Nitrogen Inflation for Passenger Car and Light Truck Tires

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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 develops models for the initial tire nitrogen purity, the inflation pressure loss rate, and the evolution of the nitrogen gas purity in the tire as a function of the gas used to top off the tire over its life. A series of simulations using the basic model is developed for air and various purities of nitrogen initial inflation with monthly top-off using air or various purities of nitrogen. The initial inflation pressure loss rate is shown as a function of the tire's initial nitrogen purity. This paper proposes the use of the total oxygen passing through the tire over its lifetime as a metric for evaluation of various inflation schemes. This metric is developed for several of the popular available nitrogen inflation purities using both air and nitrogen as a top-off gas.

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

Nomenclature

A	inner liner surface area of tire
B	reaction kinetics constant
E	activation energy for a given reaction
K	reaction rate
G	gauge (thickness) of tire
M_{O2}	mass of oxygen corresponding to a loss in partial pressure
N	number of inflation steps
P	absolute partial pressure of a gas in the tire
P_0	initial internal absolute partial pressure of a gas in the tire
P_A	absolute partial pressure of a gas in the atmosphere
Q	permeability coefficient for an ideal gas
R	ideal gas constant
R_c	compression ratio at maximum tire inflation pressure
t	time
T	absolute temperature
V	tire internal volume
η	nitrogen purity of a gas

Introduction

Nitrogen inflation has not been adopted by any vehicle manufacturers, nor has it been promoted by tire manufacturers, but 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 (IPLR), 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 suggest 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. Clearly, claims of lower rolling resistance and lower running temperature and improved wear have no hope of being scientifically valid, since these tire characteristics are controlled by the mechanical deformation of the tire's hysteretic materials. There have been several studies aimed at validating one or more of these claims, but the tire types and conditions tested have varied widely and were observed over a short time. 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 is the responsibility of 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. The first is the initial inflation of the tire with nitrogen. Since there is always some air in the tire due to the bead seating process, the inflation of a tire with nitrogen typically is done using a number of inflation and deflation cycles. A model will be presented to yield the nitrogen purity in the tire as a function of the purity of the inflating gas, the maximum inflation pressure of the tire, and the number of inflation steps used. The second issue that will be addressed is the inflation pressure loss rate. A simple model will be developed that allows the study of the evolution of the nitrogen and oxygen purities in the tire over the life of the tire. It will be shown that the inflation pressure loss rate evolves with the nitrogen purity in the tire and that, in fact, inflation with gases at a higher nitrogen purity than that of air do reduce the inflation pressure loss rate. This model is used to determine the amount of oxygen flowing out of or into the tire between top-offs of tire pressure. This paper

proposes the use of the oxygen flow across the tire material as a metric for evaluating the effectiveness of various nitrogen management strategies.

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 a switch that allows the shop 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 its 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 considerable 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 much higher. However, the purity is guaranteed to be greater than 99.98% (100% will be used for this source in all subsequent analyses), although 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. The costs for a shop to offer nitrogen inflation to consumers will be a function of the nitrogen source, direct labor, and consumable supplies.

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 in 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

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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% 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 increasing 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 in air-inflated tires actually increased 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.

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 in the atmosphere is about 79.3 kPa (11.5 psia), and the partial pressure of oxygen in the atmosphere 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.

Since 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 shows this relationship in graphical form. For a P-metric standard load tire with a maximum inflation pressure of 240 kPa (35 psi), the equilibrium nitrogen purity level would be about 93.5%. For a Load Range E light truck tire with a maximum inflation pressure of 550 kPa (80 psi), that value increases to about 96.6%. Figure 2 shows this in a slightly different manner. Each type of tire (P-metric standard load, Load Range C, D, and E Light Truck, and a Medium-Duty Truck tire) has a certain partial pressure of oxygen at any nitrogen purity. 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 (i.e., there is oxygen supply). The oxygen-rubber reaction depends upon the temperature of the tire and the presence of oxygen.

Initial Tire Nitrogen Purity

The initial nitrogen purity in a tire can be increased by successive inflations and purges of the tire with the inflation gas. This is because the tire, after a bead seating cycle, contains air at one atmosphere. 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. Subsequent inflation and deflation cycles continue this process. Obviously, the amount of the nitrogen inflation gas that is added to the tire at each inflation step depends upon the maximum inflation pressure of the tire. 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 amount of nitrogen that will be added to the tire having 100 units of air will be:

$$\eta_I(R_c - 1) \qquad [1]$$

where η_I is the nitrogen purity of the inflation gas. The total nitrogen in the tire at the end of the inflation-deflation step will be:

$$\eta_A + \eta_I(R_c - 1) \qquad [2]$$

where η_A is the nitrogen purity of air (78.1%). Since the total amount of gas in the tire that initially held 100 units would be $100R_c$, the percentage purity of the nitrogen in the tire after this first inflation step will be given as:

$$\eta_1 = \frac{\eta_A}{R_c} + \eta_I\left(1 - \frac{1}{R_c}\right) \qquad [3]$$

where η_1 is the nitrogen purity after the first inflation step. Continuing the same analysis for the second and subsequent inflation steps yields the following general relation:

$$\eta_N = \frac{\eta_A}{R_c^N} + \eta_I\left(1 - \frac{1}{R_c^N}\right) \qquad [4]$$

where η_N is the nitrogen purity at the end of the Nth inflation step. 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. Equation 4 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. Figure 3 shows the evolution of nitrogen purity with inflation steps for passenger and light truck tires when the inflation gas has 95% nitrogen purity. By the fourth inflation step, all tire types have attained nearly the same purity as the inflation gas. The P-metric standard load tire, as expected, lags the light truck tires, especially on the first and second inflation step. Figure 4 shows the same data for an inflation gas having 98% nitrogen purity. The same type of behavior is noted. Clearly, depending upon the level of initial inflation purity desired, for P-metric Standard Load tires especially, the choice of inflation gas purity is critical to the creation of an effective inflation

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practice. Figure 5, for P-metric standard load tires having a value of compression ratio $R_c = 3.4$, shows very clearly that if an initial nitrogen purity of some value is desired in the tire, then inflation gas purity must be at least that level, and higher purity inflation gas allows the use of fewer inflation-deflation steps. Needing fewer inflation steps means a more economical process in terms of nitrogen consumed and labor used. Figure 6, for Light Truck Load Range E tires having a compression ratio $R_c = 6.4$, shows that the purity evolves much more rapidly by inflation step than for the passenger car tire.

The initial nitrogen purity in the tire is obviously the primary concern of the tire service industry. However, from the standpoint of the consumer, the question becomes one of the stability of the benefits being purchased. If the nitrogen purity established at the initial service degrades over time, then it follows that the benefit in IPLR would also degrade. Also, as NHTSA showed, if an air-inflated tire's nitrogen purity increases with time, then why would the purchase of nitrogen inflation be of significant interest? To explore these issues, one must not only look at the initial nitrogen purity in the tire, but also at the evolution in that purity over time.

Development of a Lifetime Nitrogen Purity Evolution Model

The development of a purity evolution model for a tire presented here generally follows work done by Costemalle [6] on the permeability of tires to air. Costemalle's focus was on the effect of the inner liner material on the overall inflation pressure loss rate. In the present analysis, nitrogen and oxygen will be treated using the same physical relationships, but, as previously mentioned, they are assumed to act independently. Further, the model that is developed here assumes that pressure lost from the tire due to permeation of nitrogen and oxygen is made up by topping off the tire routinely throughout its life. Obviously, the nitrogen purity of the top-off gas also becomes a variable in this analysis.

Since both nitrogen and oxygen behave as ideal gases, they follow the ideal gas law:

$$PV = NRT \qquad \text{[5]}$$

where P is pressure, V is volume, N is the number of moles of gas, R is the ideal gas constant, and T is the absolute temperature for either nitrogen or oxygen. This relationship can be written in differential form as follows:

$$VdP = RTdN \qquad [6]$$

where volume and temperature are considered constants. The permeability relationship, based on Fick's Law and Henry's Law of Solubility for gases passing through a medium such as a tire, can be written:

$$dN = -Q\left(\frac{A}{G}\right)Pdt \qquad [7]$$

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 is the differential pressure across the material, and t is time. Combining Equations 6 and 7 yields:

$$-Q\left(\frac{A}{G}\right)Pdt = \left(\frac{V}{RT}\right)dP \qquad [8]$$

Rearranging Equation 8 and integrating both sides yields:

$$\int_{P_0}^{P(t)} \frac{dP}{P} = -\left(\frac{Q}{G}\right)\left(\frac{A}{V}\right)RT\int_0^t dt \qquad [9]$$

where P_0 is the initial partial pressure of a given gas in the tire, and $P(t)$ is the partial pressure of the gas at time t. The resulting integration yields:

$$ln\left(\frac{P}{P_0}\right) = -\left(\frac{Q}{G}\right)\left(\frac{A}{V}\right)RTt \qquad [10]$$

where the initial time has been assumed to be zero. When the partial pressures are written as absolute pressures, the result is then

$$P(t) - P_A = (P_0 - P_A)e^{-\left(\frac{Q}{G}\right)\left(\frac{A}{V}\right)RTt} \qquad [11]$$

where P_A is the partial pressure of the same gas in the atmosphere. This result is valid for both the nitrogen and the oxygen independently. The decrease or increase in partial pressure of either the oxygen or the nitrogen will be given by $P_0 - P(t)$. Several of the variables in Equation 11 deserve additional discussion.

The term *(A/V)* represents essentially the ratio of the tire liner surface area to the tire's contained air volume. This can be modeled for any conventional radial passenger or light truck tire by taking the maximum grown envelope dimensions given by the governing body (T&RA, ETRTO, etc.), subtracting typical crown, sidewall, and average bead thicknesses from the dimension, and then computing the liner area and tire internal volume by rotating the shapes through 360 degrees. (See Appendix A for a more detailed discussion of this approach.) Alternatively, at least for the tire maker, the liner surface area and the tire internal volume are likely known based on the design data. Both of these methods likely ignore the air volume of the wheel drop center, which is, in fact, part of the internal volume of gas. As would be expected, smaller higher aspect ratio tires have smaller *(A/V)* ratios than larger lower aspect ratio tires.

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. However, since this work is not especially concerned with the composition of inner liners, it will suffice to consider the tire as a single layer of a given rubber material. Units of Q are normally given in barrers, where one barrer unit is:

$$1 \; barrer = 10^{-10} \left(\frac{cm \times cm^3}{s \times cm^2 \times cmHg} \right) \tag{12}$$

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. These values have been used in this analysis. There appear to be few values of permeability of oxygen and nitrogen separately available for specific types of rubber in the open literature, as most of the permeation work has been done for air. Some limited data [9] shows that natural rubber has a permeability of about

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23 barrer to oxygen and about 8 barrer to nitrogen, while butyl rubber has a permeability of about 1.3 barrer to oxygen and about 0.3 barrer to nitrogen (these values at 25C). Obviously, given permeability coefficients for nitrogen and oxygen independently for various types of rubber mixes, a more elaborate model could be built for the tire following the method outlined by Costemalle. Another obvious complexity is that permeability coefficients are functions of temperature as well. Limited data presented by Dalpe [10] 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 generally increase by about a factor of three. This explains why dynamic testing shows higher inflation pressure loss rates than static testing. 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.

The term $P(t)$ yields the partial pressure for either nitrogen or oxygen in the tire at the end of the time period t. The change in partial pressure for either the oxygen or the nitrogen will be $P_0 - P(t)$. The sum of the change in partial pressures of nitrogen and oxygen in each time step analyzed represents the overall pressure loss in the tire (recall that Equation 11 requires an evaluation over some time period t). Therefore, for the purpose of a long term model of the tire, there must be some top-off gas added to replace this pressure loss. 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 term 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:

$$M_{O2} = \frac{(P_0 - P(t))V}{RT} \qquad [13]$$

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where M_{O2} is the mass of oxygen corresponding to the drop (or increase) in partial pressure of oxygen during the tire period t. 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 the 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. The present analysis will focus on the contribution of nitrogen inflation in reducing the oxygen flow across the tire over its lifetime.

Lifetime 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. Then, Equation 11 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 13 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 Standard Load tire was chosen as the tire size for analysis. Such a tire would have a maximum inflation pressure of 240 kPa (35 psi). In addition, the *(A/V)* ratio for this size tire was estimated to be 0.165 cm^{-1}, and the tire's internal volume was estimated at 51.6 liters, ignoring the gas volume of the drop center in the wheel. Including the drop center volume would reduce the *(A/V)* ratio slightly, which would produce slightly lower pressure drops. Since the purpose of this

analysis was to show trends in gas purity, it was felt that this was an acceptable simplification to make in light of the assumption of the tire as a single material. The gauge for the tire's sidewall was taken as 6 mm, following Costemalle's recommendation that the sidewall gauge gave the best representation of the inflation pressure loss rate.

Air Inflation with Air Top-off

For a tire that is initially inflated with air, and then topped off monthly with air, Figure 7 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 IPLR, which starts out at 2.61%, evolves to a lower value (in this case, 2.08%) over the simulated lifetime of the tire. Figure 8 shows the gas purity evolution for both nitrogen and oxygen in the tire during the same time. The nitrogen purity in the tire increases from 78.1% to about 87.6%. Recall that NHTSA observed this trend in empirical testing. The initial partial pressure losses in Figure 7 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 9 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. Note that since the oxygen flow in the first half of the tire life is much higher than later, air-inflated tires are likely to be negatively impacted by operations that require dismounting and remounting (i.e., puncture repair, resale as a used tire, etc.) since this oxygen flow process restarts each time this occurs.

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

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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 10 shows the partial pressure change for a P235/75R15 Standard Load tire having an initial nitrogen purity of 93%. It can be seen that the initial pressure loss for nitrogen and oxygen are very different, reflecting the initial tire nitrogen purity. The initial IPLR for this case is 1.78%, a reduction of 31.8% over the tire with an initial air inflation. 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 93% initial nitrogen purity and monthly air top-off is 2.05%, which is nearly what the air-inflated tire has at that point. Note that the oxygen loss curve, instead of having a downward trend as for the air-inflated tire, has an upward trend. This reflects the fact that 93% initial tire nitrogen purity results in an oxygen purity nearly that required for equilibrium of the partial pressure of the oxygen inside and outside the tire. However, it is clear that this equilibrium cannot be maintained in this case. As air is added to top off the tire, the oxygen permeation through the tire rises. 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.

Figure 11 shows the partial pressure loss for a P235/75R15 Standard Load tire having an initial nitrogen purity of 96%. The characteristics of this set of curves are similar to those shown in Figure 9. However, the oxygen curve clearly shows that, at the beginning of the tire's life, oxygen flows into the tire from the outside. After some months, the partial pressure of the oxygen inside the tire becomes larger than the partial pressure of the oxygen outside the tire, and oxygen begins to permeate out of the tire. The initial IPLR for this case was 1.61%, which was a reduction over the 93% initial purity case. The IPLR at the end of the simulated life was 2.05%, again only marginally different from the air-inflation case. The total oxygen flow across the tire in this case was estimated to be 34,127 mg, a small reduction over the 93% initial purity case (and 57% better than the air-inflated tire).

Further increase in the tire initial nitrogen purity in passenger car tires leads to decreasing returns (benefits), as will be shown in the summary section. However, the use of nitrogen as an inflation

gas results in a substantial reduction in the total oxygen that flows across the tire material during its lifetime. When considered in comparison to the use of a higher quality or thicker inner liner that reduces the IPLR by a factor of two, the reduction in lifetime oxygen flow would be about the same. 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 likely 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 with increasing initial nitrogen purity. This suggests that significant additional improvements could be obtained by adopting other nitrogen strategies. For example, adopting the recommendation that the nitrogen fill process be redone every two to three years would reset the initial IPLR to the original value and have the additional benefit of an even more significant reduction in lifetime oxygen flow across the tire. Figure 12 shows a comparison of oxygen flow across the tire for three cases all being topped off monthly with air: the air-inflated tire, the tire with a 93% initial nitrogen purity, and the tire with a 93% initial purity where the nitrogen inflation is renewed every two years. The nitrogen renew cycles in this simulation were assumed to be a single inflation step using 98% purity inflation gas. Note that the renew process is a single step reinflation, since the nitrogen purity of the tire even after two years is such that the resulting nitrogen purity after reinflation will be above the oxygen equilibrium point. Clearly, this approach resets the initial nitrogen inflation and produces a lower lifetime oxygen flow than nitrogen inflation without any renewal.

Figure 13 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 11. 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 initial nitrogen purity, 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. In fact, the IPLR at any time is linear with the nitrogen purity at that point in time, so Figure 13 applies at any level of nitrogen purity. As was shown, the nitrogen and oxygen purities in the tire evolve over the simulated lifetime of the tire, and consequently so does the IPLR. In the case where the top-off gas is air, the IPLR at the end of the tire life is not significantly different from an air-inflated tire at initial nitrogen purities being offered by the tire service industry.

Another approach to nitrogen inflation would require that nitrogen providers also provide top-off services over the life of the tires. While this is not generally done in the industry today, it could be implemented at some additional cost to nitrogen providers. The question is really whether or not there is a significant benefit from nitrogen top-off. In this case, there are two variables; the initial purity of the nitrogen in the tire and the nitrogen purity of the top-off gas being used.

Figure 14 shows the results of a simulation made assuming that the tire's initial nitrogen purity was 93%, and the top-off gas had a nitrogen purity of 95%. This initial nitrogen purity corresponds to using a nitrogen supply of 95% purity to inflate a passenger car standard load tire in two steps, as was shown on Figure 5. This case, then, corresponds to what would occur if a nitrogen provider was using a nitrogen supply of 95% purity and provided monthly top-off service. In Figure 14, it can be seen that both the nitrogen permeation and the oxygen permeation are relatively constant, in stark contrast to the strong evolution of those quantities when the tire was topped off monthly with air. The initial IPLR was 1.25% and the final IPLR was 1.28%, demonstrating that the reduction over air inflation alone was maintained over the simulated life of the tire. The total oxygen flow across the tire was estimated to be 9,202 mg, a significant reduction over the nitrogen inflation, air top-off cases discussed above, and an even more significant reduction (88%) over the standard air management.

Figure 15 shows the results of a simulation made assuming that the tire's initial nitrogen purity was 96%, and the top-off gas had a nitrogen purity of 98%. This initial nitrogen purity corresponds to using a nitrogen supply of 98% purity to inflate a passenger car standard load tire in two steps, as was shown on Figure 5. This case, then, corresponds to what would occur if a nitrogen provider was using a nitrogen supply of 98% purity and provided monthly top-off service. Figure 15 shows that the oxygen permeation is directed into the tire over about half the simulation life. The nitrogen purity in the tire approaches 93%, so the oxygen permeation in the second half of the tire's life is extremely small. The initial IPLR is 1.14%, while the final IPLR is 1.25%, consistent with a slight increase over the simulated life of the tire. The estimated oxygen flow across the tire over the simulated life is 5,245 mg, a 93% reduction over the air-inflated case.

Figure 16 shows the results of a simulation made assuming that the tire's initial nitrogen purity was 93%, and the top-off gas had a nitrogen purity of 100%. This initial nitrogen purity corresponds to using a nitrogen supply of 100% purity to inflate a passenger car standard load tire in one step, as was shown in Figure 5. This case, then, corresponds to what would occur if a nitrogen provider was using a tank nitrogen supply and provided monthly top-off service. Figure 16 shows that the oxygen permeation is nearly zero over the simulation life. The nitrogen purity in the tire began and stayed very close to 93.5% at which the equilibrium partial pressure of oxygen was maintained. The initial IPLR is 1.25%, while the final IPLR is 1.23%, consistent with a slight decrease over the simulated life of the tire. The estimated oxygen flow across the tire over the simulated life is only 1,190 mg, a 98% reduction over the air-inflated case.

Figure 17 shows a combined view of oxygen flow by month for each of the simulation cases described above. It is obvious from this graph that initial nitrogen inflation has a dramatic effect on the oxygen flow in the first month. The evolution of the oxygen flow is clearly driven by the top-off gas purity. In the case of a tire filled initially with some purity of nitrogen and then topped off regularly with air, the oxygen permeation rate evolves over time toward the same value as for the air-inflated tire. Note that if the tire has an initial partial pressure of oxygen that is less than that of the atmosphere, then oxygen flows into the tire, and the total monthly oxygen curve goes to zero and then back up, reflecting the increase of the oxygen partial pressure over time inside the tire. The benefit in the reduction of the total oxygen flow across the tire is attained largely in the first half of the tire's life. Tires that are inflated with nitrogen and then subsequently topped off with nitrogen tend to maintain a substantially lower level of oxygen flow across the tire over their entire life as compared to tires inflated initially with nitrogen and then topped off routinely with air.

Figure 18 shows a comparison of total oxygen flow across the tire over a six-year simulated lifetime. In this chart, the initial tire nitrogen purity is shown on the horizontal axis, and the lifetime total oxygen is shown on the vertical axis. The curve describing nitrogen-inflated tires topped off with air is clearly and dramatically separate from the curves describing nitrogen-inflated tires topped off with various nitrogen gas purities. Of particular note is the inflection point found in the curves. This suggests that initial tire nitrogen purities greater than 92%-95% serve no useful purpose except decreasing the IPLR to its maximum extent for the first few months of the tire's

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lifetime. This is consistent with the finding that initial IPLR was directly related to the initial tire nitrogen purity.

Figure 19 shows a comparison of IPLR over time for several of the cases discussed above. The case of the air-inflated tire shows the decreasing IPLR that results from the increasing purity of nitrogen that occurs naturally due to the differing permeability of the tire rubber to nitrogen and oxygen. The case of a tire inflated initially to 93% nitrogen purity and topped off with air shows that the IPLR at the end of the tire's life approaches that of the air-inflated tire. The case of a tire initially inflated to 93% nitrogen purity and topped off monthly with 98% nitrogen (corresponding to a single step inflation with 98% purity inflation gas) shows that the IPLR starts out low and gradually drifts lower over the lifetime of the tire. The last case shown, that of the tire initially inflated to 93% nitrogen purity and topped off monthly with air, and then reinflated with 98% nitrogen purity inflation gas every two years, shows the effect of the reinflation process discussed above. Clearly, both the routine top-off with nitrogen and periodic reinflation with nitrogen help provide the necessary maintenance to preserve the IPLR benefit being purchased by the consumer, although periodic reinflation with nitrogen is slightly less effective than routine top-off.

From Figures 1 and 2, it would be expected that tires having a higher maximum inflation pressure would be described by the same type of curves, but that the inflection point would be at a higher value of initial nitrogen purity. Figure 20 shows the results of a set of simulations for a LT245/75R16 Load Range E light truck tire. For this tire, the value of *(A/V)* was estimated to be 0.168 cm^{-1}, the internal volume was estimated to be 55.5 liters, and the sidewall thickness was set at 10 mm. First, it is interesting that the benefit of nitrogen inflation with air top-off in terms of reduction in oxygen flow is larger than that found in the case of the standard load passenger tire. Assuming an initial inflation purity of 97%, corresponding to a 98% purity source and two inflation steps, the total oxygen flow is reduced from 138,287 mg to 44,964 mg, a reduction of about 67% compared to the air-inflated tire. Note that the inflection points of the nitrogen top-off curves have moved, as expected, to a higher range of initial nitrogen purity, consistent with the higher equilibrium oxygen partial pressure found in a Load Range E tire (as shown on Figures 1 and 2).

Tables 1 and 2 present the results discussed above in a slightly different format. Table 1 presents the results of several simulations for the P235/75R15 Standard Load tire. The results can be lumped into three distinct categories:

1. The tire inflated with air and topped off with air has a slight reduction of IPLR over its life, corresponding to an increase in the purity of the nitrogen in the tire with time. The total oxygen that passes across the tire is estimated at about 79,000 mg.

2. The tire inflated with various purities of nitrogen and topped off routinely with air shows a reduction in IPLR with initial tire purity (from 66% to 69% as nitrogen purity increases from 93% to 96%), in accord with the previous discussions. The oxygen flowing across the tire due to permeation has been significantly reduced by 50% to 57% over the air-inflated tire. Again the difference between the 93% and 96% initial nitrogen purity is not large. And, as predicted, the IPLR increases as the tire ages.

3. The tire inflated with various purities of nitrogen and topped off with nitrogen of some purity shows another large reduction in oxygen flow across the tire (from 88% to 98% better than the air-inflated tire) and another step change in reduction in IPLR. Again, the initial tire purity does not seem to have a large effect on the outcome, but the IPLR does remain essentially constant over time.

A review of Table 2, which presents the results for several Load Range E light truck tire simulations, shows the same trends. These categories make more sense when considering that the simulations discussed here represent a simplified view. In particular, field work would include many tire sizes and types, as well as top-off intervals and gas purities that would be variable. The differences in IPLR between the air-inflated case and any of the nitrogen inflated cases would likely be difficult for the average driver to appreciate, given the difficulty the average driver has in performing routine tire pressure maintenance. The small differences in oxygen flow likely explain why experiments into the influence of nitrogen inflation do not detect differences in durability above about the 93% level of initial nitrogen purity.

Oxygen flow has been used in this analysis as a comparative value, or metric, to show differences among the various nitrogen inflation strategies available in the tire service industry. A significant number of studies have linked air permeation to tire durability, and significant care is taken in the

development of modern radial tire inner liners to reduce the overall tire permeability. Operations requiring dismount and remount of the tire, such as puncture repair, are likely to negatively impact the tire's long-term durability for an air-inflated tire, since the oxygen permeation is significantly higher just after inflation. Significantly, nitrogen inflation, even with air top-off, significantly reduces the lifetime exposure of the tire to oxygen.

Relation to Aging Studies

Much of the previous work involving nitrogen 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 [8]. The rate of the oxidation reaction of the tire's rubber hydrocarbon was described in terms of the standard Arhennius relationship:

$$K = Be^{-\left(\frac{E}{RT}\right)} \hspace{3cm} [14]$$

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, that the value of the activation energy, E, was about 42 J/g-mole. Given a situation where a rubber sample is exposed to a certain temperature T_l for a time t_l in the laboratory, it can be shown that the same material exposed to a field service temperature, T_f, would be expected to undergo the same total reaction in a time, t_f, given by:

$$t_f = t_l e^{\left[\frac{E}{R}\left(\frac{1}{T_f}-\frac{1}{T_l}\right)\right]} \hspace{3cm} [15]$$

If Equation 15 is evaluated using a laboratory (rapid aging) condition of 60C, and 25C is used as a field condition, it is easily shown that the rate of the oxidative reaction at 60C is about six times the rate at 25C. 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. [11] gives the activation energies for permeation through natural rubber as about 37.8 J/g-mole for nitrogen and about 28.8 J/g-mole for oxygen. 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. Using the values presented for nitrogen and oxygen, along with Equation 15, allows the prediction of permeation coefficients for nitrogen and oxygen at various temperatures. The model presented above was used to predict the oxygen flow across the tires involved in the aging studies previously discussed.

The work of Baldwin, et al., involved inflating LT245/75R16 Load Range D tires with initial nitrogen purities of 56%, 78% (air), 96% and 99.9%, and then subjecting them to accelerated aging at 60C for periods of 3, 6, 9, and 12 weeks. Samples of the wedge material from the aged tires were compared to un-aged tires. The results showed that the tires that were inflated with 56% nitrogen and air had a substantial change in the normalized strain ratio at break after only three weeks, and this trend continued to develop over the 12-week period. The tires filled with 96% and 99.9% initial nitrogen purity showed essentially no change in the normalized strain ratio. Table 3 shows the result of a simulation using the previously-described methodology for the various cases in the Baldwin study. Note that there is a significant difference in oxygen flow over these short oven periods between the low nitrogen inflation cases (56% nitrogen and air) and the high nitrogen purity cases. While a LRD tire of this size inflated with air would experience about 112,000 mg of oxygen flow over a six-year life, the tire inflated with 56% purity nitrogen would be expected to experience 44,885 mg, and the tire inflated with air would experience 20,062 mg in the twelve-week aging process. Oxygen flows with nitrogen purities of 96% and 99.9% were significantly lower, as expected. Significantly, 96% nitrogen purity results in significantly lower oxygen flows than 99.9% nitrogen purity due to the permeation of oxygen from the outside of the tire in the high purity case.

Karmarker's studies also involved the belt skim material. The tires in this study were LT245/75R16 Load Range E tires such as those discussed in the previous section. These tires were inflated to initial nitrogen purities of 78.1% (using air alone), 89%, and 99%. The tires inflated to 78.1% and 99% initial nitrogen purity were aged at 50C and 70C for 1 week and 4 weeks. The tires inflated to an initial nitrogen purity of 89% were aged at 60C for 4 weeks, thereby completing a "box" style experimental design. The paper indicated that tires were "routinely" purged and re-inflated to keep the partial pressure of the oxygen within 5% of the target value. Tires were then run on an endurance wheel test, and examined shearographically at 10, 22, 34, 38, and 42 hours. In

this study, shearography areas recorded for belt edge separations developed much more quickly for the tires aged at 70C in air than for the other test cases. Table 4 shows simulation results of oxygen flow for the test cases in Karmarker's study. As expected, the air-inflated cases show significantly more oxygen flow than did the cases having higher nitrogen purity, although the total oxygen flows attained were seen to be very low compared to the 138,000 mg predicted over a six-year life.

The NHTSA study involved a number of different passenger and light truck tires. NHTSA measured IPLRs across this range of tires and experimentally determined that the IPLR for nitrogen tire inflation was about 66% of that for an air-inflated tire on average. This is in the range of the results shown in Tables 1 and 2, given that NHTSA studied initial tire nitrogen purities of 94% to 99% and covered a number of different tire types and sizes. NHTSA also subjected tires with initial nitrogen purities of 50%, 78.1% (using air alone), and 94-99% to oven aging at 65C for 5 weeks followed by FMVSS 139 endurance testing. It was observed that some tires having initial nitrogen purities of 50% did not complete the endurance test of 35.5 hours. Table 5 shows the result of the simulation of oxygen flow for the conditions considered by NHTSA for the LT245/75R16 Load Range E light truck tire assuming that the initial nitrogen inflation purity was 95% for the "nitrogen" case. Note that the oxygen flow through the tire inflated with an initial nitrogen purity of 50% was about 2.5 times greater than for the tire with air inflation. Some of the tires in NHTSA's study group failed FMVSS testing when aged at the 50% nitrogen purity level.

Discussion

It is clear that nitrogen inflation, either as an initial tire treatment or together with an on-going maintenance approach, can significantly reduce the amount of oxygen that flows through a tire during the course of its life. The studies cited above showed that increased oxygen levels in the tire's inflation gas can increase the oxidation of the rubber materials in the tire and thereby reduce its durability even on some short-term testing. It is, however, far from clear exactly what threshold of oxygen flow corresponds to that required to cause a breakdown in the tire's durability. Indeed, this likely depends upon the design and manufacture of the tire, as was shown in NHTSA's data where some tires tested at 50% nitrogen purity did not complete the FMVSS endurance test while others did.

From the current study, initial tire nitrogen purities vary widely depending upon the tire maximum inflation pressure, the nitrogen purity of the inflation gas, and the number of inflation steps used at a particular facility. It is also clear that initial inflation with nitrogen with air top-off imparts a significant reduction in lifetime oxygen flow, with most of the benefit occurring in the early years of a tire's service lifetime. Table 6 shows a comparison of the simulated six-year oxygen flow across the tire at various inflation gas purities and inflation steps for both Passenger Car and Light Truck LRE tires. The differences between the inflation gas nitrogen purity of 95% and one inflation step and a nitrogen purity of 100% and two inflation steps appear to be small considering this simulation covers only two distinct sizes and a fixed six-year life with regular top-off intervals. It is very likely that, in practice, the differences among all these conditions would be less distinct. This means that the nitrogen purity of the inflation gas and the number of inflation steps likely become less significant, i.e., single-step inflation with nitrogen may be just as effective and more cost efficient than two-step inflation, given the wide variation of tire sizes and tire maintenance strategies found in the field. In any event, the reduction in oxygen flow across the tire due to nitrogen inflation, even with air top-off maintenance, is on the order of 50%. This is equivalent to building a tire with an inner liner that reduces the IPLR by a factor of two, all other conditions being equal. The data also suggest that for tires with nitrogen inflation and air top-off that remain in service for extended periods of time beyond six years, the percentage benefit in oxygen flow reduction over the service lifetime would be reduced from the results presented here because the tire's inflation gas will evolve more completely toward that of an air-inflated, air topped-off tire.

For tires that are inflated with nitrogen and topped off with nitrogen, the oxygen flow through the tire tends to be driven from the outside toward the inside, at least initially, and will remain significantly lower on a monthly basis throughout the tire's service life. This has the potential to generate another significant reduction in oxygen flow over both the air-inflated tire and the nitrogen-inflated tire topped off with air. However, the burden of providing this top-off service along with nitrogen inflation would fall directly on the tire service industry and would require a significant increase in the availability of nitrogen inflation gas outlets. As mentioned previously, a perhaps more palatable approach would be to redo the nitrogen inflation every two to three years, given that the significant benefits in the initial nitrogen inflation will have become significantly degraded at that point. This would provide a more stable IPLR for the customer, an additional

significant reduction in lifetime oxygen flow across the tire, and a more stable income stream for the nitrogen service industry. In any event, this study clearly shows that IPLR cannot be maintained at low levels without some form of nitrogen purity maintenance.

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 nitrogen is over three times higher than oxygen. This means that the initial permeation of gas out of an air-filled tire is almost half nitrogen and half oxygen. This also results in an evolution of the nitrogen purity in the tire over its service life.

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. For an air-inflated tire, the oxygen flow across the tire decreases over the life of the tire. This means that tires that are dismounted and remounted have significantly more oxygen exposure than those that are not so treated. Therefore, puncture repairs and used tire sales likely adversely affect tire long-term durability.

5. Initial inflation of a tire with nitrogen at some purity level results in an initial reduction in inflation pressure loss rate. 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. Since the nitrogen purity of a tire evolves over time, IPLR improvements are transient if the tire is topped off with air rather than nitrogen.

6. Initial inflation of a tire with nitrogen at some purity 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 compared to 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 will reduce the percentage reduction in oxygen flow.

7. Initial inflation of a tire with nitrogen at some purity and topping it off with nitrogen results in another significant reduction in the amount of oxygen that flows across the tire during its lifetime. A similar improvement could be obtained by repeating the nitrogen inflation process every two to three years, given that the bulk of the benefits accrue in the early years of the tire's lifetime.

8. The reduction in oxygen flow across the tire using nitrogen inflation is likely to be substantially the same in the field across large populations of tires 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. This suggests that the nitrogen service industry could settle on a more efficient and economical initial inflation process coupled with a maintenance program including nitrogen.

9. The oxidation reaction rate in oven-aged tires appears to increase more rapidly with temperature than does the rate of oxygen permeation through the tire. This fact likely contributes to the change from aerobic to anaerobic reaction kinetics as oven aging temperature is increased.

Appendix A

Estimation of (A/V) ratio for a Passenger or Light Truck tire

The approach used for estimating the ratio *(A/V)* for a passenger or light truck tire will be illustrated using the passenger car tire data. This approach is based upon the definition of the maximum envelope dimensions for the grown tire, as given in the Tire & Rim Association (T&RA) Yearbook, and shown on Figure A-1. In this definition, every dimension of the outside profile of the tire is given in terms of the rim diameter, the maximum section height, and the maximum overall width. In order to estimate the tire's internal volume and its internal surface area, it is necessary to generate an approximation of the tire's internal profile. Figure A-1 also shows the construction of four straight lines internal to half the T&RA envelope that can be used to make such an estimation. Vertical Line 1 is drawn parallel to the sidewall, inset from the outer sidewall line by the sidewall thickness, G_s, and extending from H_1 to H_2 on the figure. Horizontal Line 2 is drawn inset from the crown curve by the crown thickness, G_c, at the tire centerline. Line 3 is drawn from the upper end of Line 1 and offset from the shoulder line by the sidewall thickness. Line 4 is drawn from the lower end of Line 1 to intersect with the base line a distance inside the rim flange equal to the average bead thickness, G_b. Using this straight-line approximation, the half internal volume of the tire will be given by the sum of the two trapezoidal and one rectangular areas swept through 360 degrees using the radius to the appropriate centroid of each area. The half liner area will be the length of lines 1 through 4 each swept through 360 degrees using the radius to the appropriate centroid of the line. This approach, based on simple geometry, can easily be implemented on a spreadsheet for calculation purposes. Generally, passenger car section thicknesses are relatively consistent. For example, the approach outlined above was used to compute the *(A/V)* ratio for eleven different tire sizes where this value had been experimentally measured and reported by Costemalle. The same values of the three thickness results were used for all tires: G_c = 15 mm, G_s = 6 mm, and G_b = 10 mm. The comparison between the experimentally determined values and the approximations obtained from the above approach are shown in Figure A-2. A similar approach can be used for light truck tires using the maximum grown envelope model for that tire type found in the T&RA Yearbook. Again, section thicknesses

will be relatively consistent among light truck tires except for variations in tread depths for off-road and highway uses.

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TABLE 1 - *Monthly Average IPLR and 6-year O2 Flow Across tire: P235/75R15 SL.*

Year	Inflation N2 Purity/Top-off Gas N2 Purity						
	Air/Air	93%/Air	93%/95%	93%/100%	96%/Air	96%/98%	96%/100%
1	2.50%	1.80%	1.80%	1.80%	1.70%	1.70%	1.60%
2	2.30%	1.90%	1.80%	1.80%	1.90%	1.70%	1.70%
3	2.20%	2.00%	1.80%	1.80%	2.00%	1.70%	1.70%
4	2.10%	2.00%	1.80%	1.80%	2.00%	1.80%	1.70%
5	2.10%	2.00%	1.80%	1.80%	2.00%	1.80%	1.70%
6	2.10%	2.10%	1.80%	1.80%	2.00%	1.80%	1.70%
Average IPLR (%)	2.22%	1.98%	1.80%	1.76%	1.94%	1.73%	1.72%
IPLR Reduction		10.8%	18.9%	20.7%	12.6%	22.1%	22.5%
Total mg O2	78,881	39,466	9,202	1,190	34,127	5,245	5,641
Total O2 Reduction		50.0%	88.3%	98.5%	56.7%	93.4%	92.8%

TABLE 2 – *Monthly Average IPLR and 6-year O2 Flow Across tire: LT245/75R16 LRE.*

Year	Inflation N2 Purity/Top-off Gas N2 Purity						
	Air/Air	94%/Air	94%/95%	94%/100%	97%/Air	97%/98%	96%/100%
1	1.60%	1.20%	1.10%	1.10%	1.10%	1.10%	1.10%
2	1.50%	1.20%	1.10%	1.10%	1.10%	1.10%	1.10%
3	1.40%	1.20%	1.10%	1.10%	1.20%	1.10%	1.10%
4	1.40%	1.20%	1.10%	1.10%	1.20%	1.10%	1.10%
5	1.30%	1.20%	1.10%	1.10%	1.20%	1.10%	1.10%
6	1.30%	1.20%	1.10%	1.10%	1.20%	1.10%	1.10%
Average IPLR (%)	1.41%	1.22%	1.12%	1.10%	1.18%	1.08%	1.08%
IPLR Reduction		13.5%	20.6%	22.0%	16.3%	23.4%	23.4%
Total mg O2	138,287	59,613	21,673	11,372	44,964	3,216	2,626
Total O2 Reduction		56.9%	84.3%	91.8%	67.5%	97.7%	98.1%

TABLE 3 – *Total Oxygen Flows (mg) for Rapid Aging Cases Discussed by Baldwin.*

N2 Purity	Aging Time (weeks)			
	3	6	9	12
56.0%	12886	24592	35226	44885
78.1%	5760	10992	15745	20062
96.0%	13	24	35	44
99.9%	1270	2424	3473	4425
Note: Temp = 60C				

TABLE 4 – *Total Oxygen Flows (mg) for Rapid Aging Cases Discussed by Karmarker.*

N2 Purity	Temp	Aging Time (weeks)		
		1	4	7
78.1%	50C	1730	6699	11352
99.0%	50C	224	869	1472
89.0%	60C	1002	3822	6385
78.1%	70C	3279	12283	20159
99.0%	70C	425	1593	2614

TABLE 5 – *Total Oxygen Flows (mg) for Rapid Aging Cases Discussed by NHTSA.*

N2 Purity	O2 (mg)
50.0%	32664
78.1%	12968
95.0%	1122
Temp = 65C, Time = 5 weeks	

TABLE 6 – *Comparison of Oxygen Flow Reduction for Nitrogen Inflation at Various Purities and Number of Inflation Steps with Air Top-Off to Air-Inflation.*

Passenger	Inflation Gas Nitrogen Purity		
Steps	95	98	100
1	40%	47%	52%
2	52%	57%	58%
LT LRE	Inflation Gas Nitrogen Purity		
Steps	95	98	100
1	51%	60%	66%
2	59%	69%	72%

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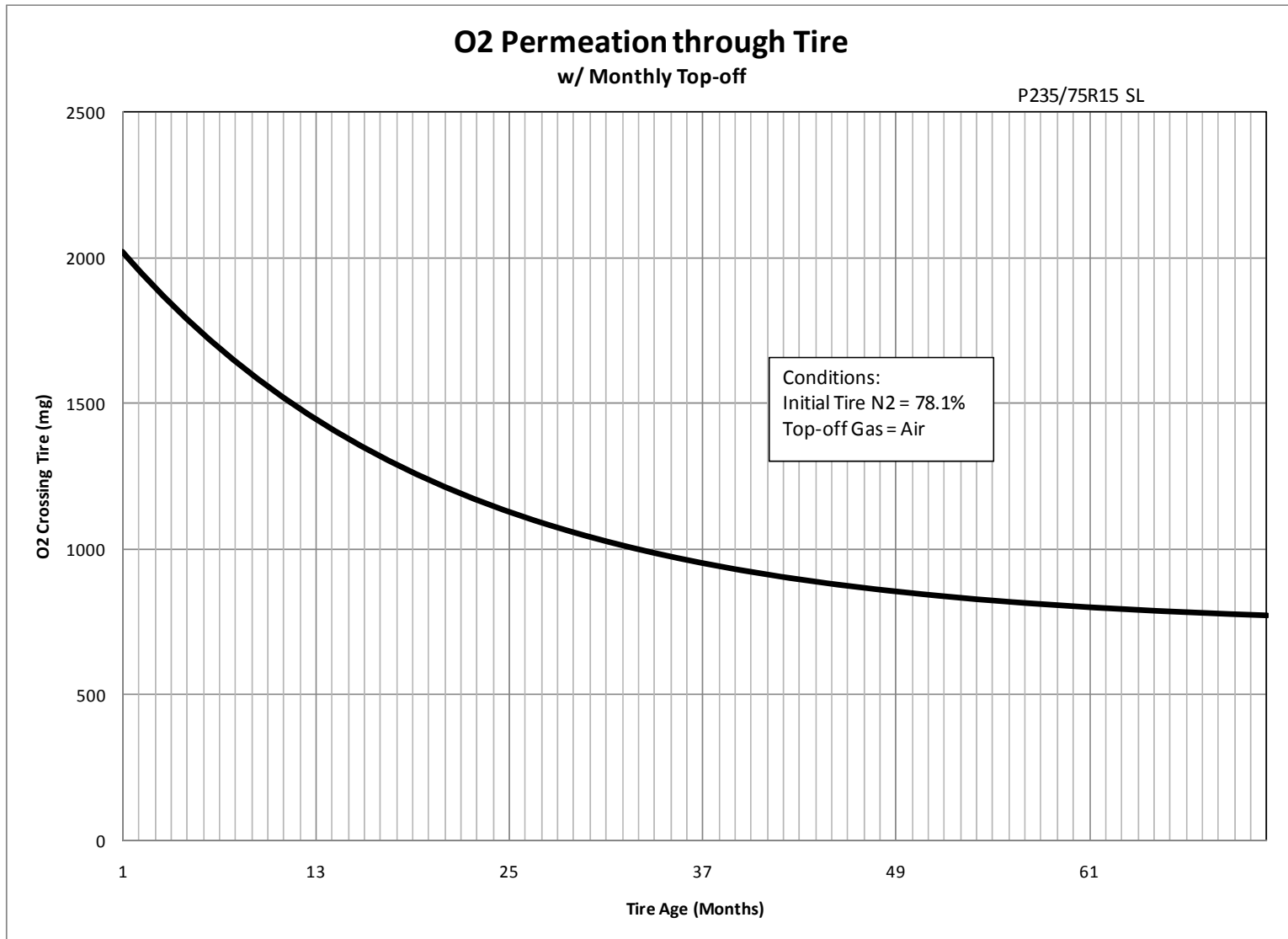
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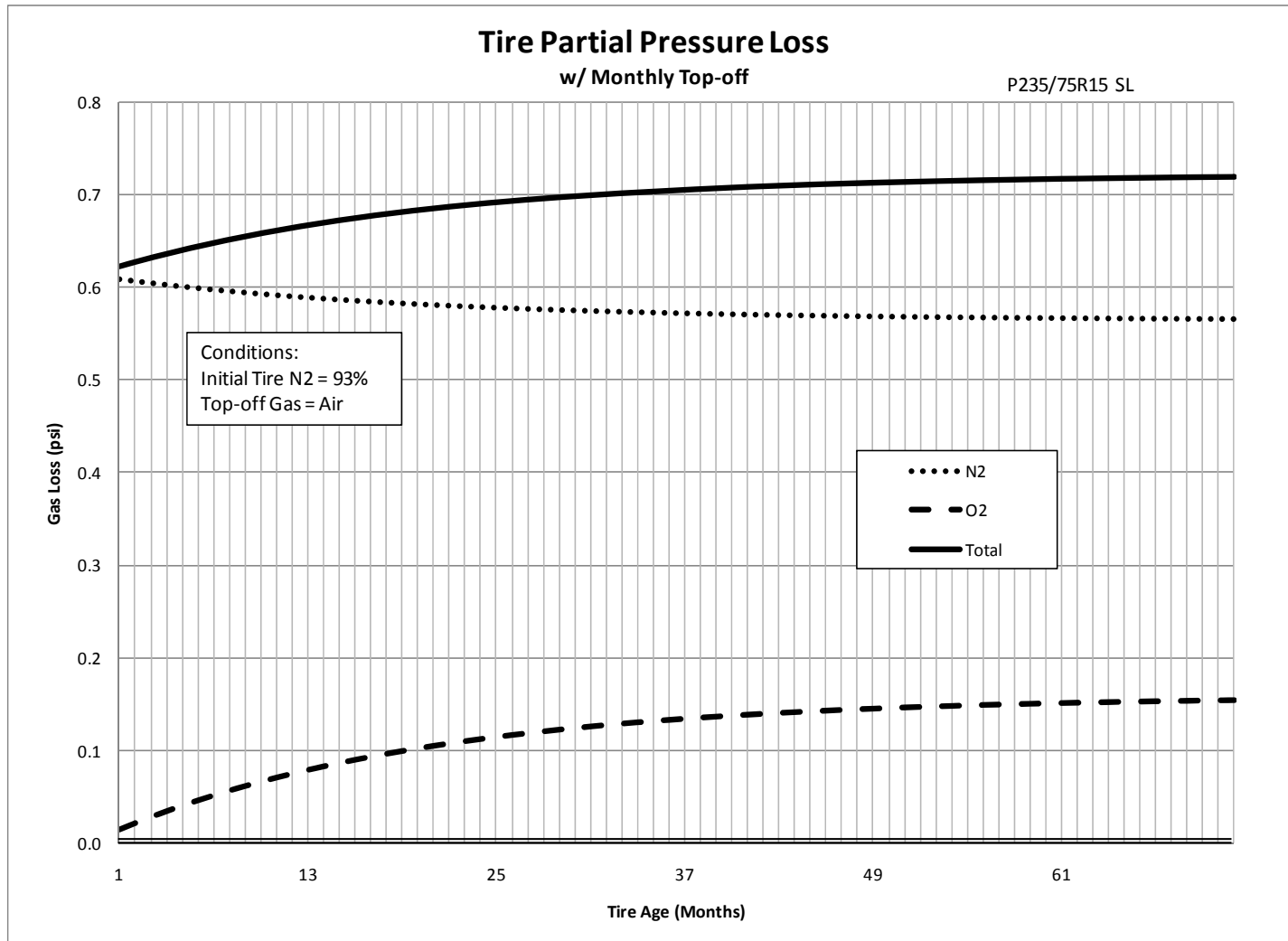
FIGURE 10. *Partial Pressure Evolution over Service Life for P235/75R15 SL Tire Inflated with 93% Nitrogen and Topped Off With Air.*
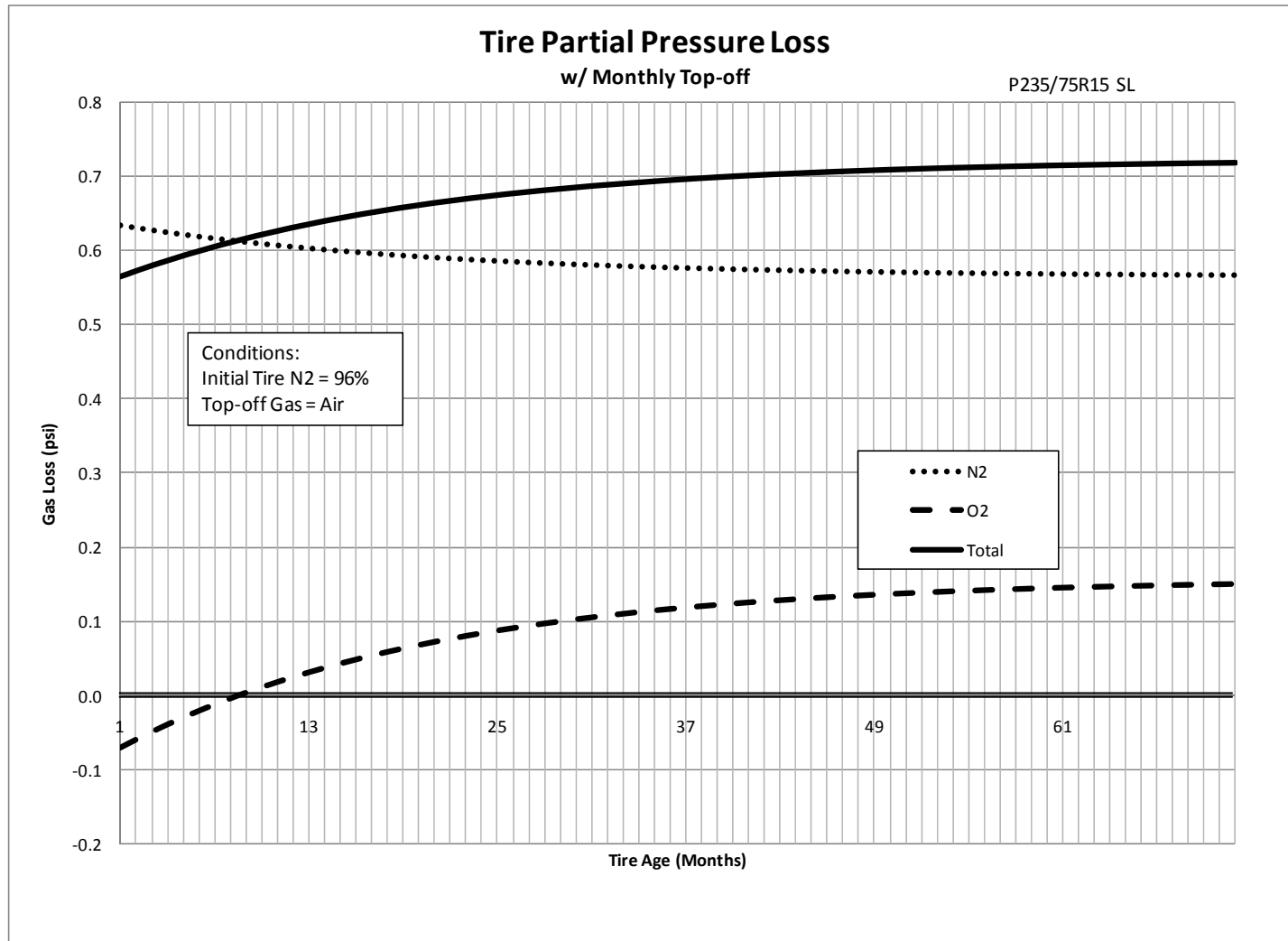
FIGURE 11. *Partial Pressure Evolution over Service Life for P235/75R15 SL Tire Inflated with 96% Nitrogen and Topped Off With Air.*
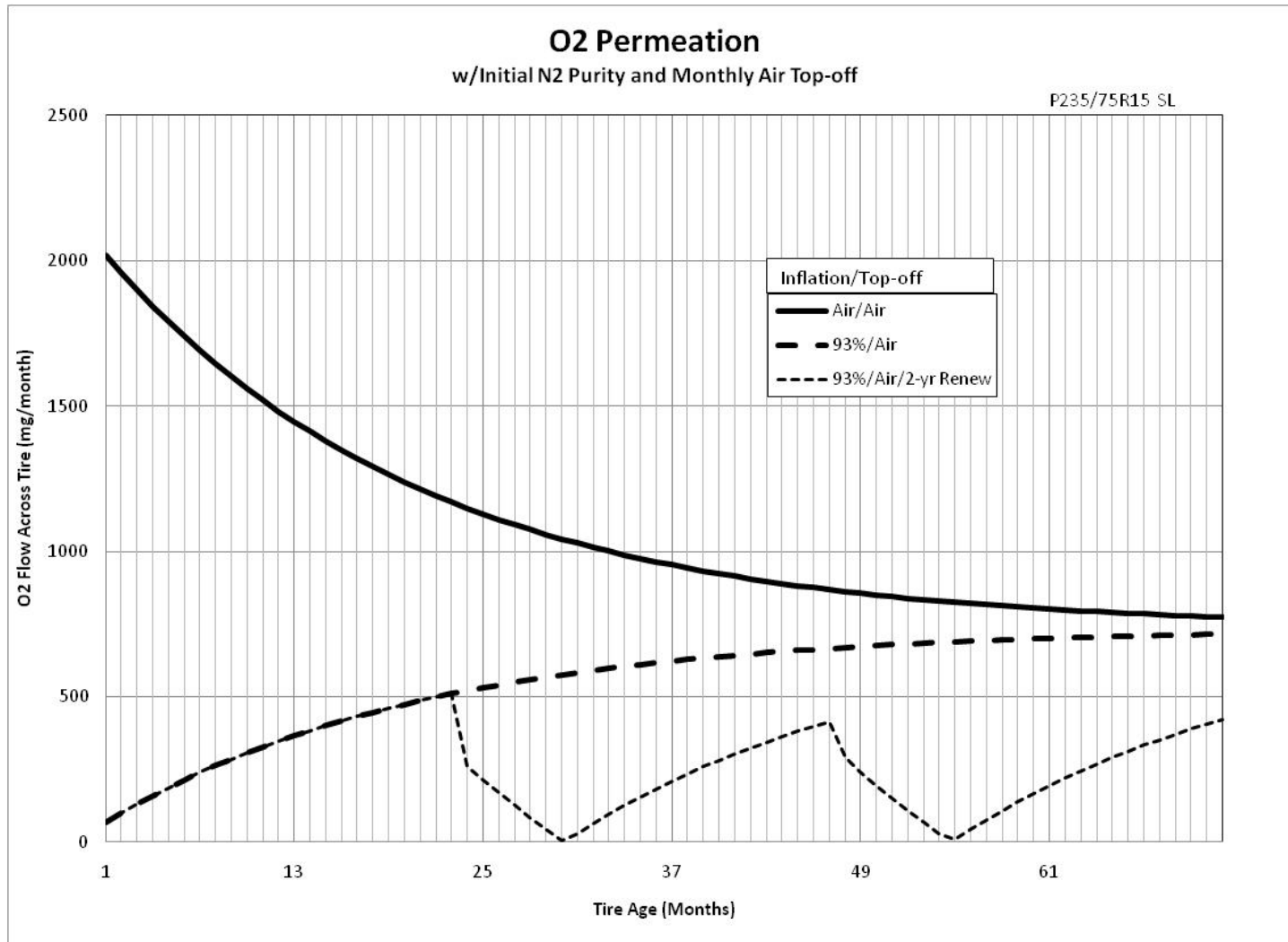
FIGURE 12. *Comparison of Oxygen Permeation in P235/75R15 SL over Tire Lifetime Showing the Benefit of Nitrogen Inflation and Maintenance of Tire Nitrogen Purity.*
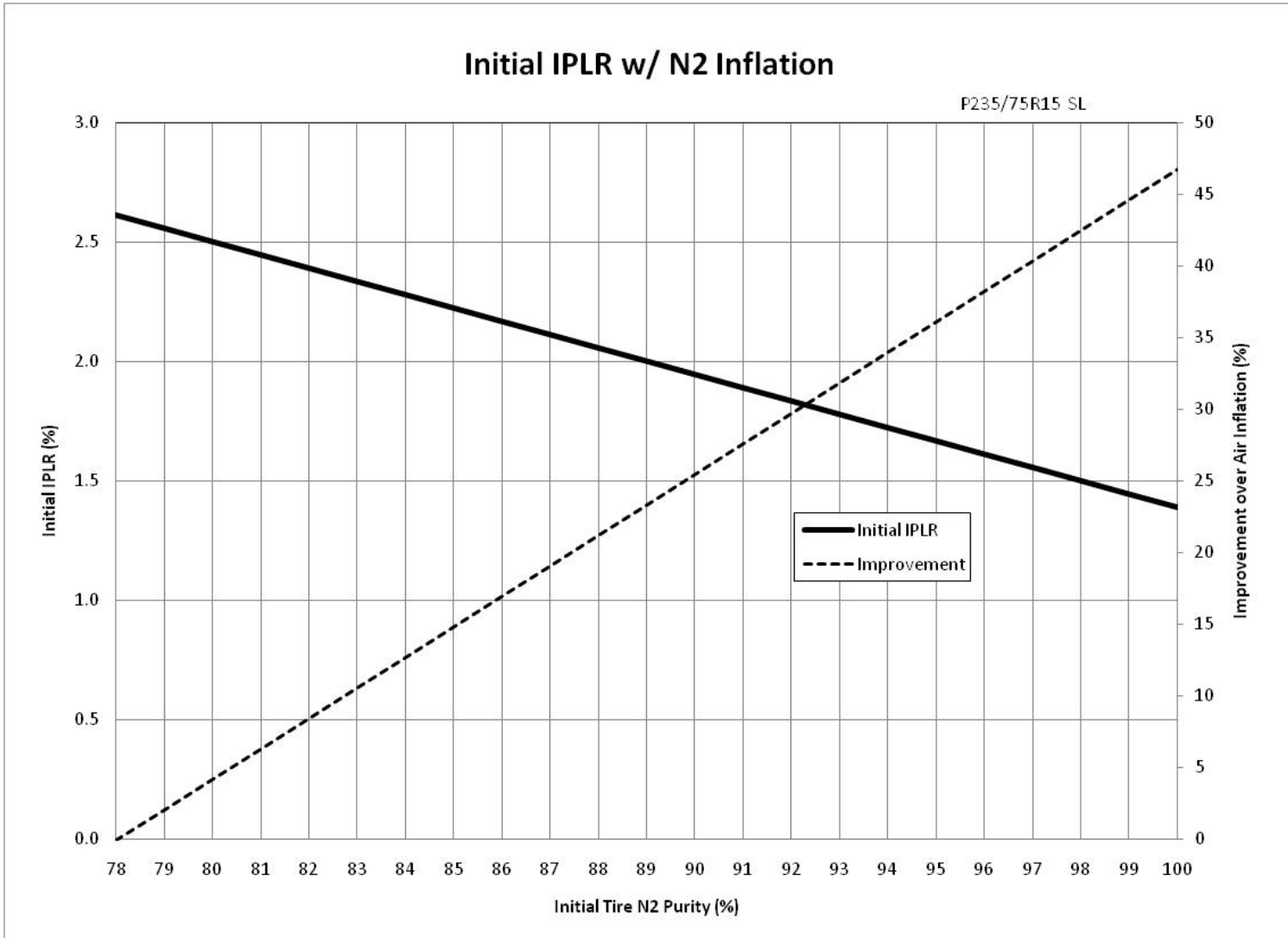
FIGURE 13. *Initial IPLR for P235/75R15 SL Tire Inflated with Nitrogen.*
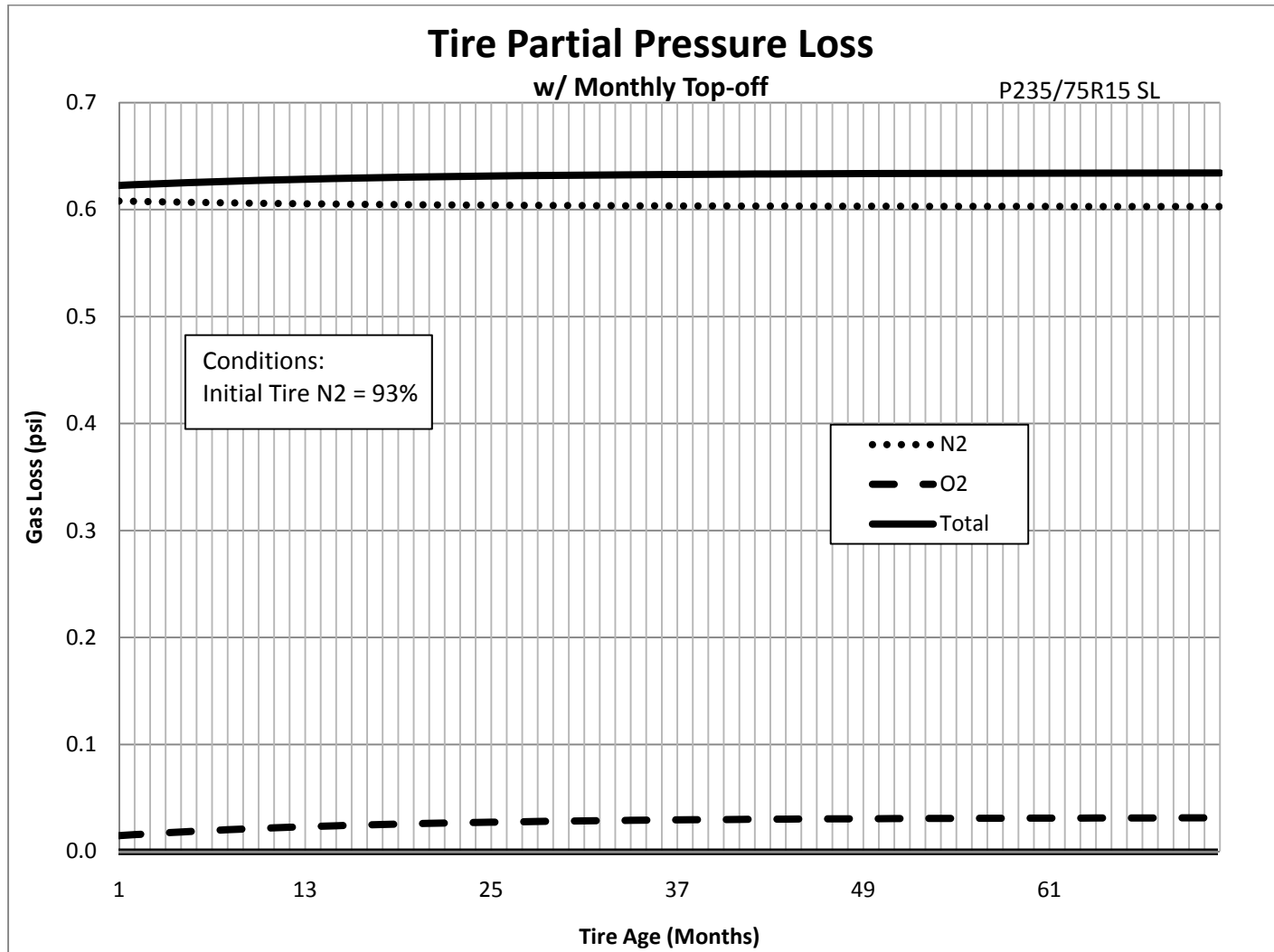
34

FIGURE 1. *Tire Nitrogen Purity for Equilibrium Oxygen.*

FIGURE 2. O*xygen Partial Pressure as a Function of Tire Maximum Pressure and Nitrogen Purity.*

FIGURE 3. *Inflation Purity Evolution for Inflation Gas of 95% Nitrogen Purity.*

FIGURE 4. *Inflation Purity Evolution for Inflation Gas of 98% Nitrogen Purity.*

FIGURE 5. *Nitrogen Purity Evolution by Inflation Step for Standard Load Passenger Car Tires.*

FIGURE 6. *Nitrogen Purity Evolution by Inflation Step for LRE Light Truck Tires.*

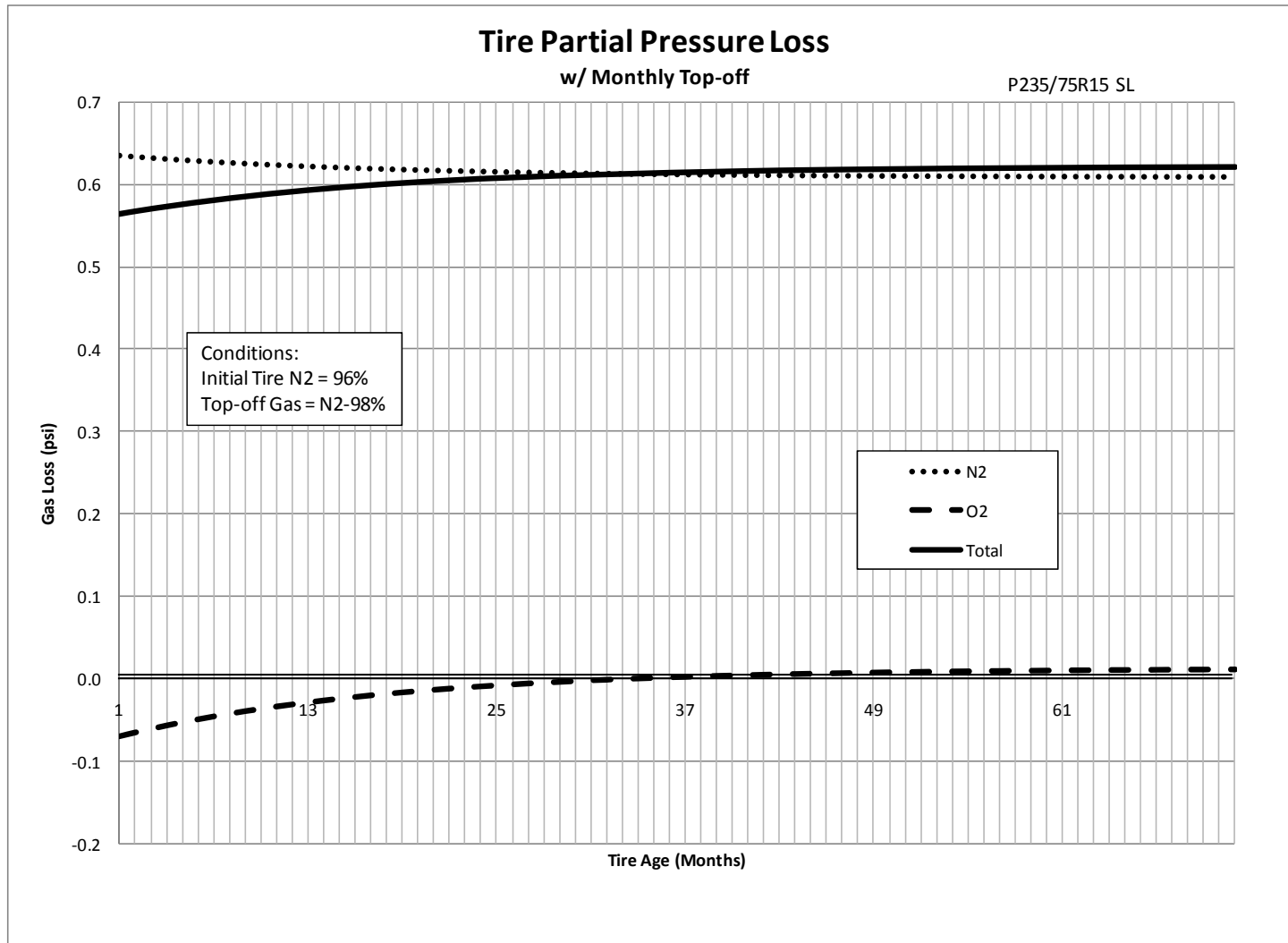FIGURE 7. *Gas Purity Evolution over Service Life for P235/75R15 SL Tire Inflated with Air and Topped Off With Air.*

FIGURE 8. *Partial Pressure Evolution over Service Life for P235/75R15 SL Tire Inflated with Air and Topped Off With Air.*

FIGURE 9. *Oxygen Permeation over Service Life for P235/75R15 SL Tire Inflated with Air and Topped Off With Air.*

Tire Partial Pressure Loss
w/ Monthly Top-off

P235/75R15 SL

Conditions:
Initial Tire N2 = 93%
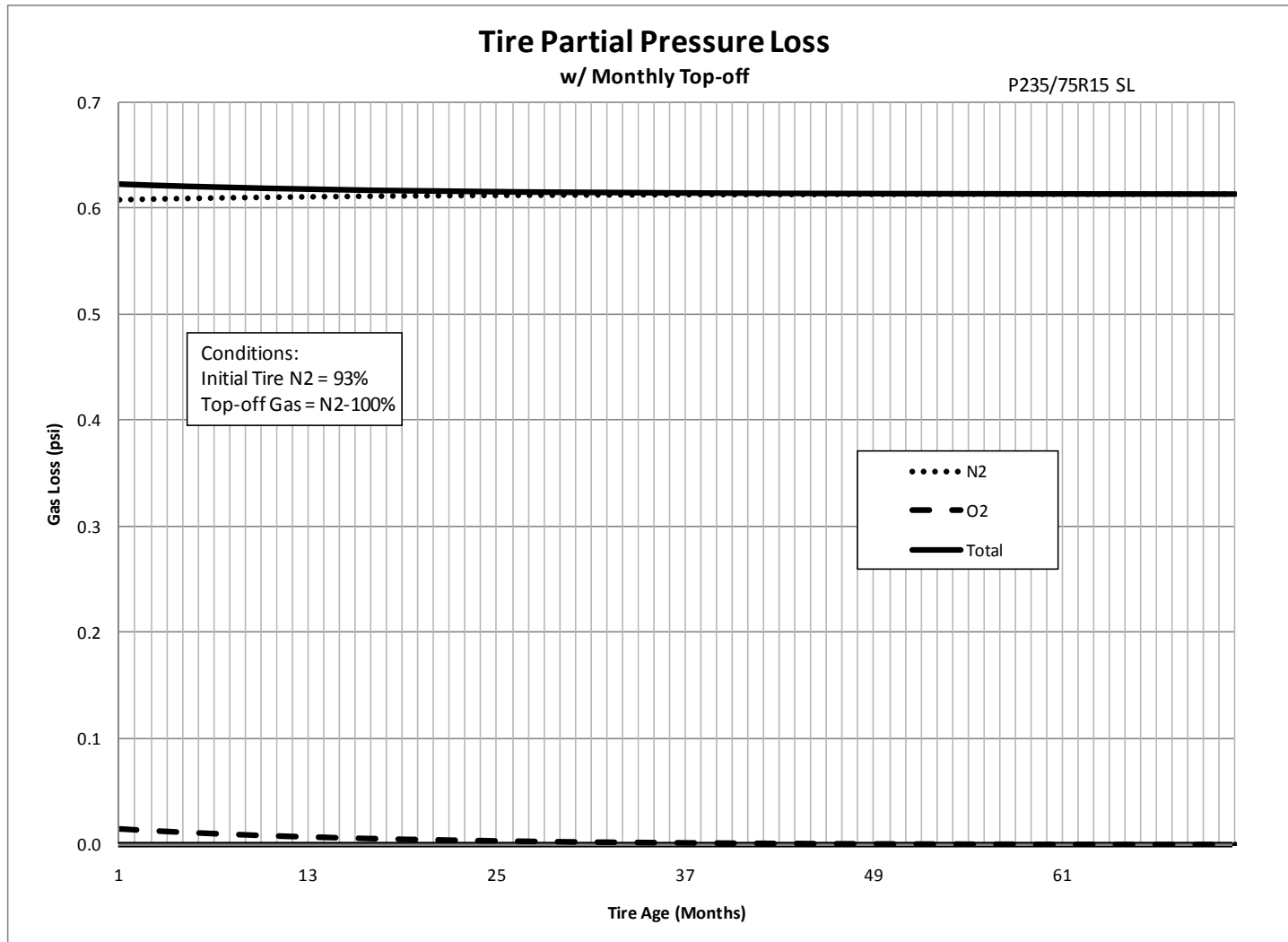Top-off Gas = Air

N2
O2
Total

Gas Loss (psi)

Tire Age (Months)

FIGURE 10. *Partial Pressure Evolution over Service Life for P235/75R15 SL Tire Inflated with 93% Nitrogen and Topped Off With Air.*

FIGURE 11. *Partial Pressure Evolution over Service Life for P235/75R15 SL Tire Inflated with 96% Nitrogen and Topped Off With Air.*

FIGURE 12. *Comparison of Oxygen Permeation in P235/75R15 SL over Tire Lifetime Showing the Benefit of Nitrogen Inflation and Maintenance of Tire Nitrogen Purity.*

FIGURE 13. Initial *IPLR for P235/75R15 SL Tire Inflated with Nitrogen.*

FIGURE 14. *Partial Pressure Evolution over Service Life for P235/75R15 SL Tire Inflated with 93% Nitrogen and Topped Off With Inflation Gas at 95% Purity.*

FIGURE 15. *Partial Pressure Evolution over Service Life for P235/75R15 SL Tire Inflated with 96% Nitrogen and Topped Off With Inflation Gas at 98%.*

FIGURE 16. *Partial Pressure Evolution over Service Life for P235/75R15 SL Tire Inflated with 93% Nitrogen and Topped Off With Inflation Gas at 100%.*
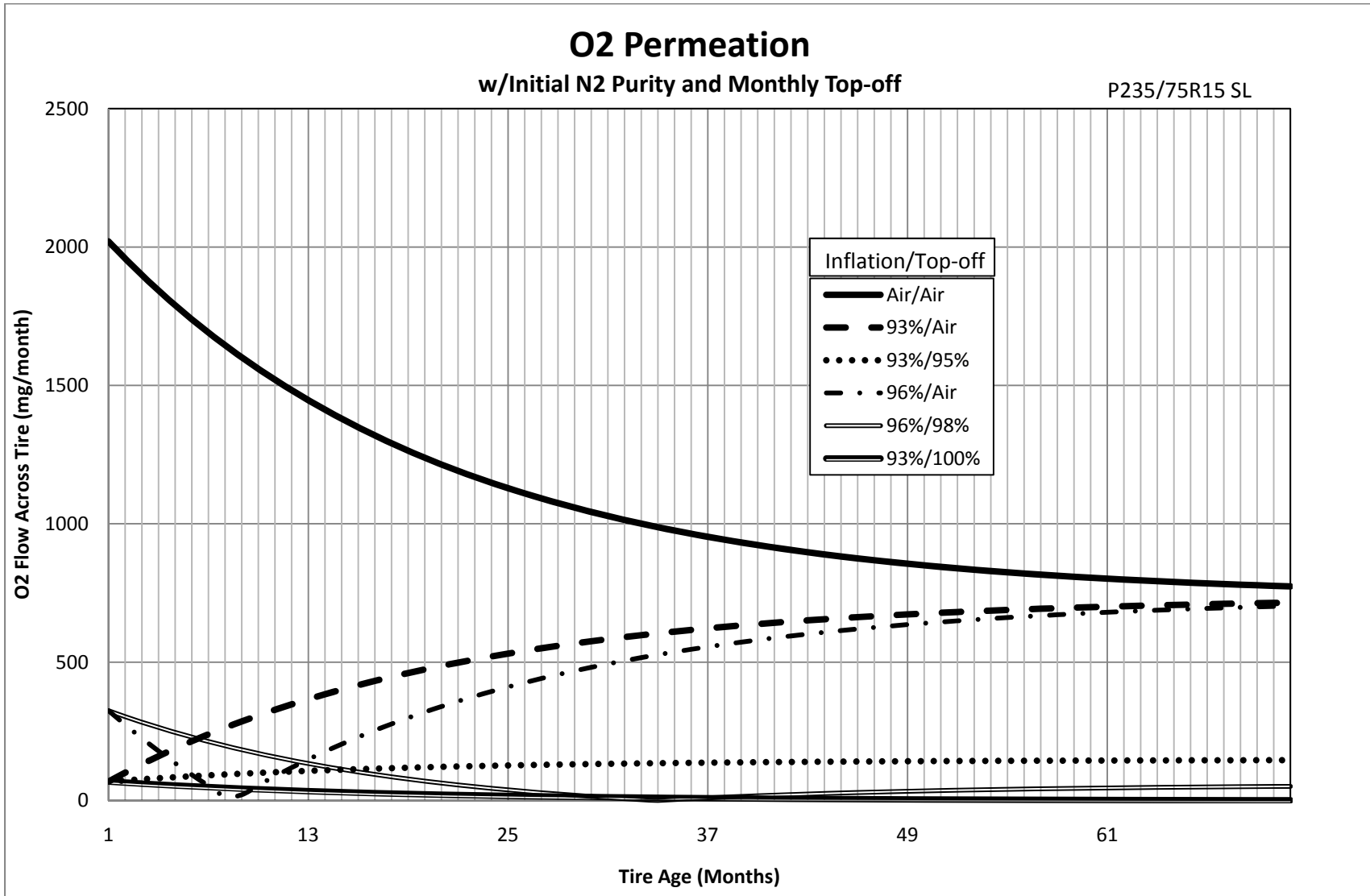
FIGURE 17. *Comparison of Oxygen Flow Curves over the Service Life for P235/75R15 SL Tire.*
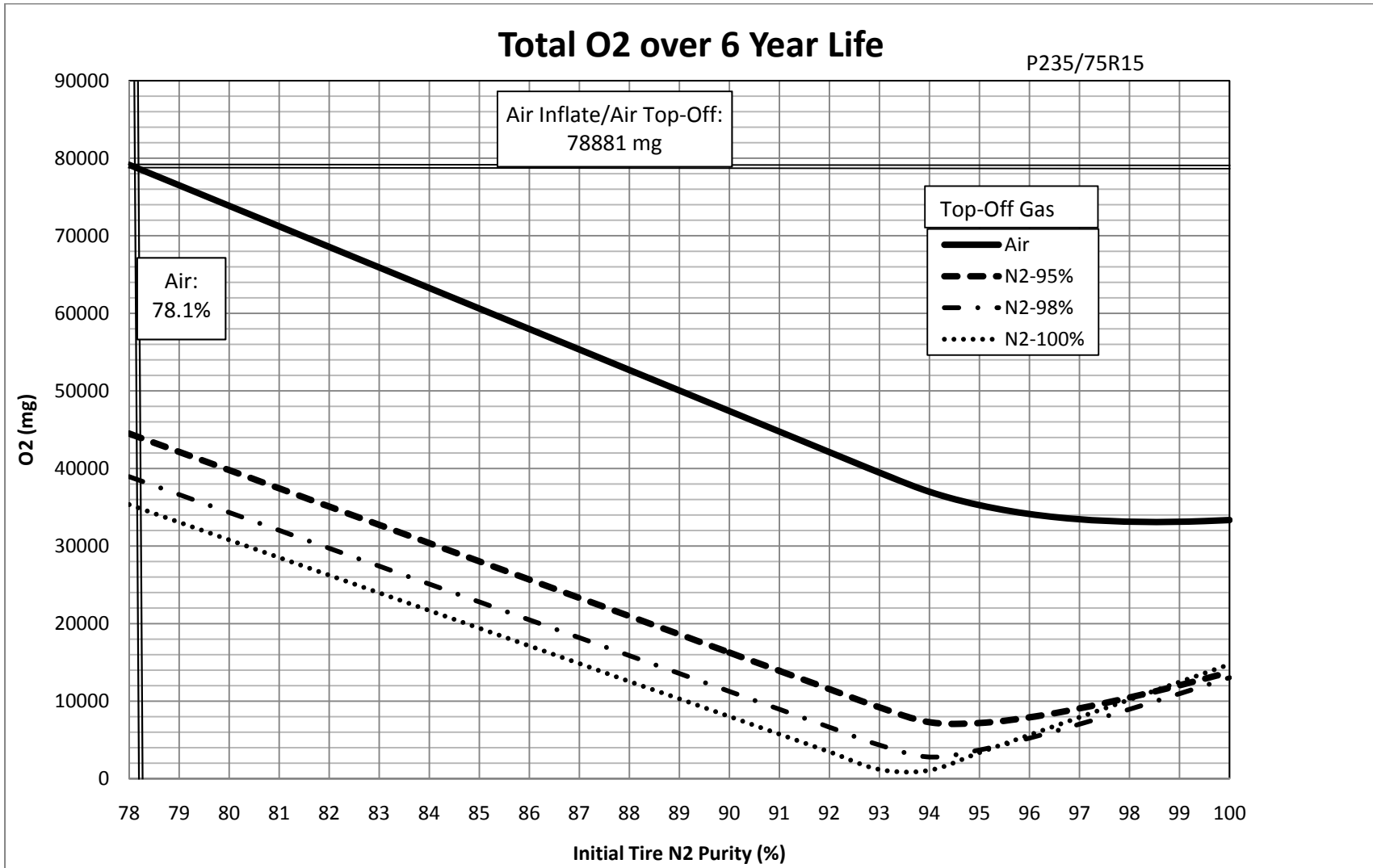
FIGURE 18. *Service Life Oxygen Flow Across P235/75R15 SL Tire for Various Initial Nitrogen Purities and Top-Off Gases.*
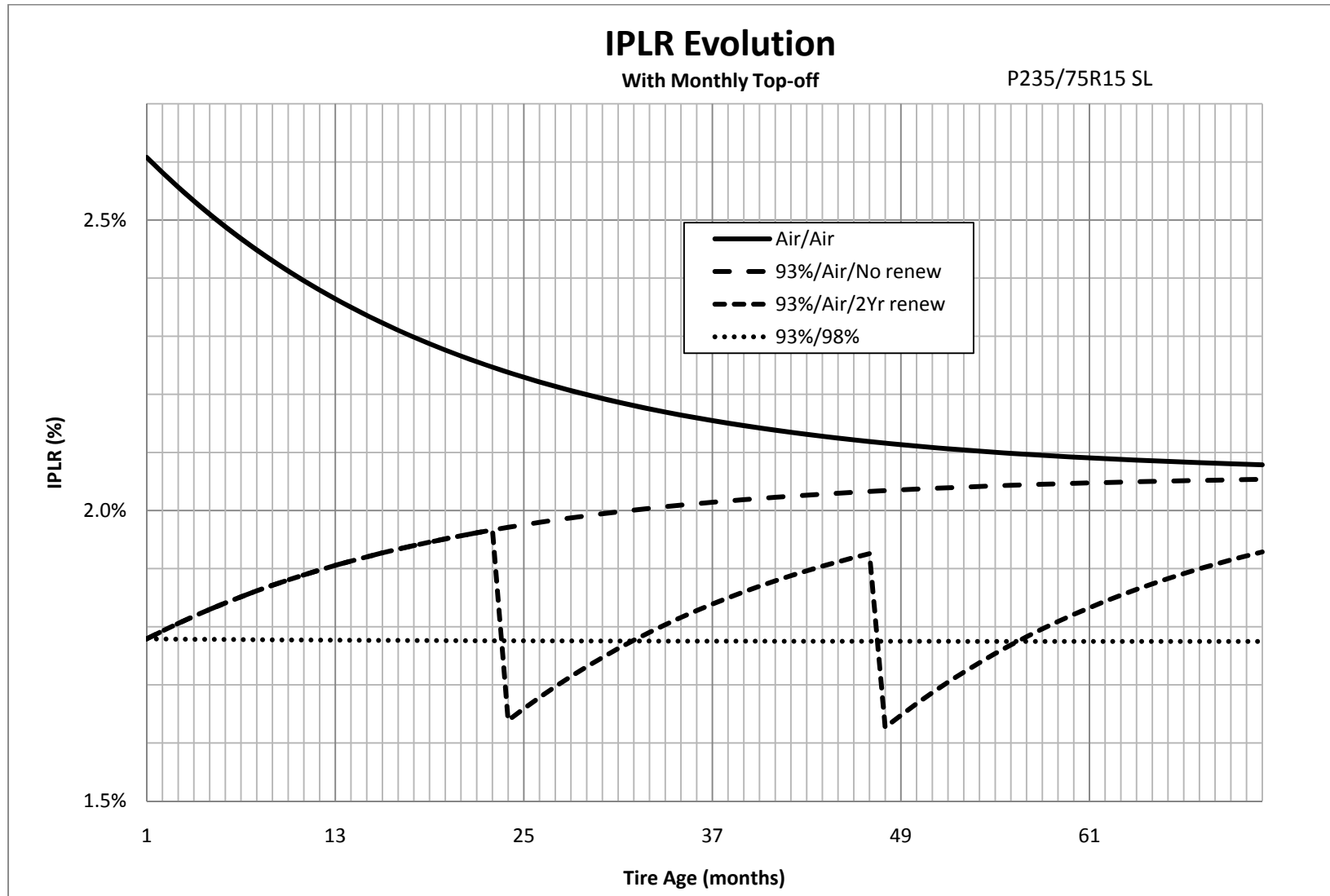
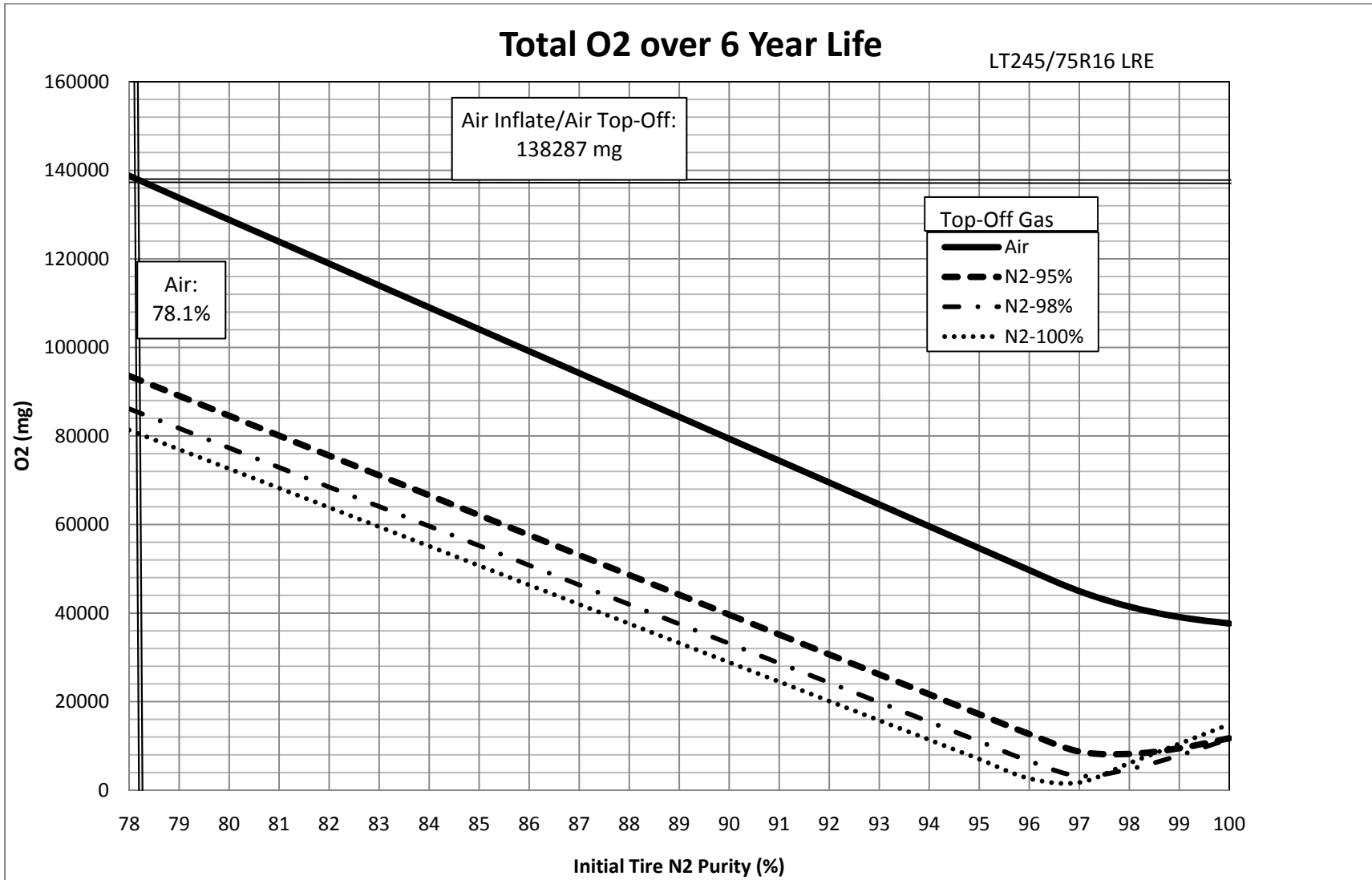FIGURE 19. *Comparison of IPLR in P235/75R15 SL Tire for Nitrogen Inflation with Various Maintenance Strategies.*

FIGURE 20. *Service Life Oxygen Flow Across LT245/75R16 LRE Tire for Various Initial Nitrogen Purities and Top-Off Gases.*
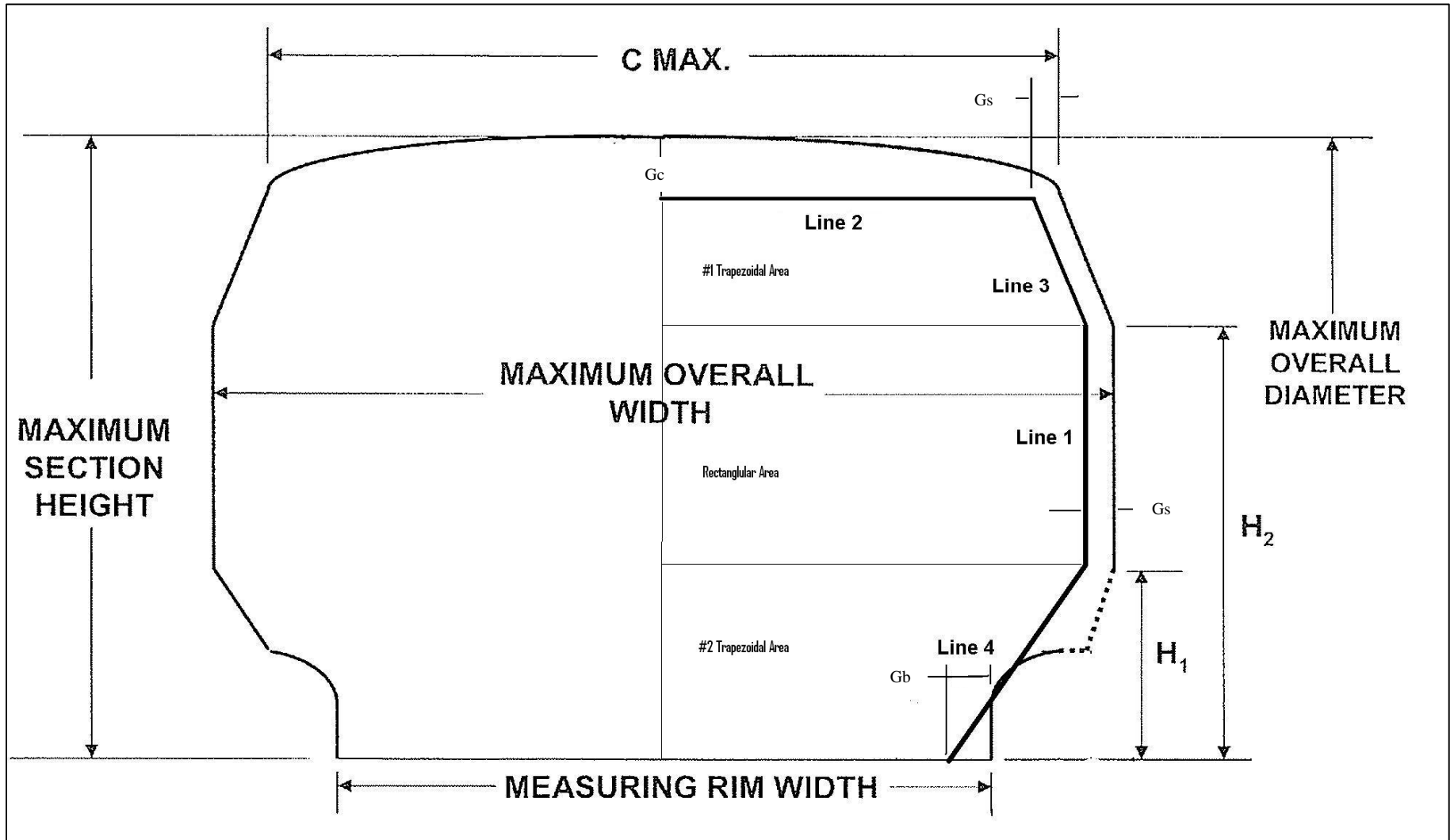
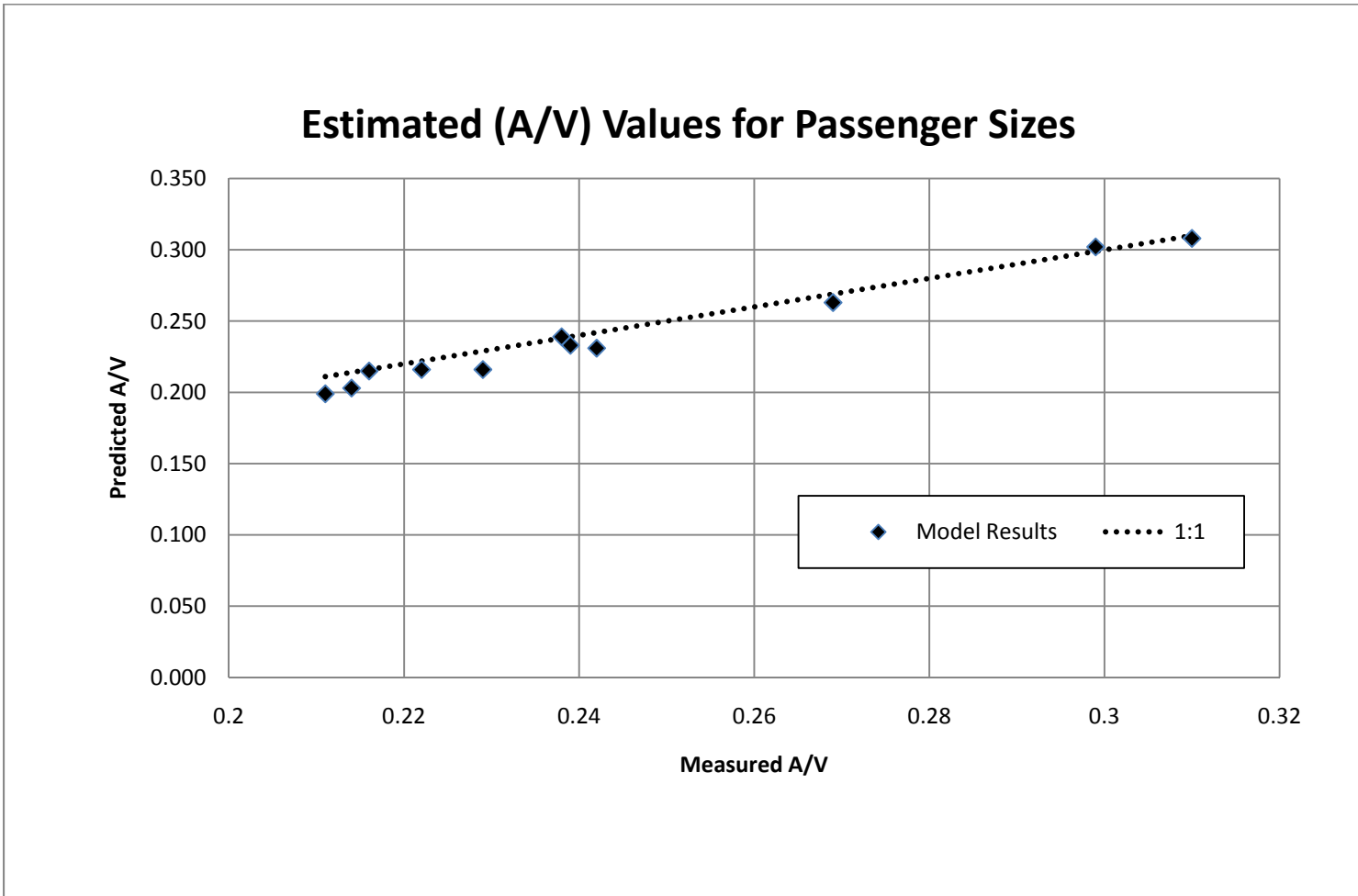FIGURE A-1. *Cross-Section Development for Estimation of (A/V) Ratio.*

FIGURE A-2. *Comparison of Estimated and Experimentally-Determined (A/V) Ratios for Passenger Car Tire Sizes Reported by Costemalle.*