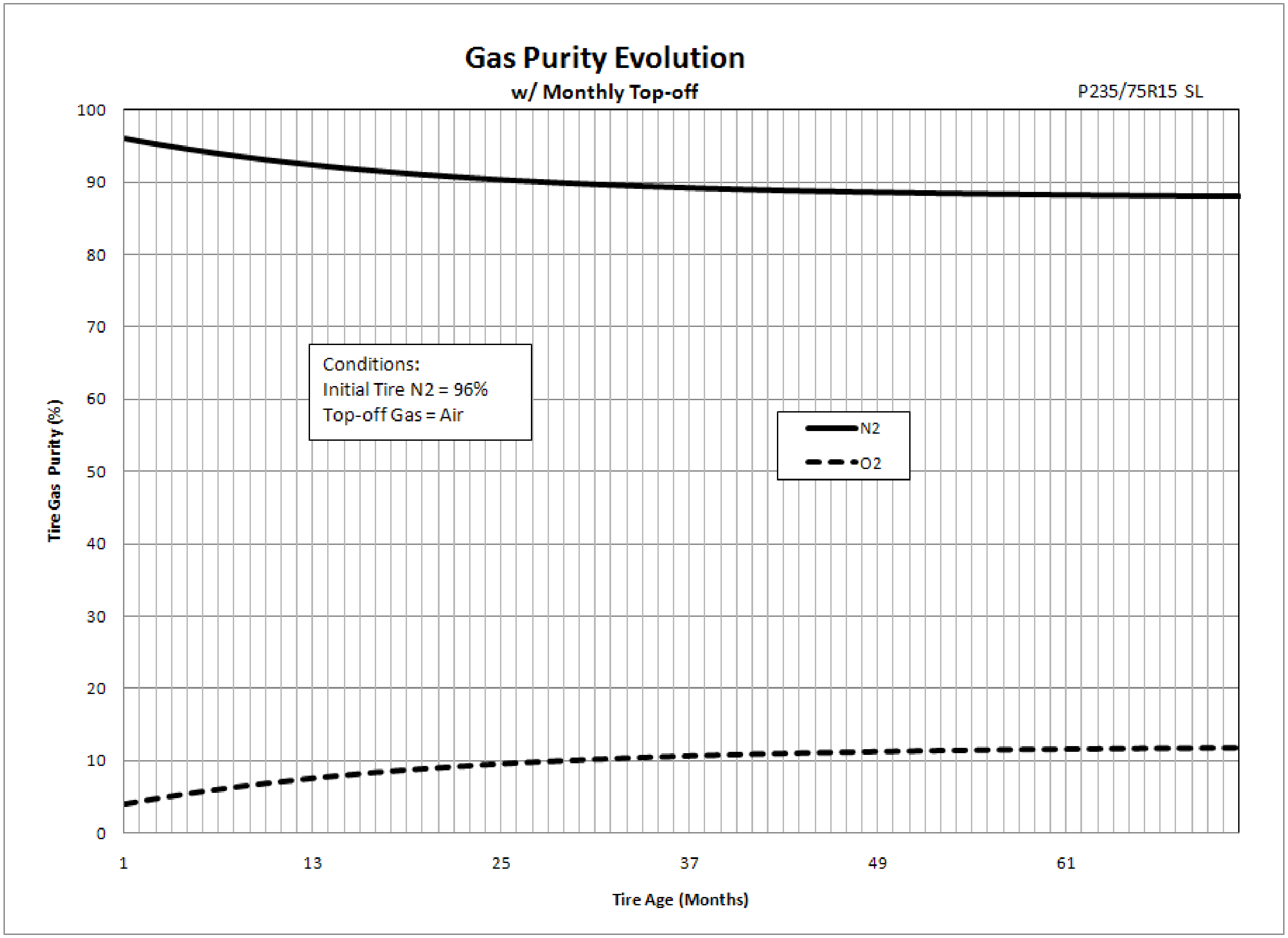


FIGURE 7. *Gas Purity Evolution over Service Life for P235/75R15 SL Tire Inflated with 96% Nitrogen and Topped Off With Air.*

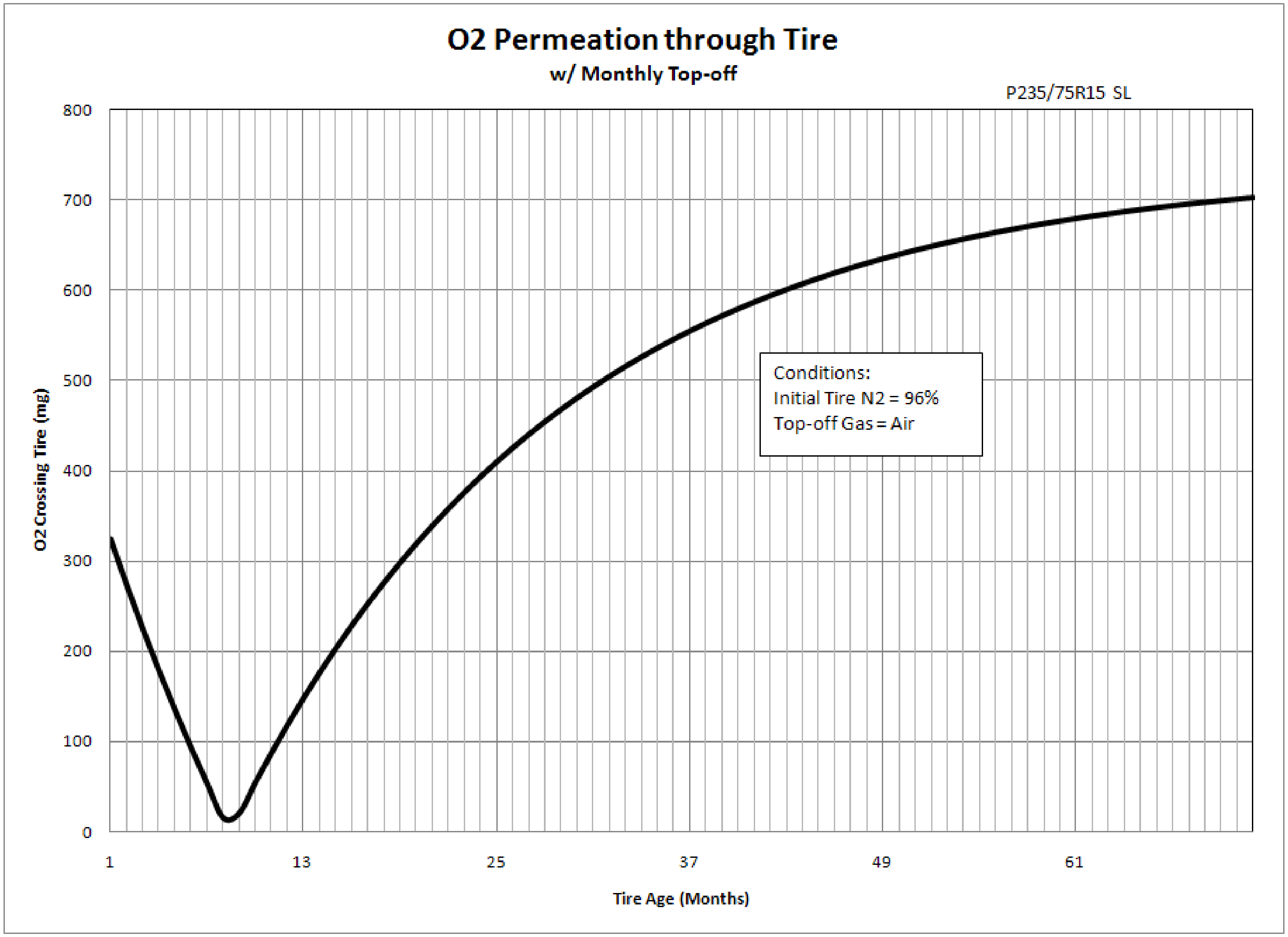
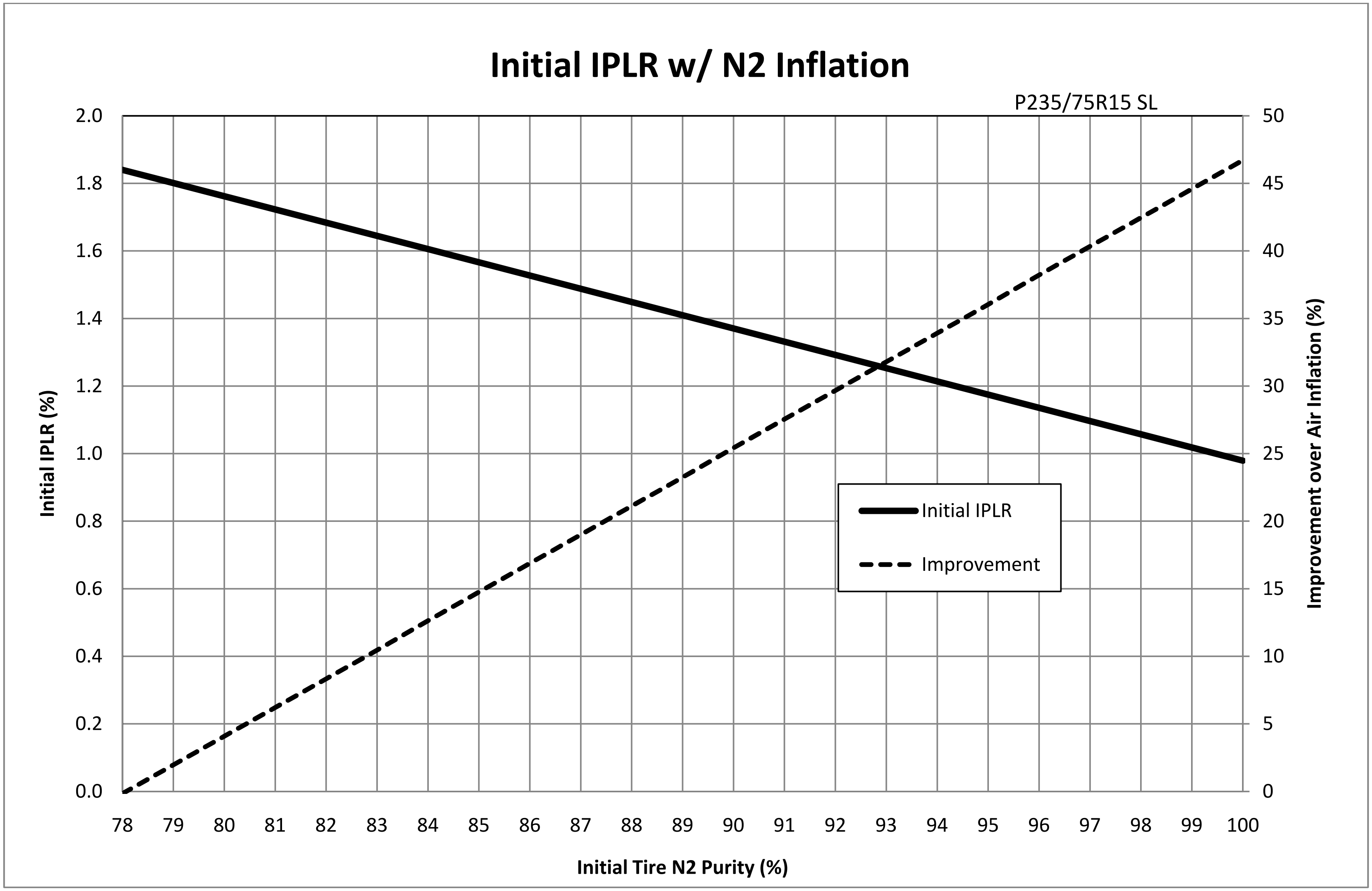


FIGURE 8. *Oxygen Permeation over Service Life for P235/75R15 SL Tire Inflated with 96% Nitrogen and Topped Off With Air.*



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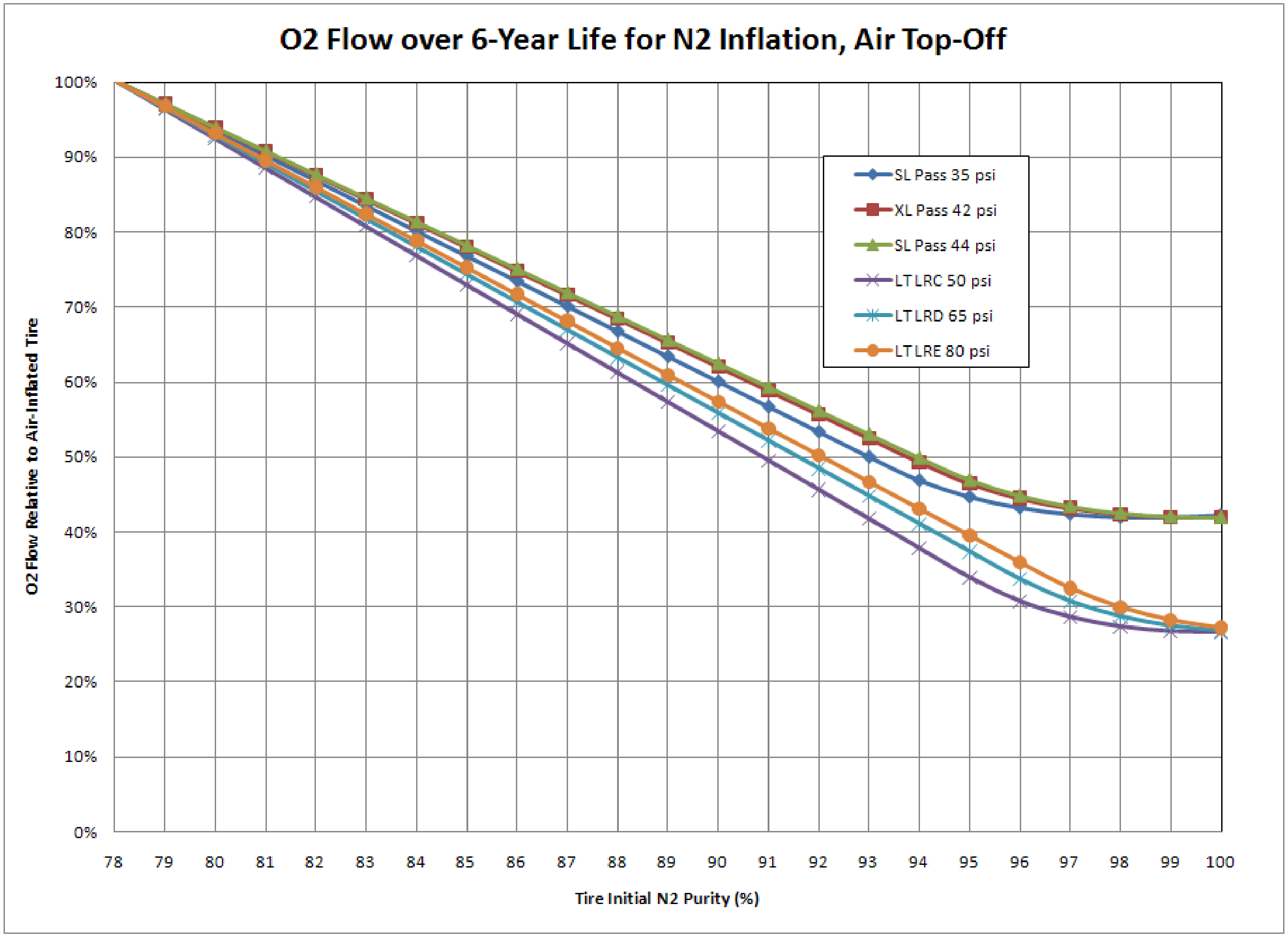

FIGURE 10. *Comparison of Oxygen Flow over Service Life for Various Tire Types at Various Initial Nitrogen Purities and Topped off With Air.*

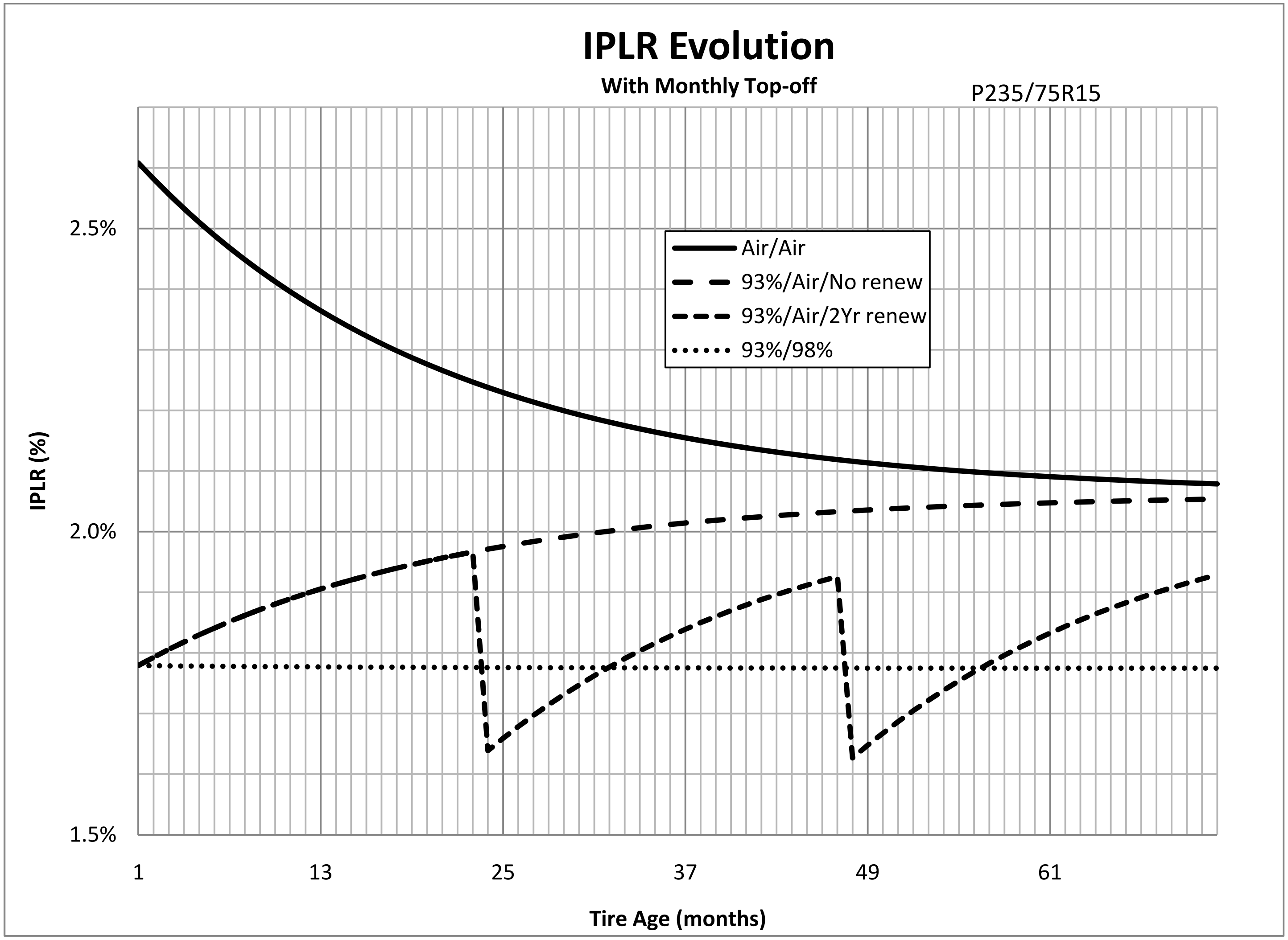

FIGURE 11. *Comparison of Oxygen Flow over Service Life for Various Tire Types at Various Initial Nitrogen Purities and Topped Off with Air.*