TIRE NITROGEN FILLING SYSTEM

A FINAL REPORT TO:
Industrial Technologies Sector of Ingersoll Rand Corporation
BY:

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1. PROJECT SUMMARY:

The Industrial Technologies sector of Ingersoll Rand Corporation has sponsored two projects on nitrogen inflated tires with the Mechanical Engineering Department at Clemson University. Clemson University operated such tests with third parties to provide unbiased results to Ingersoll Rand on the topic of nitrogen inflated tires for fleets and passenger vehicles. All results are tabulated below.

The rolling resistance of inflated tires is an important component of resistance to vehicle motion and contributes to the total load and fuel consumption. Therefore, many research works have been focused on how the various tire parameters (e.g., load (L), inflation pressure (P), and speed (V)) affect rolling resistance so that fuel economy can be increased. Recent research findings indicate that filling tire with nitrogen can maintain proper inflation and decrease the deterioration of the rubber. Therefore, the primary goal of this project is to explore the probability of using nitrogen filling tires to improve the vehicle safety, performance, and operating cost. The first phase of the project has focused on how pressure varies with time in static state. Two types of tests namely; Qleak and Sleak tests were performed at Michelin to study tire inflation gas leakage at different test temperatures and times (see figure 1).

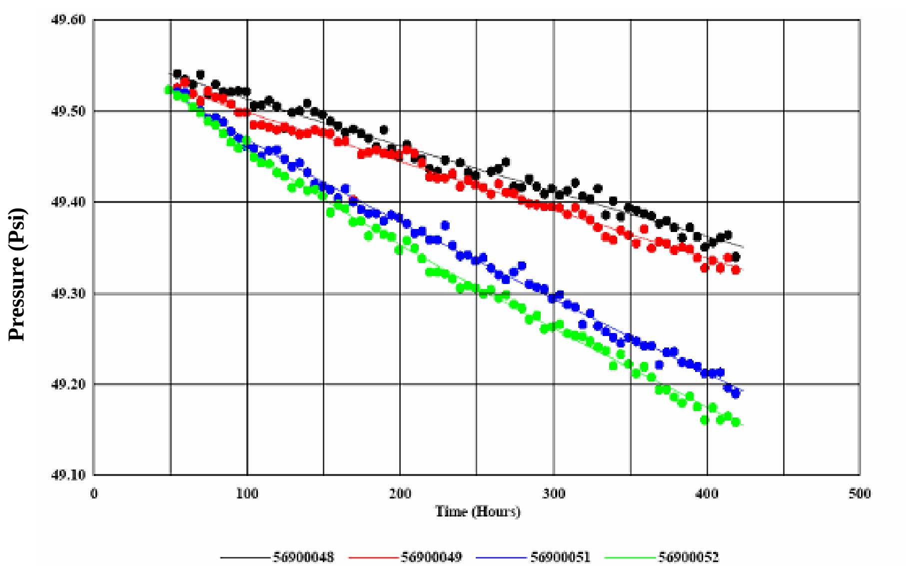


Figure 1: Inflation Pressure vs Time in Qleak Test

The typical test result is depicted in Figure 1 to illustrate the different leakage effects due to different tire inflation gas. The Qleak experimental study indicated that nitrogen inflation can maintain the tire pressure 35% - 55% better than shop dry air per month at room temperature depending on different tire type. On the other hand, the Sleak experimental study indicated that nitrogen inflation can maintain the tire pressure 29% - 35% better than shop dry air per month at oven temperature. However there are some issues that require further research. For instance, various affecting parameters including pressure, load and velocity as well as nitrogen inflation should be considered. The current data can only show that the nitrogen tire inflation can reduce the air leakage in tires.

The second phase of the project focuses on the contribution of tire inflation pressure on rolling resistance and tire tread wear. Tire inflation pressure readings were recorded on Fleet tractors at various time frames at three different locations namely; DC 1, DC 2 and DC 3. Rolling resistance of each tire were first calculated and then used to find the average rolling force of each truck and then extended to all the trucks in each location and compared for both Air and Nitrogen inflated tires. The rolling resistance of tires calculated from the test data shows that nitrogen filled tires produce lower tire rolling force than air filled tires and this corroborates the statement that nitrogen filled tires help improve tire life and vehicle fuel economy and reduce the overall operating cost.

Figure 2 shows a simple comparison of rolling resistance of the test tires at various locations for both inflation types.

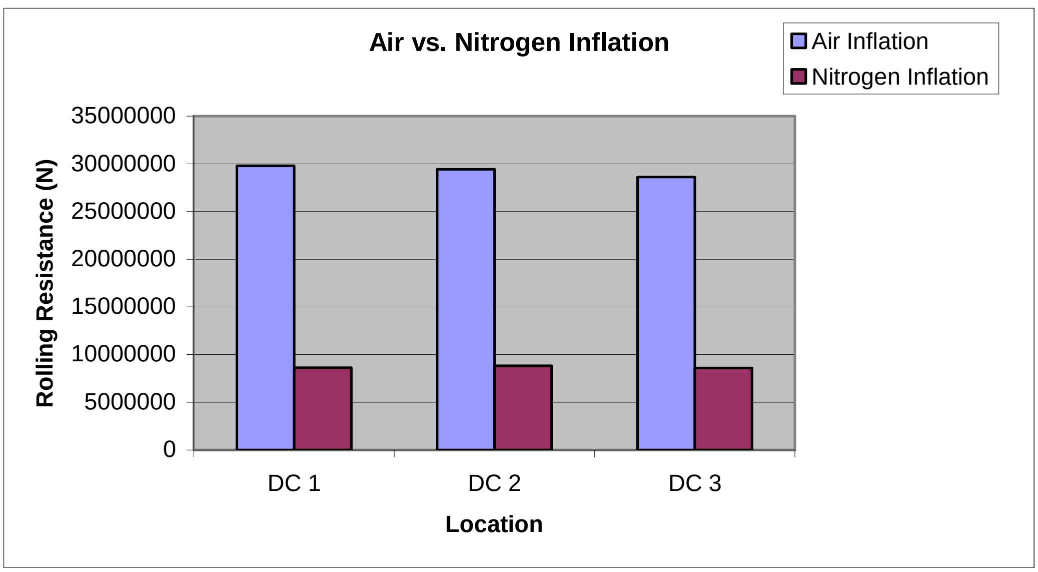


Figure 2: Comparison of rolling resistance at each location

From figure we can note that the leakage rate of inflation gas in air inflated tires is higher than that of nitrogen filled tires and hence an increase in rolling force. If we consider that a truck travels 2500 miles/week, then leakage rate of air inflated tires is about 0.11 Kpa per week whereas leakage rate of nitrogen inflated tire is only 0.029 Kpa per week. Hence nitrogen inflated tires can maintain tire pressure 74% better than shop air per month at normal operating conditions. As a result, nitrogen inflated tires produce about 70% less rolling resistance than air inflated tires.

The tables and plots presented in the report are calculated from data obtained from truck tires in static state and rolling resistance with variation of pressure was studied. The conclusions derived here can represent real condition in road testing with respect to pressure variation. All the results presented in the report are consistent with the objective.

2. INTRODUCTION

2.1. Arbitrary Forces Acting on a Vehicle:

Forces and moments are normally defined as they act on a vehicle under arbitrary conditions based on the application of Newton's second law. Consider the vehicle shown in Figure 3, in which most of the significant forces on the vehicle are shown [2].

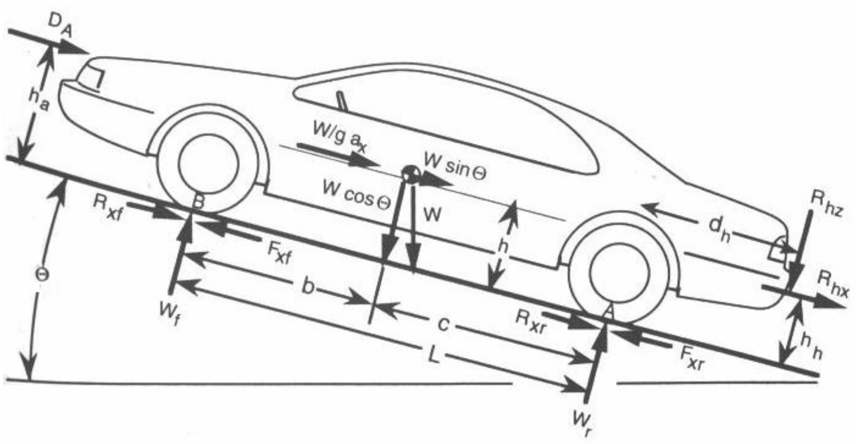


Figure 3: Arbitrary forces acting on a vehicle.

where W is the weight of the vehicle acting at its central gravity (CG), W_f and W_r are the normal forces on the front and rear wheels, F_{xf} and F_{xr} are the tractive forces on the front and rear wheels, R_{xf} and R_{xr} are the rolling resistance on the front and rear wheels, DA is the aerodynamic force, R_{hz} and R_{hx} are vertical and longitudinal forces acting at the hitch point.

2.2. A Brief Overview on Rolling Resistance (RR):

The RR is essentially a moment, however, active force is needed to move the wheel forward. As a result, this force acts in the travel direction at the axle of a towed wheel and at the perimeter of a driving wheel [2].

Certain fundamental equations are established at an early stage in the development of the discipline. Vehicle researchers first use Coulomb's equation to express the peripheral force acting on a running gear as:

$$F_k = \phi \tag{1}$$

This equation is inadequate for a detailed analysis of cross-country motion. Researchers working under Dr. Bekker's supervision at the Land Locomotion Laboratory have progressed beyond the above simple equation. As a result, Janosi's well-known equation was published in 1961 [3]:

$$F_k = (Ac + Qtg\phi)\left[1 - \frac{K}{sL}\left(1 - \exp\left(\frac{-sL}{K}\right)\right)\right] \tag{2}$$

where A is the contact area, c is the cohesion, Q is the vertical load, ϕ is the angle of internal friction, K is the tangent modulus of the soil-shear stress vs. deformation curve, s is the slip, and L is the contact length.

There is another interpretation according to basic mechanical principles. The RR of tires on hard surfaces is primarily caused by the hysteretic in tire materials due to the deflection of the carcass while rolling. As a result of tire distortion, the normal pressure in the leading half of the contact patch is higher than that in trailing half. The center of normal pressure is shifted in the direction of rolling. This shift produces a moment about the axis of rotation of the tire, which is the rolling resistance moment. In a free-rolling tire, the applied wheel torque is zero; therefore, a horizontal force at the tire-ground contact patch must exist to maintain the equilibrium. The resultant horizontal force is generally known as the rolling resistance (see Figure 4, [4, 5]).

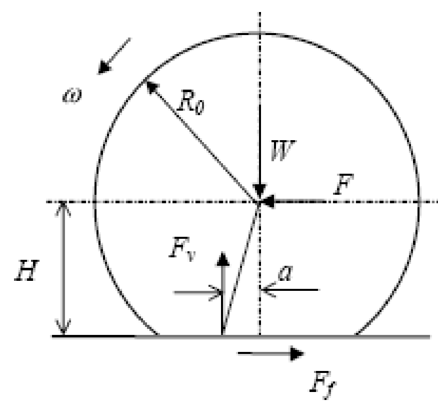


Figure 4: Tire deformation causes horizontal shift of the resultant normal force

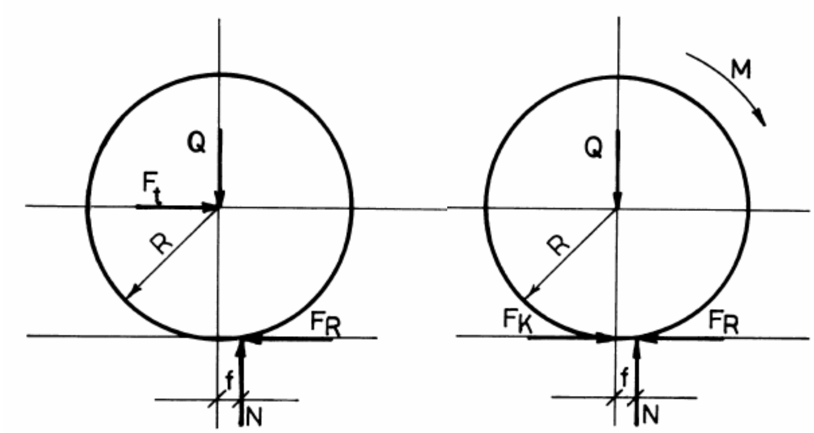
Since the roll resistance F_r is proportional to the normal force, it is natural to define the coefficient of rolling resistance C_r as:

$$F_r = C_r R \tag{3}$$

C_r depends on many variables including the operating conditions (inflation pressure, tire temperature, vehicle speed wheel adjustments) and the structure of the tire (construction and materials).

The mechanical characteristics of towed and driving wheels are identical. One can transfer the static analysis from one case to the other. Figure 4a shows a wheel which rolls over terrain. A force F_t is acting on the wheel, which pushes it in the direction of travel. The reaction force created by the deformation is represented by two components. So, for a towed wheel we have:

$$F_R R = fN \tag{4}$$



a) b)

Figure 5: Mechanical relationship between towed and driving wheels:

a) towed wheel, and b) driving wheel

where F_t is the force required to tow a rigid wheel in deformable soil. F_R is the RR, F_K is the peripheral force, Q is the Load, and R is the radius. The force needed to move the wheel forward can be calculated from the equation of moment equilibrium:

$$F_t = fQ/R \tag{5}$$

where $N = Q$ and $F_R = F_t$.

Figure 5b shows the moments and forces acting on a driven (or driving) wheel. This represents the static conditions under which a wheel operates while moving itself in deformable soil.

The forces needed to roll a driving or a towed wheel is of equal magnitude, if the conditions are the same. The sense of the force vector points in the direction of travel. It occurs at the center of a towed wheel, which is $F_t R$, and at the bottom of the driving wheel, which is $F_K R$, the latter being the peripheral force.

2.3. Rolling Resistance and Its Relationship with Tire Pressure Load and Speed:

Later, researchers found out that the coefficient of rolling resistance for pneumatic tires is dependent on hysteretic loss from tire deformation which is affected by the vertical force applied to the tires and the tire inflation pressure in real driving situation. Grappe et el determined the relative influence of five different levels of pressure (P) and four different levels of load (Z) on rolling resistance coefficient (C_r) and to examine the relationships of C_r with P and L during the cycling locomotion. He also concluded that this relationship for cycling is nonlinear [6]. In fact, for the passenger cars' tires and trucks' tires, the RR increases with the tire inflation pressure decreasing and it also increases with the vertical load increasing. In addition, previous studies showed that vehicle speed has effect on the rolling resistance as well. The higher the speed, the more rolling resistance experienced.

In 2000, field studies carried out on road revealed that the tires of more than half of the cars were under-inflated by at least 4.5Psi. This results in a considerable increase in RR by 6% and 30%, when the inflation pressure is 4.5 psi and 14.5 psi below the recommended value respectively.

2.4. Effect of Rolling Resistance on Fuel Economy:

A tire's rolling resistance does affect the fuel economy. A 30% increase in RR increases fuel consumption by between 3 and 5 % depending on driving conditions and vehicle type.

As we know, a vehicle's fuel economy is the result of its total resistance to movement. This includes overcoming inertia, driveline friction, road grades, tire rolling resistance and air drag. During stop-and-go city driving, the relative percent of influence from tire rolling resistance is about 15%, comparing with the steady speed highway driving of about 25% [7].

Previous testing data presented that 1.5 to 4.5% of total gasoline use could be saved if all replacement tires in use had low rolling resistance. Therefore, one of the most promising opportunities for fuel savings across the entire fleet of existing vehicles is to utilize low rolling resistance tires instead of standard replacement models. This change improves the inherent efficiency fuel over the typical 30,000 to 50,000 miles lifetime of a set of tires [8].

3. NITROGEN USING IN TIRES

In order to increase the fuel efficiency and improve the tire performance, nitrogen, a dry and inert gas, is used to inflate airplane, off-road truck, military vehicle, and race car tires instead of airs recently [9].

3.1. Nitrogen Characteristics:

Compared to nitrogen, oxygen in compressed air permeates through the wall of the tire much faster, thus reducing the tire inflation pressure. Dry nitrogen can maintain the proper inflation pressure to make tires run cooler, which can decrease the rolling resistance and prevent overload. Tires degrade over time because oxygen oxidizes the rubber compounds when it migrates through the carcass of the tire, which cause under-inflation and deterioration of the rubber. There is a significant reduction in tire failure. Nitrogen is an inert gas, which will not corrode rims and will help the tire to run cooler [10].

3.2. The Benefits of Using Nitrogen:

Because of these characteristics, there are some advantages of using nitrogen in tires.

- Improve Tire Life
- Reduced Operating Cost
- Enhanced Safety for Vehicles

4. RESEARCH OBJECTIVES AND TECHNICAL APPROACH

4.1. Research Objectives:

In order to achieve the primary goal of the project, two individual although correlated objectives are identified. The first one is to investigate the relationship between RR and various tire parameters including pressure, load, velocity as well as tire filling strategy. The second objective is to provide the technical support for the statement that nitrogen filling tires do have a positive effect on the tire performance and vehicle fuel efficiency.

4.2. Technical Approach:

We propose to compare a series of mathematical models side by side and identify the most appropriate one, which will be used to predict the RR with the contribution of the physical, independent variables (i.e. load, pressure, and velocity). After that, we refine the identified model to give consideration to nitrogen tire filling. Experimental study will be performed to feed the data for calibrating the RR forecasting model. Statistical analysis is the method to determine the parameters in the model and answer the question of whether there is difference in RR due to different filling gas. Finally, the tire performance and life length as well as vehicle fuel efficiency are related to the proposed tire filling strategy through conducting statistical analysis again.

4.2.1. Mathematical Modeling:

The coefficient of RR for pneumatic tires depends on hysteretic loss from tire deformation which is affected by the vertical force applied to the tires and the tire inflation pressure in real driving situation. The tests following the guidelines in SAE standard procedure J1269 were performed before. This test method involves testing under various load-pressure conditions (at 80kph), other than the actual test conditions. However, the trend over the recent past has been to account for the effect of the speed on rolling resistance as well. Therefore, a new test method and a new model are used to predict rolling resistance at various vehicle operation conditions (load, pressure, speed), other than the test conditions [11].

In the past, two equations have been used to model RR test data, including data at different speeds.

$$RR = A_0 + A_1 + A_2\frac{L}{P} + A_3V^2 + A_4\frac{LV^2}{P} + A_5\frac{1}{P} \tag{6}$$

$$RR = A_0 + A_1 + A_2V + A_3\frac{L^2}{P} + A_4LV + A_5V^2 \tag{7}$$

Traditional modes as showed above provide good mathematical description of the data, but are often not very appealing from the point of physically describing the relationship between RR and the independent variables. Moreover, since this approach primarily searches for the best mathematical fit for any given data set, it results in a plethora models such that the model for each tire could have different terms. Thus, there is no common basis for comparing the models of various tires either. In view of these disadvantages, the following models were utilized in the study:

$$RR = KP^{\alpha}Z^{\beta}V^{\gamma} \tag{8}$$

$$RR = P^{\alpha}Z^{\beta}(a + bV + cV^2) \tag{9}$$

where RR is the rolling resistance (N), P is inflation pressure (kPa), Z is applied vertical load (N), V is speed (kph), K is constant, α, β, γ are exponents, a, b, c are constant coefficients. Equation (8) is reference to as model 1 and the equation (9) as model 2. The difference in tire pressure can be modeled from the knowledge of gas diffusion rates for both air and nitrogen inflation as:

$$P = P_{air}^{\alpha} - P_{N_2}^{\alpha} \tag{10}$$

Actually, equations (6) and (7) can be derived from equation (8) using Taylor Series expansion and selecting only those terms that provide the best fit

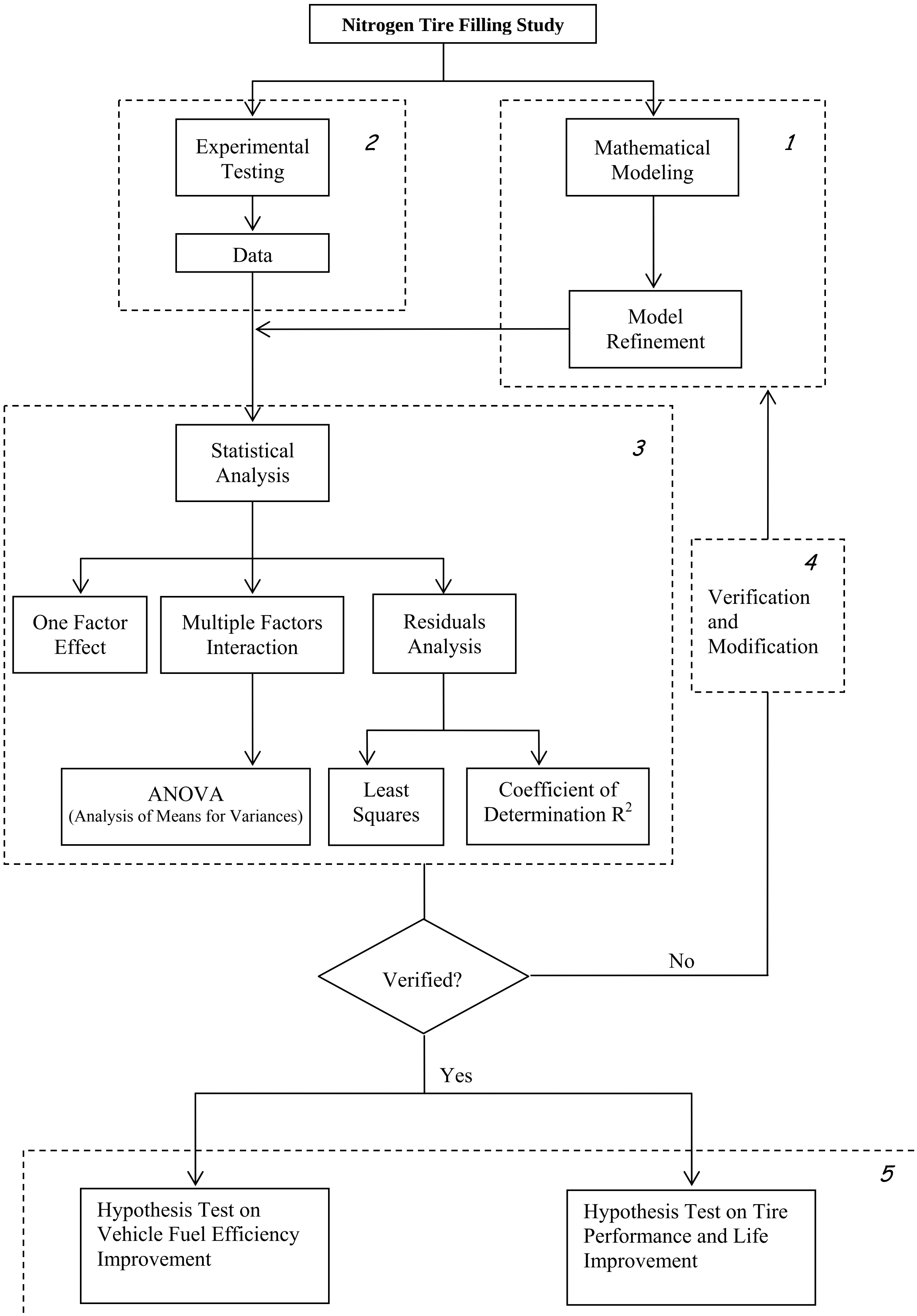


Figure 6: Technical Procedure

Following are some advantages of using model 1:

1) It is appealing from a physical point of view since it accounts for the effect of the three known variable; speed, pressure and load.
2) It allows the test data to determine the contribution of various terms to RR rather than selecting only those terms that result in a good mathematical fit for a given data set.
3) It is applicable for both passenger car and light truck tires.

From the SAE proposed coast down test, it was observed that the second order polynomial provided a better representation of the rolling resistance vs. speed relationship for any given load-pressure combination, this led to the development of model 2, which is better than model 1 in representing rolling resistance test data. In model 2, the correlation between calculated RR and measured values R^2 exceeds 0.99 for all those testing tires. Moreover, the residuals, which is the difference of calculated RR and measured RR, are randomly scattered. Usually, the dispersion in residual was higher for light truck tires as compared to passenger car tires. Model 2 also has the advantages mentioned before.

This new test practice J2452 over the model J1269 is that the former includes the speed dependence of rolling resistance. Hence, it is important that the parameters used for comparing tires capture their RR performance over a range of speed. However, the typical output of comparing two tires from different manufactures is a series of RR vs. speed curves. It is challenging to quantitatively compare the rolling resistance performance for two tires by only comparing their RR vs. V curves [12].

In this new test method, because the data are collected at multiple speeds for each load/pressure condition, new parameters are defined and a new methodology for comparing tires using data generated as per SAE J2452. The new parameters are MERF (Mean Equivalent Rolling Force) and SMERF (Standard Mean Equivalent Rolling Force).

MERF for a tire, at a given load/pressure condition, is defined as the average of all rolling resistance values corresponding to every single speed-time point in a fixed driving cycle. Mathematically, MERF is defined as:

$$MERF_{U/H} = \frac{\int_{t_o}^{t_f} RRdt}{\int_{t_o}^{t_f} dt} = \frac{P^{\alpha} Z^{\beta} \left[\int_{t_0}^{t_f} (a + bV + cV^2) dt \right]}{\int_{to}^{t_f} dt} \quad (11)$$

where $MERF_{U/H}$ is the mean equivalent rolling force over any standard urban (U) or highway (H) cycle. The term t_o is the time corresponding to the start of the cycle and t_f corresponds to the end of the cycle.

Since $RR = f(V)$ and $V = f(t)$ for a giving driving cycle is known, 'V' in equation (11) can be expressed as a function of time. Hence, the integral can be solved by standard numerical integration methods, and equation (11) can be simplified to:

$$MERF_{U/H} = \frac{P^{\alpha} Z^{\beta} \left\{ at_f + b\sum_{i=1}^{f}(t_i - t_{i-1})(V_i - V_{i-1}) + c\sum_{i=1}^{f}(t_i - t_{i-1})(V_i^2 - V_{i-1}^2) \right\}}{t_f - t_o} \qquad (12)$$

Selecting a unit time interval ($\Delta t = t_i - t_{i-1} = 1\sec$) between successive speed points on the speed vs. time curve for a driving cycle

$$MERF_{U/H} = \frac{P^{\alpha} Z^{\beta} \left\{ at_f + b\sum_{i=1}^{f} V + c\sum_{i=1}^{f} V^2 \right\}}{t_f - t_o} \qquad (13)$$

where t_f now represents the duration of the cycle because t_o =0.

It is noted that equation (13) can be used to calculate the MERF for any cycle. At a given load/pressure, the final MERF for a tire is a weighted average of the EPA urban and highway cycles.

$$MERF = 0.55(MERF_U) + 0.45(MERF_H) \qquad (14)$$

SMERF for any tire is the MERF for that tire under standard load/pressure conditions defined in SAE J2452.

MERF values for two tires at a given load/pressure condition can be directly compared, where a lower value is better. One of the advantages of using MERF is that for one tire to be better than others, it would have to be better over a range of speeds.

However, the limitation of the methodology J 2452 should be kept in mind:

1. Stabilizing the tire at some speed other than 80 kph does not have a significant effect on the speed dependence.
2. No other phenomenon, such as standing waves, contributes to the tire rolling resistance. There are some worked are recommended to be done in the future.
3. A more precise estimate of the standard deviation of the distribution of MERFs (σ_{MERF}) should be obtained using a larger variety of tires.
4. The error in the measurement of RR during a stepwise coast down test should be experimentally determined to obtain a more accurate estimate for σ_{MERF} .

4.2.2 Experimental Study:

Figure 7 shows the experimental data requirement including data range and data format for this project. The format of final result is also presented below.

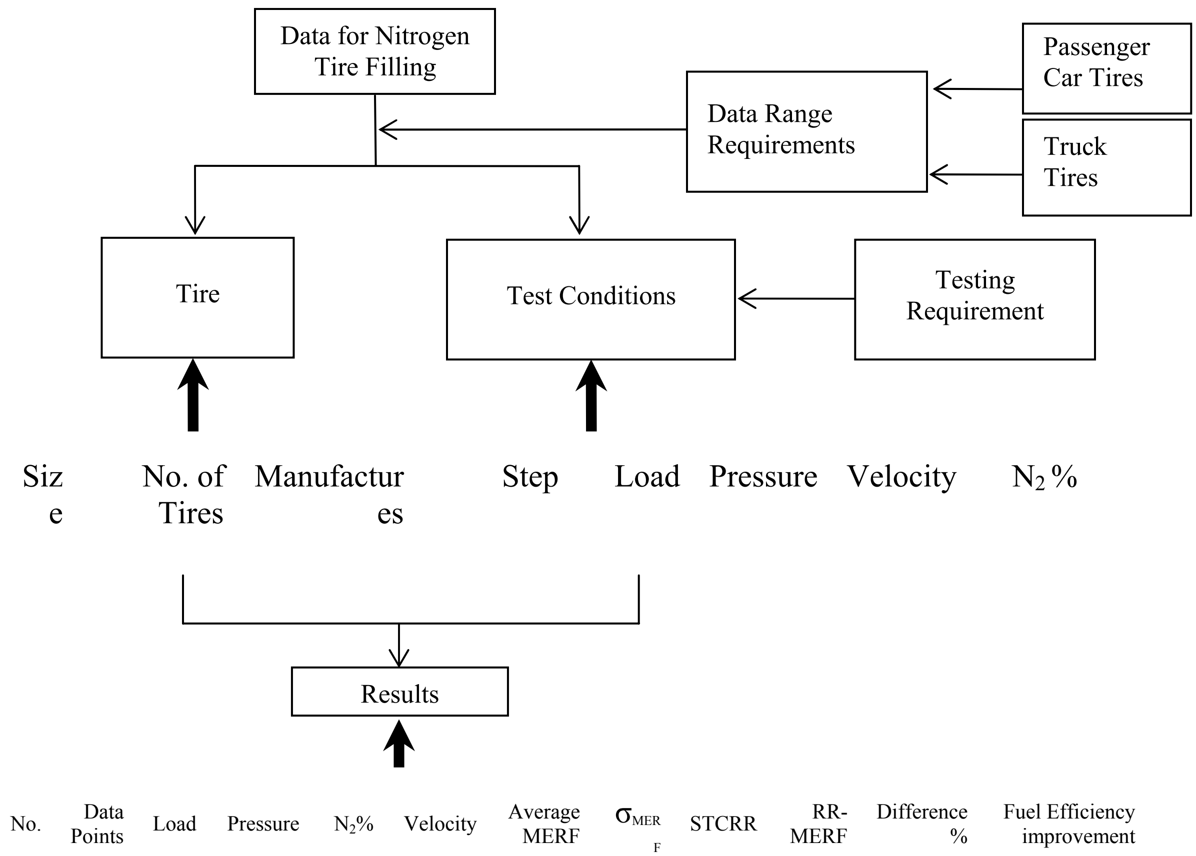


Figure 7: Experiment data

Since this study will be preformed over a range of load/pressure according different speed, the recommended range for each parameter should be described. Table 1 shows the proposed test range for the experimental parameters.

Table 1: Proposed test range

Parameters	**Range**
Air Pressure	Normal±80kpa
Load	0% of Max - 100% of Max
Speed	60mph - 150mph
N_2 Pressure	0% - 100% Total inflation

The test conditions should be described. The warm-up speed, warm-up time, environment temperature, tire heat-up temperature and speed increment which proposed by SAE guide are needed. For passenger car and light truck, they should have different values.

The number of tires used in each set of tests is needed as well.

4.2.3. Statistical Analysis:

Statistical analysis was conducted in both module 4 and module 5 using available statistical tools (e.g. Statistical Analysis Software and Microsoft Excel), as shown in Figure 7.

The methods involved in module 4 include Single Parameter Effect, Multiple Factor Interaction and Residual Analysis. One-factor interaction analysis focuses on finding how each parameter affects Rolling Resistance. Multiple Factor Interaction focuses on interaction between different factors. It can be performed by Analysis of Means (ANOM) and Analysis of Means of Variance (ANOMV). Residual analysis on the other hand can be used to check errors and show the correlations. This can be performed by Least Squares and coefficient of determinations.

Module 5 was completed by calculating the rolling resistance and tire tread wear from the data collected from the fleet truck tires. Equation (9) was used to calculate the rolling resistance of truck tires filled with both air and nitrogen and compared side by side to study the effect of inflation pressure on the rolling resistance of tires. All the data collected from the fleet trucks were tabulated to first find the rate of leakage of inflation pressure for both inflation types. The tread depth of tires for both inflation types were periodically recorded for the corresponding pressure reading. Based on this the rate of wear of tire tread was calculated.

5. RESULTS PRESENTING AND ANALYSIS:

5.1. PHASE I RESULTS AND ANALYSIS

5.1.1. Introduction:

There are two types of testing were performed in the first phase of study: Qleak test and Sleak. Qleak tests were performed to test the air permeation happen in tires with nitrogen or dry air inflation during certain days in room temperature. Sleak tests were performed to test the air permeation happening in tires with nitrogen or dry air inflation during certain days in high temperature.

5.1.2. Test Conditions:

All the tests were done in static state. A testing period of 17.7 days (or 16 days) was used for Oleak tests and 28 days for Sleak. The air permeation in Qleak was occurred in room temperature around 21℃. The start/end pressure varies according to different tire type. The Sleak tests were performed in oven temperature. The tires were heated up first in the testing beginning and cooled down in 4 hours at the end. Test pressure was 5.5 bar (80 Psi) for Sleak tests.

5.1.3. Test Tires

Four tires, each with the dimensions shown in Table 2 corresponding to various categories, were tested at 4 different laboratories in both Qleak tests and Sleak tests. Two tires were inflated with nitrogen (95% purity) and the other two similar tires were inflated with dry shop air in each test.

5.1.4. Data Analysis:

In the first phase of the study only temperature and pressure were considered in the model. B0, B1 and B2 are constatnts.

In order to obtain the constants used in model, nonlinear regression techniques can be used. How the inflation pressure changed with time in different environmental temperature was studied. Non-linear technique that iteratively arrives at a solution by minimizing the sum of the square of errors (SSE) was applied to obtain the parameters for the regression model. This can be easily accomplished using a spreadsheet that includes an inbuilt routine for solving iterative problems. Results are also discussed in the next section.

All the tests were performed at Michelin America Research Corporation.

Table 2: Tire Serial No, Inflation type and Size

Test		Tire Serial No.	Inflation type	Tire Size
QLeak	SLeak			
Test 148913	Test 148916	93066627	Nitrogen	LT265/65R18122/119R
		93066688	Nitrogen	
		93066689	Dry air	
		93066696	Dry air	
Test 148918		A09L	Nitrogen	T125/70D15 MINI SPARE 95M
		CIR0	Nitrogen	
		A04L	Dry air	
		A01R	Dry air	
Test 148914	Test 148917	56900048	Nitrogen	P235/55R17 98VTLEN
		56900049	Nitrogen	
		56900051	Dry air	
		56900052	Dry air	
Test 148919	Test 148921	37504265	Nitrogen	445/50R22.5 XONEXDAHT+TL
		37504267	Nitrogen	
		37504072	Dry air	
		37504074	Dry air	
Test 148920	Test 148922	33104382	Dry air	275/80 R22.5 PILOT XZE TL LRG
		33104383	Dry air	
		33104386	Dry air	
		33104388	Dry air	

5.1.5. Results and Discussion

5.1.5.1 Qleak Test Results and Discussion

Figures 8 through 11 show the inflation pressure change with time in Qleak test.

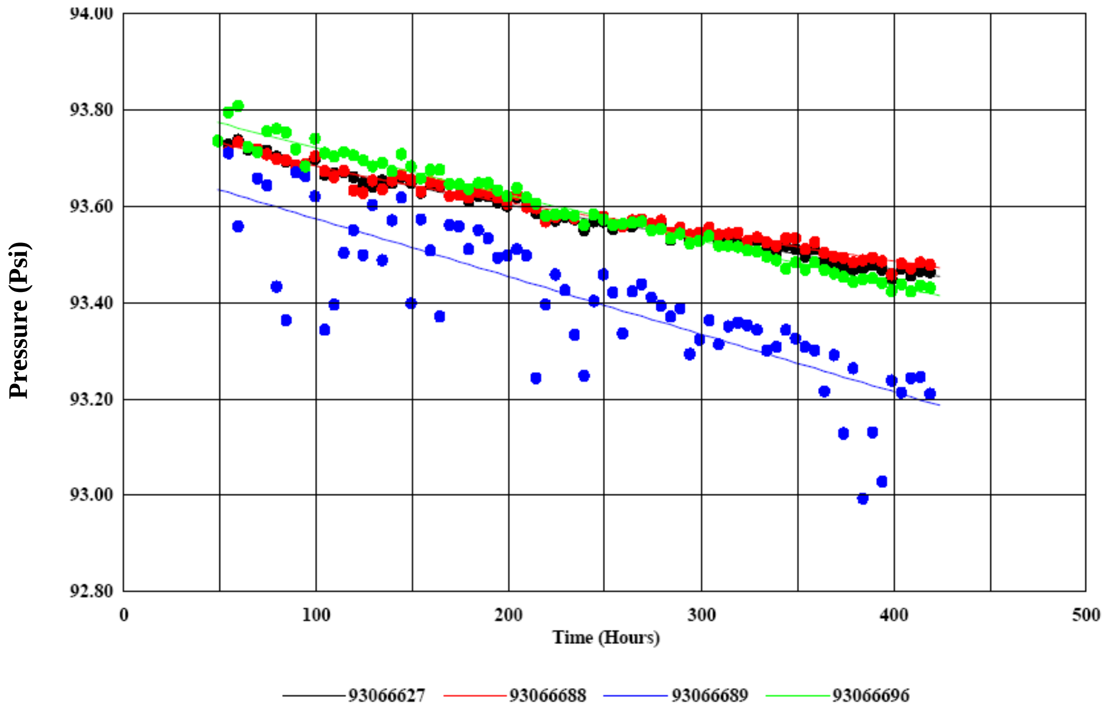


Figure 8: Measured inflation pressure change with time in Qleak test for LT265/65R18122/119R

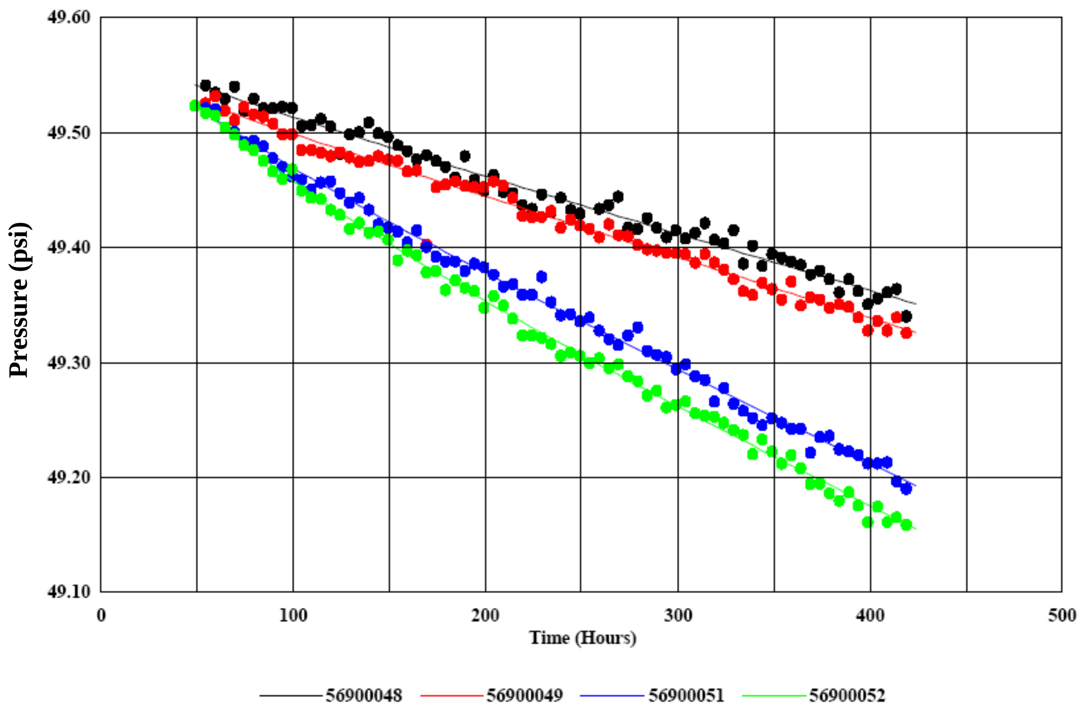


Figure 9: Measured inflation pressure change with time in Qleak test for P235/55R1798VTLEN

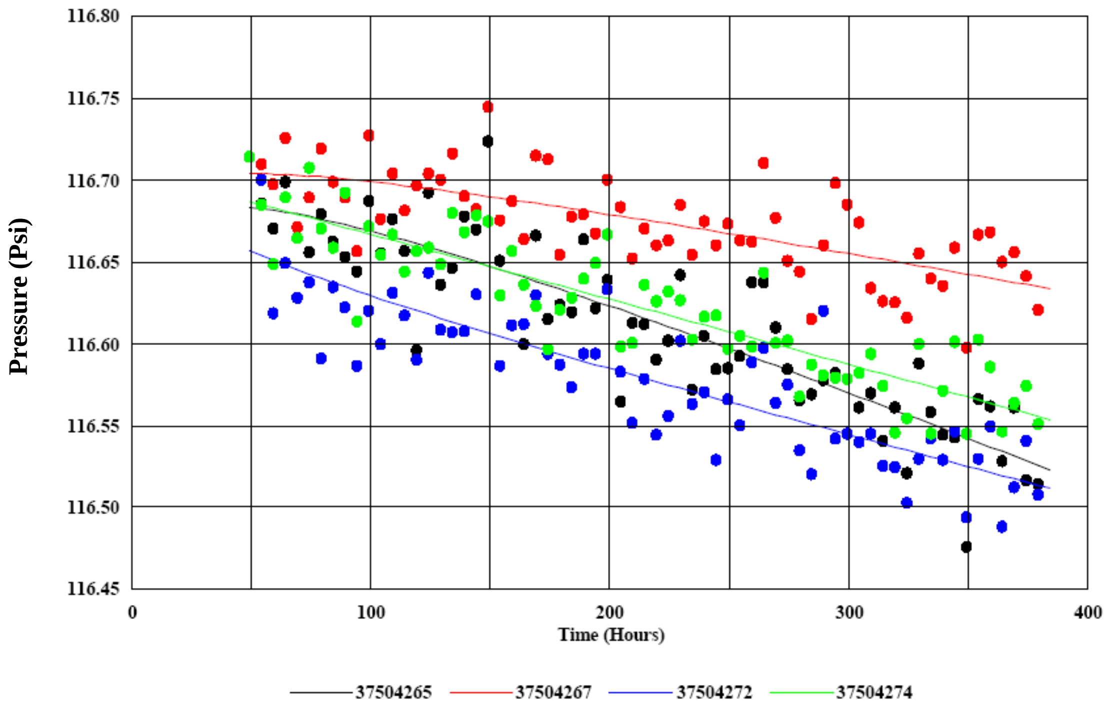


Figure 10: Measured inflation pressure change with time in Qleak test for T125/70D15 MINI SPARE 95M

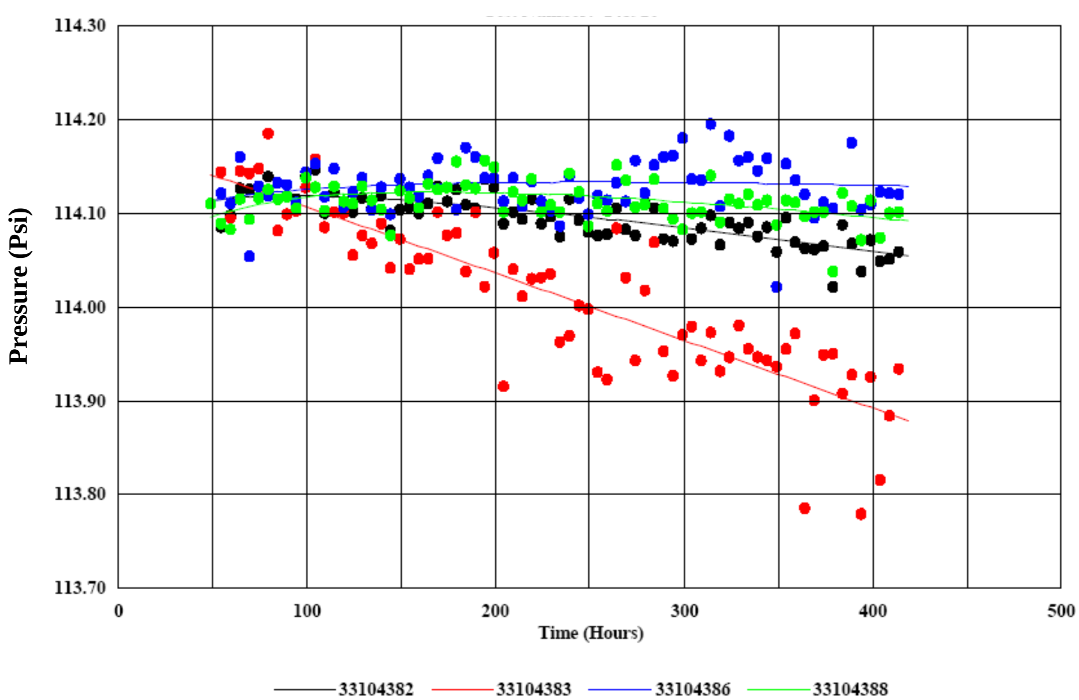


Figure 11: Measured inflation pressure change with time in Qleak test for 275/80 R22.5 PILOT XZE TL LRG

As seen from Figure 8 - 11, for nitrogen inflation and air inflation in 4 different tires, the measured pressure decreased almost linearly as time passes by. It was observed that the current model provide a better representation of the inflation pressure vs. time relationship with any given tire types. However, it was observed that the SSE for the same tire in one test compared to other three. This requires further analysis and study.

Tables 3 - 6 show the air loss in tires in Qleak test.

Table 3: Air leakage in Qleak test for LT265/65R18122/119R

Serial Number	Air Loss in %/Month	standard Error in %/Month
93066627-N	0.48%	0.04%
93066688-N	0.43%	0.04%
93066689-A	1.08%	0.31%
93066696-A	0.82%	0.05%

Table 4: Air leakage in Qleak test for P235/55R17 98VTLEN

Serial Number	Air Loss in %/Month	standard Error in %/Month
56900048-N	0.99%	0.07%
56900049-N	1.07%	0.08%
56900051-A	1.51%	0.05%
56900052-A	1.48%	0.05%

Table 5: Air leakage in Qleak test for T125/70D15 MINI SPARE 95M

Serial Number	Air Loss in %/Month	standard Error in %/Month
37504265-N	0.45%	0.09%
37504267-N	0.21%	0.07%
37504272-A	0.24%	0.09%
56900052-A	0.28%	0.07%

Table 6: Air leakage in Qleak test for 275/80 R22.5 PILOT XZE TL LRG

Serial Number	Air Loss in %/Month	standard Error in %/Month
33104382-A	0.24%	0.05%
33104383-A	0.53%	0.13%
33104386-A	0.07%	0.08%
33104388-A	0.22%	0.05%

The experimental study showed that nitrogen inflation can maintain the tire pressure 35% - 55% better than shop day air per month in room temperature depending on different tire type.

5.1.5.2 Sleak Test Results and Discussion:

Figures 12 through 15 show the inflation pressure change with time in Sleak test.

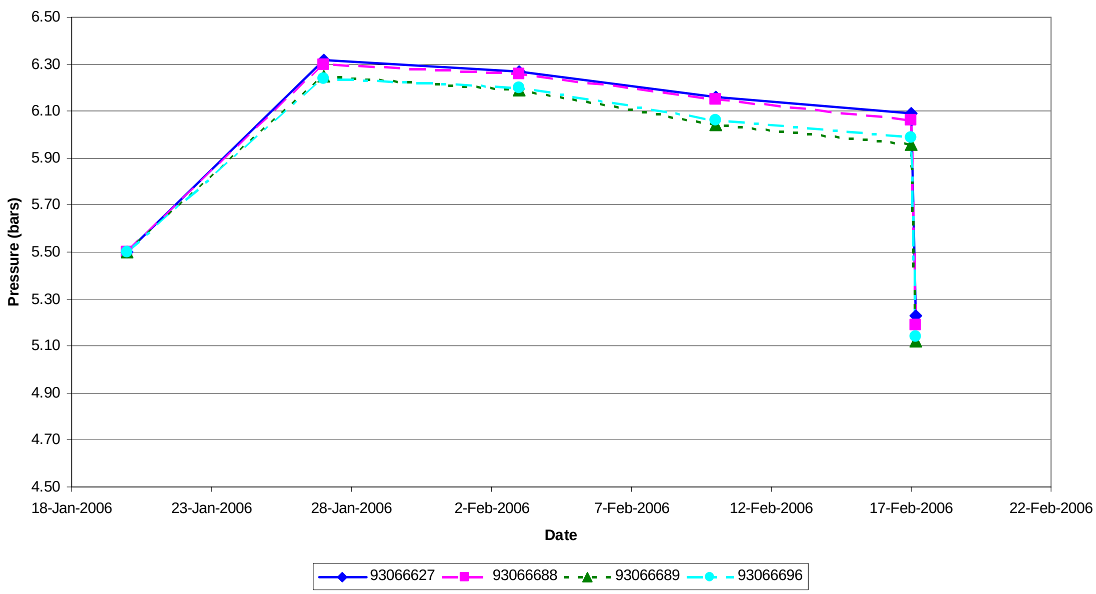


Figure 12: Measured inflation pressure change with time in Sleak test for LT265/65R18122/119R

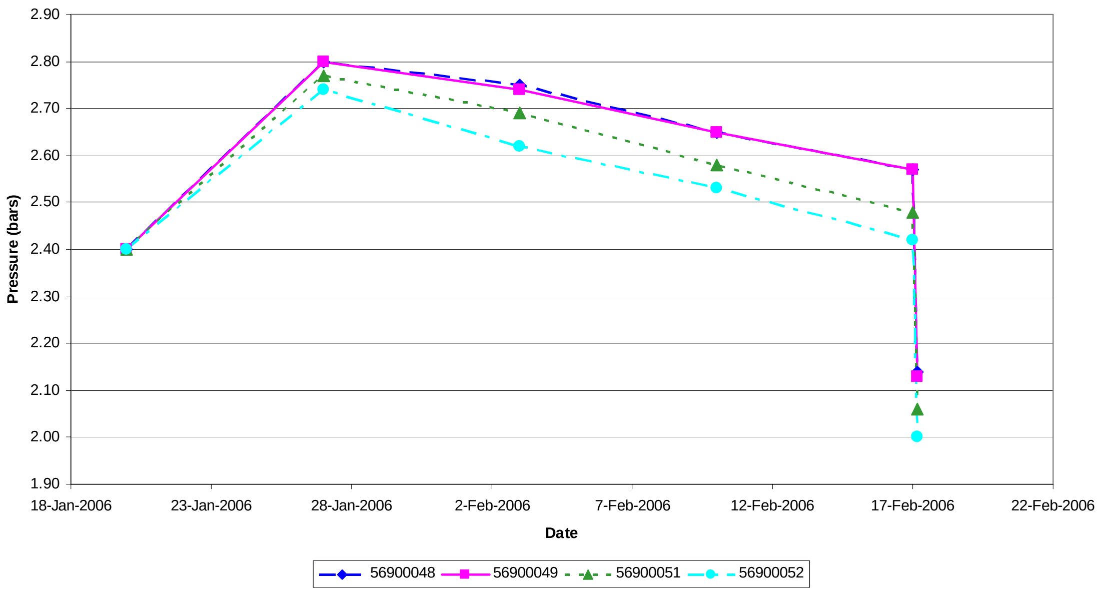


Figure 13: Measured inflation pressure change with time in Sleak test for P235/55R17 98VTLEN

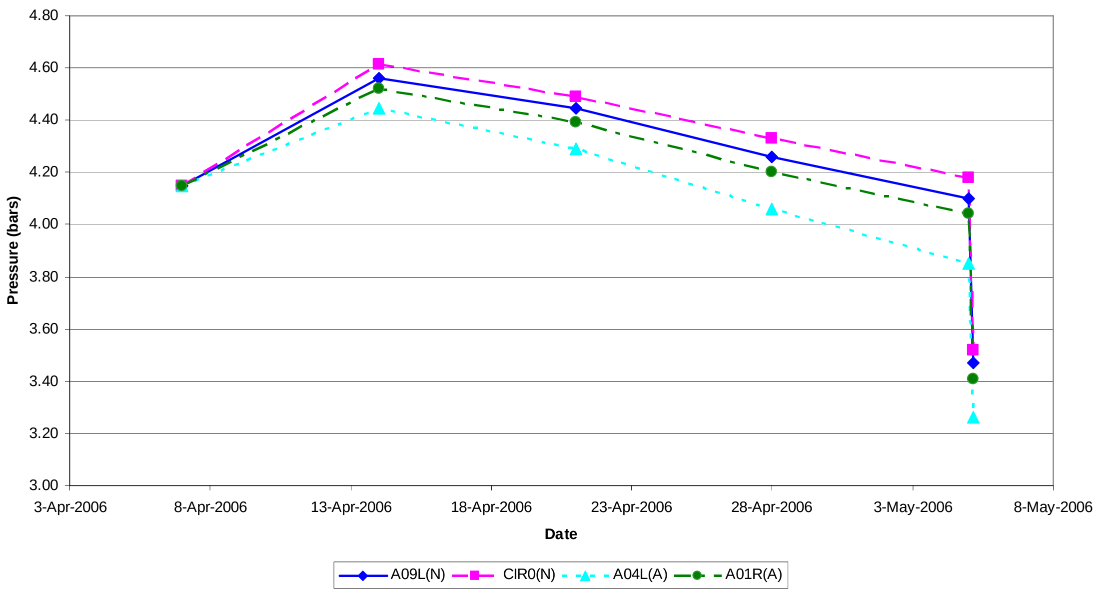


Figure 14: Measured inflation pressure change with time in Sleak test for T125/70D15 MINI SPARE 95M

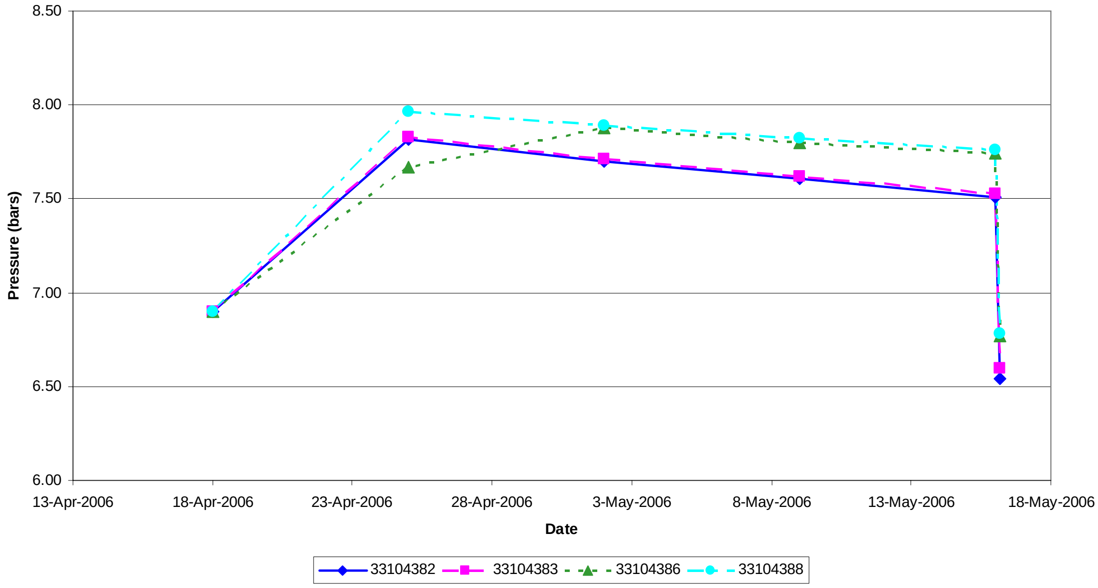


Figure 15: Measured inflation pressure change with time in Sleak test for 275/80 R22.5 PILOT XZE TL LRG

As seen from Figure 12 - 15, the pressure goes up in the first week because of the high temperature in the oven. Then, similar to what happened in Qleak tests, the pressure decrease as time passes by. After 4 hours cool down at the end of the test, the tire pressure goes down straight to the normal value. The experimental study showed that the nitrogen inflation can maintain the tire pressure 29% - 35% better than shop day air per month in oven temperature depending on different tire type.

5.2. PHASE II RESULTS AND ANALYSIS

5.2.1 INTRODUCTION

In phase 2, a large corporate truck fleet in 3 separate distribution center locations were filled with both nitrogen and air and the inflation pressure and tread depth of all the 10 tires of each truck were recorded periodically to investigate inflation pressure leakage at different time frames. The absolute value of rolling resistance of the tires are calculated and tabulated to show decrease in rolling resistance with increase in tire pressure and how this increases the fuel economy of the vehicle and improve tire performance.

5.2.2 TEST CONDITIONS

Each truck at a specific location was filled with one of the inflation gases and readings were recorded at the end of every 2 weeks. The trucks carried an average load of 80,000 lbs and travel about 2500 miles per week. Every time a pressure reading is noted, the tread depth of each tire of each truck corresponding to the inflation pressure is also recorded. The inflation pressure of each tire is noted in terms of kilo pascals and tire depth in terms of millimeter. Mileage readings of the truck were also noted to calculate the life of each tire and its inflation pressure leakage rate depending on the distance covered by tire per week for a given load.

5.2.3 TEST TIRES

Two different types of tires, namely Michelin and Bridgestone tires are used for testing. All the tires in all the 3 locations along with their corresponding sizes, the vehicle model and the inflation types are represented in Table 7. The tire sizes, model and serial numbers of each of the ten tires of each truck were systematically recorded to calculate the rolling resistance of each tire and each truck.

5.2.4 DATA ANALYSIS

There are two different types of tires, namely Michelin and Bridgestone tires are used for testing. Since we are interested in finding the influence of inflation pressure on rolling resistance, the tire characteristics and parameters such as load (Z) and velocity (V) are considered constants. In fact the regression exponents used for both the tires are considered to be the same as it is determined that for truck tires the value of Alpha (α) and Beta (β) are respectively -0.2 and 0.9.

Since the roll resistance force Fr is proportional to the normal force acting on the tire, it is natural to define the coefficient of rolling resistance Cr as:

$$Fr = Cr\ Z \tag{15}$$

Where, Cr is the Coefficient of rolling force and L is the Normal load acting on the tire.

The normal coefficient of rolling resistance for trucks is about 5kgf/T. Plugging this in equation (15) yields that the normal rolling force of truck tires is about 654349 N when we consider the load to be 80,000 lbs. To determine the influence of Load (Z), Velocity (V) and Pressure (P) on rolling resistance, we consider equation (9) to be the rolling force equation.

Since only absolute values of rolling resistance is found, we neglect the effect of velocity on rolling resistance and hence values of normal load and the velocity terms are considered to be constant values for both the type of tires.

Now equation (9) becomes,

$$F_r = P^{\alpha}\ Z^{\beta}\ k \tag{16}$$

By picking out a value of inflation pressure, the value of constant (k) is determined to be 477.45. All the calculations were done by using this constant (K) value of 477.45 and substituting inflation pressure in the above equation to determine the corresponding rolling resistance.

Table 7: Location, Tire Size and Inflation type

Location	Vehicel Model	Tire Make	Tire Size	Inflation Type
DC 1	9400 i	Michelin	275/80R22.5	Air
				Nitrogen
DC 2	Class 8	Bridgestone	295/75R22.5	Air
				Nitrogen
DC 3	9400 i	Michelin	275/80R22.5	Air
				Nitrogen

5.2.5 RESULTS AND DISCUSSIONS

5.2.5.1 Rolling Resistance Results and Discussions

The absolute value of rolling resistance of the trucks for its corresponding values of inflation pressure at all the locations is given in the table below. The rolling resistance values are shown for both air and nitrogen filled tires.

Table 8: Rolling Resistance comparison at each Location

Location	Filling Type	Starting Pressure (Kpa)	Ending Pressure (Kpa)	RRs (N)	RRe (N)	Increment (N)	Percentage (%)
DC 1	Nitrogen	5.17	5.05	30212482	30354721	142238.46	
	Air	5.85	5.38	29474968	29972852	497883.39	71
DC 2	Nitrogen	6.67	6.55	28711729	28816170	104440.7	
	Air	6.88	6.48	28534274	28878160	343885.7	70
DC 3	Nitrogen	5.56	5.45	29776220	29895459	119238.77	
	Air	6.06	5.67	29267794	29659779	391984.46	70

Based on the test data, rolling resistance statistics were calculated using different inflation pressures at the beginning and end of each test run, where other parameters were kept constant. As seen from Table 8 the nitrogen filled tires have 70% less rolling resistance compared to air filled tires due to their capability to hold the inflation pressure longer. To further understand the leakage rate of nitrogen and air in the truck tires, the pressure drop per mile of both tires were calculated. Considering that a truck travels about 2500 miles/week, Table 9 represents pressure drop per week at each location based on inflation pressure value at start and end of each run and the distance traveled during that time.

Table 9: Inflation pressure drop per week a each Location

	Inflation Pressure drop/week (Kpa)		
Filling Type	DC 1	DC 2	DC 3
Nitrogen	0.030	0.029	0.029
Air	0.118	0.102	0.01

Inflation pressure plays an important role in rolling resistance of tires as the contact patch area of the tire is a direct function of the inflation pressure. With decrease in inflation pressure, contact patch area increases, hence more energy is expelled in moving the tire increasing the rolling resistance. Lower inflation pressure causes the premature and irregular tire wear as more tire area comes in contact with the road during rolling.

5.2.5.2 Tire Tread Wear Results and Discussions

We know that tire tread wears out with time and there are various factors that affect the rate of tread wear. As tire inflation pressure plays an important role in tire tread wear, it is important to study the wear rate of tires with inflation gas diffusion rate. Table 10 shows the wear rate per mile of front and rear tires of a truck for both nitrogen and air filled tires.

Table 10: Comparison of rate of decrease in tread depth per mile.

	Front Tires				Rear Tires			
	Nitrogen Inflation	Air Inflation			Nitrogen Inflationed	Air Inflation		
Location	Wear/mile (mm)	Wear/mile (mm)	Increment (mm)	Percentage (%)	Wear/mile (mm)	Wear/mile (mm)	Increment (mm)	Percentage (%)
DC 1	0.00005082	0.0001	0.000049	49	0.000071	0.00015	0.000079	53
DC 2	0.000068	0.00013	0.000062	48	0.000081	0.00016	0.000079	49
DC 3	0.000052	0.0001	0.000048	48	0.00006	0.00012	0.00006	50

Due to smaller contact patch area of nitrogen inflated tires, they wear at a slower rate than air filled tires. Table 10 describes the wear rate of front and rear tires of a truck for both inflation types. It can be observed that the life span of front tires of a truck on an average can be increased by 48% and front tires of a truck can be increased by 51%. This helps increase the mileage of tires thus reducing the cost of replacement tires.

Truck tires are replaced at periodic intervals based on the number of miles they run and the tire tread depth. Typically the front truck tire is replaced every 130,000 miles when the tire tread depth reaches 6/32nds of an inch (4.7mm). The rear tires are replaced every 250,000 miles when the tread depth reaches 4/32nds of an inch (3.2mm). Nitrogen inflated tires increase the tire mileage by 49% and 53% of front and rear tires respectively at DC 1, 48% and 49% of front and rear tires at DC 2 and 48% and 50% of front and rear tires at DC 3. The number of additional mileage and total tire mileage of nitrogen inflated tires for front and rear tires of each truck is given in Table 11.

Table 11: Mileage increase of nitrogen inflated tires

	Front tire			Rear tire		
	Air inflation	Nitrogen inflation	Increment	Air inflation	Nitrogen inflation	Increment
Location	Mileage (miles)	Mileage (miles)	Mileage (miles)	Mileage (miles)	Mileage (miles)	Mileage (miles)
DC 1	130,000	193,700	63,700	250,000	382,500	132,500
DC 2	130,000	192,400	62,400	250,000	372,500	122,500
DC 3	130,000	192,400	62,400	250,000	375,000	125,000

5.2.5.3 Fuel Economy and Environmental Effects

It is important to improve fuel efficiency of trucks as it would drastically cut down the money spent on fuel. Previous studies have concluded that a 4 to 10% improvement in fuel economy could be realized. The above results show that by using nitrogen inflated tires, the rolling resistance can be decreased by about 70%. For every 3% reduction in rolling resistance, fuel economy can be improved by 1%. Hence for a reduction of 70% rolling resistance in tires, fuel economy can be improved by 23%. It is important to note that is a mathematical model. Other variables such as road conditions and environment temperature affect this percentage.

However, if we consider that a truck using air inflated tires, on an average, gives a mileage of 7 miles per gallon, then the mileage of a truck using nitrogen inflated tires would increase to 8.6 miles per gallon due to 23% improvement in fuel economy. A truck traveling 2500 miles per week would use up only 290 gallons of fuel running on nitrogen inflated tires when compared to 357 gallons of fuel for a truck using air inflated tires. Hence one can save about 67 gallons of diesel every week by using nitrogen inflated tires. This is about 270 gallons of fuel savings every month and about 3240 gallons of diesel every year. Considering the cost of diesel to be $2.47/gallon as per government norms, one can save $667 per month per truck and $8003 per truck per year. For a fleet consisting of 150 trucks, cost savings on fuel is $1200450 per year.

Improving fuel economy by decreasing rolling resistance also has a positive impact on the environment. We can save 3240 gallons of fuel every year which means CO2 emission due to burning 3240 gallons of diesel into the atmosphere is prevented. As presented by EPA burning 1 gallon of diesel emits 10.1 kg of carbon dioxide into the atmosphere. By saving 3240 gallons of diesel we can reduce CO2 emissions by 32.7 tones every year per truck. Hence for a fleet of 150 trucks CO_2 emission can be reduced by 4905 tones every year by using nitrogen inflated tires.

6. CONCLUSION

All the tests conducted clearly indicate that nitrogen inflation in passenger car tires can improve passenger safety and tire life while improving the fuel economy of the vehicle. Nitrogen inflated tires can maintain tire pressure 74% better than shop air per month at normal operating conditions. As a result, nitrogen inflated tires produce about 70% less rolling resistance than air inflated tires.

Reducing rolling resistance of tires has a positive influence on the fuel economy and life of a truck tire. This prevents premature wear of truck tires. By inflating truck tires with nitrogen, fuel economy can be increased by about 23.3% and tire life be increased by 50%. Overall cost incurred on fuel and replacement tires is drastically reduced and a CO2 emission into the atmosphere is cut down by 19%. Decreasing rolling resistance by 70% increases the fuel economy of the vehicle by about 23%. It also helps improve tire life by 50%. All these improvements help reduce the money spent on fuel and replacement tire. Apart from this it reduces CO2 emission into atmosphere due to burning of diesel. This provides the technical support for the statement that nitrogen filled tires has a positive effect on vehicle fuel economy and tire performance.

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