White paper

Role of innerliners in improving "in-use rolling resistance"

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Fuel efficiency improvement

Improving the fuel efficiency of passenger cars (PC), light trucks (LT) and medium heavy commercial vehicles (MHCV) has been a priority for vehicle manufacturers and component suppliers; partly due to preset regulations such as the Corporate Average Fuel Economy (CAFÉ, USA) standards [1, 2].

In 1975, the average fuel economy in the United States was 13.5 MPG; in 2016, it was 26 MPG[1]. The 2008-2016 USA administration had set an objective of doubling the fuel economy by 2025; which currently, the EPA is considering to scale back, as it is extremely difficult to achieve[1].

Whatever the drivers were, it can be said that the fuel efficiency improvements made in the past forty years have cut the annual cost of fuel by a significant amount. For medium and heavy commercial fleet owners, achieving the maximum possible fuel efficiency is extremely important as fuel costs are a significant portion of their operating costs.[1,2]

Passenger car fuel economy depends on several factors. Fuel economy can be lowered by excessive loads, high speeds, long idling times, aggressive driving (high acceleration and excessive braking), high aerodynamic drags (due to wind speed or cargo), cold weather, short travel distances, use of electrical accessories (such as the air conditioning system), driving on various terrains/uphill routes and use of a four wheel drive[3].

It can also be further reduced if the engine is not properly tuned or maintained, use of reformulated gasoline, lack of engine break-in (i.e. new vehicles), energy inefficient tires, poorly aligned tires, poorly inflated tires, dirty air filters, brake drags, and slight differences in component assembly (vehicle variations)[3].

In this paper we will focus on the contribution of the tire to fuel efficiency. Specifically, we will discuss the effect of the air loss on the actual rolling resistance (as experienced after months of driving) and its subsequent effect on fuel efficiency.

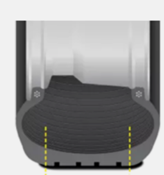
We will also recommend possible avenues to minimize the "in-use" rolling resistance as experienced by consumers to maximize fuel efficiency.

Rolling resistance and air pressure correlation

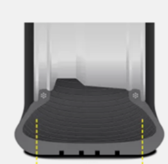
It is important to understand the physical context of rolling resistance and how it relates to air pressure. The energy to move a vehicle forward is supplied by the fuel and transmitted via the axles to rotate the tires. As the rotating tire is in contact with the road (contact patch), it deforms[4]. All forces for accelerating, braking and cornering are transmitted through this contact patch; this deformation also absorbs the surface asperities of the road which is responsible for providing grip and comfort.

Since tires are primarily viscoelastic rubber compounds, this deformation also results in some heat dissipation (which results in lost energy) also called the resistance to rolling. Hence, rolling resistance can be defined as the energy consumed by the tire (in the form of heat) per unit distance covered[4].

Difference in deformation between properly inflated tires and underinflated tires[5]



Proper inflation
= lesser deformation
= lesser rolling resistance



Underinflation
= higher deformation
= higher rolling resistance

Now let us talk about how air pressure affects rolling resistance. If the tire is properly inflated and there is no air loss, then this would lead to low amounts of deformation; thereby, reducing rolling resistance. It can also be visualized that in this case, the tire is stiffer and hence, more resistant to any deformation.

However, tires are not entirely leak-proof systems; they lose a certain amount of air on a continuous basis. Over the course of time, air loss from tires would lead it to be slightly underinflated. In an underinflated tire, the tire is less stiff and the deformation would be much higher, leading to a larger amount of heat dissipation. This would lead to a higher actual on-road rolling resistance experienced by the driver and poor fuel efficiency.

Significant effort and resources are spent by the tire industry every year on the research and development of new tire materials and designs to meet increasingly strict regulatory and performance expectations, with respect to lowering the rolling resistance and improving fuel efficiency. All these can be realized in a meaningful way only if the tire retains its full inflation pressure.

Most manufacturers and regulators mandate relative rolling resistance values on the tire label. Selecting low rolling resistance tires would be key; however, these are relative rolling resistance ratings from a laboratory test method.

There is a difference between the rolling resistance values obtained from standard test methods (reported values) and the "in-use" rolling resistance resulting from actual driving conditions and its correlations to the actual fuel efficiency experienced during various driving conditions.

The two most standard methods for measuring rolling resistance are the ISO 28580 test and the SAE 1269J test, both of which are single point laboratory tests[6] measured under controlled conditions, where the tire is mounted on a free rolling spindle and turned by contact against a large powered test drum. The magnitude of the rolling resistance value obtained (both tests yield very similar values) depends on the surface of the drum, inflation pressure, load and speed – all of which are held constant during the test (hence, called single-point test).

The rolling resistance is not an intrinsic property of the tire, but a function of several operating variables. Are all these parameters constant in the real world? Even if most surfaces and loads are similar, the air pressure definitely changes over time as the tire leaks air. Since air loss over time changes the inflation pressure, the "in-use" rolling resistance experienced in actual driving conditions can be higher leading to lower fuel economy.

Unfortunately, these aspects might not be captured in the laboratory tests for measuring rolling resistance[6].

Rolling resistance improvement

It is extremely difficult to design a tire that is entirely leak proof. So how can air loss in a tire be minimized or how could one effectively manage air pressure?

There are multiple ways to do this. Mandatory implementation of the tire pressure monitoring system (TPMS) is a good first step. These systems alert the driver once the air pressure drops below a certain threshold (usually 15-25% drop[9,10]), but the system doesn't automatically correct the problem.

Several new large fleets use automatic tire inflation systems (ATIS) that keep tire pressure constant. However, these systems are expensive and very often, it is cumbersome to retrofit an existing vehicle with a new system. An existing but highly underutilized solution to minimizing the air loss from tires is the thin innerliner layer that holds the air in the tires[7].

The innerliner is the innermost layer used in tires; the composition and design of this layer are the most crucial factors affecting air retention. Internal studies have shown that among the three factor that contribute most to air retention, the biggest contributor is the permeability component. For example, decreasing the innerliner end to toe distance by 50% (from 20 mm to 10 mm) and increasing thickness by 15% (0.65 mm to 0.75 mm) gives an Inflation Pressure Loss Rate (IPLR) improvement of 10% and 18% respectively; whereas, increasing the halobutyl content by 20% reduces the permeability coefficient by 40%, giving an IPLR improvement of 30%[7].

By designing effective innerliner systems, air loss can be minimized so as to minimize the "in-use" rolling resistance and maximize fuel efficiency.

Conventional innerliner compounds include bromobutyl and chlorobutyl polymers. To achieve best performance, it would be desirable to use high performance polymers such as brominated isobutylene-co-paramethylstyrene (BIMSM, trade name Exxpro™ specialty elastomer) which has a lower permeability than conventional halobutyl polymers[7].

"In-use" rolling resistance case study

We would like to present an "in-use" rolling resistance case study comparing three tires (identical in manufacturer, make, model, design, construction, and rating) with 3 different innerliners –

(a) one using a conventionally used halobutyl system with natural rubber (80/20 BIIR/NR)

(b) the second using 100% halobutyl

(c) third using 100% Exxpro based innerliners (composition of the tires are shown in **Table 1**).

In conventional systems, most manufacturers use some natural rubber to enhance the processing characteristics of the compound and lower the cost.

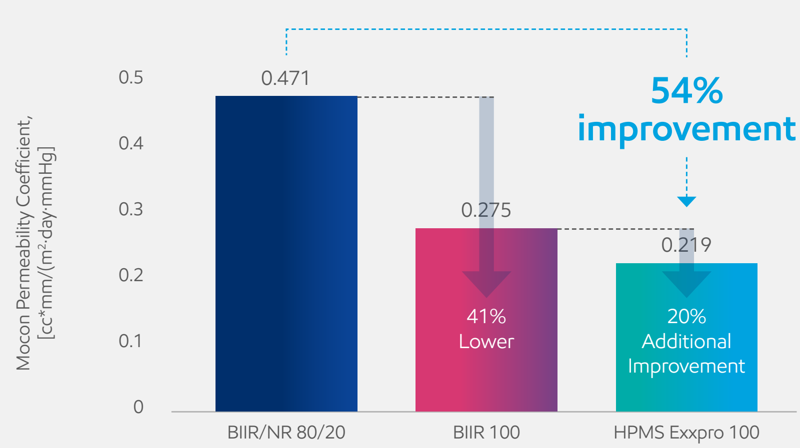
This however, increases the air loss rates. **Figure 1** shows the permeability comparison of the three innerliner compounds used to build the tires for the study. It should be noted that when compared to these conventional halobutyl systems (80/20 BIIR/NR), high performance pure Exxpro systems show almost a 54% improvement in air loss rates.

Table 1:
(a) Innerliner compositions for tires · (b) Innerliner fabrication & tire construction details

Raw material	BIIR/NR 80/20	BIIR 100	HPMS Exxpro 100
Exxon™ Bromobutyl 2222	**80**	**100**	-
Natural Rubber	**20**		
HPMS Exxpro™ NPX 1603		-	100
N 660 (Carbon Black)	60	60	60
Naphthenic Oil	8	8	8
Struktol 40 MS	7	7	7
Escorez 1102	4	4	4
Stearic Acid	1	1	1
MgO	0.15	0.15	0.15
Zinc Oxide	1	1	1
MBTS	1.25	1.25	1.25
SULFUR	0.5	0.5	0.5
TOTAL PHR	182.9	182.9	182.9

Details	BIIR/NR 80/20	BIIR 100	HPMS Exxpro 100
Innerliner Fabrication Details			
Innerliner Mixing Pass	2 Pass	2 Pass	
Mixer	F270	F270	
Sheeting	Calendar	Calendar	
Cushion	Yes	Yes	
Splice	Overlap	Overlap	
Tire Construction Details			
Tire Size	205/55r16	205/55r16	205/55r16
Load Rating	91V	91V	91V
Cured Innerliner Thickness (mm)	0.9 - 0.95	0.9 - 0.95	0.9 - 0.95
Toe Distance	Equal	Equal	Equal
Uniformity	A	A	A

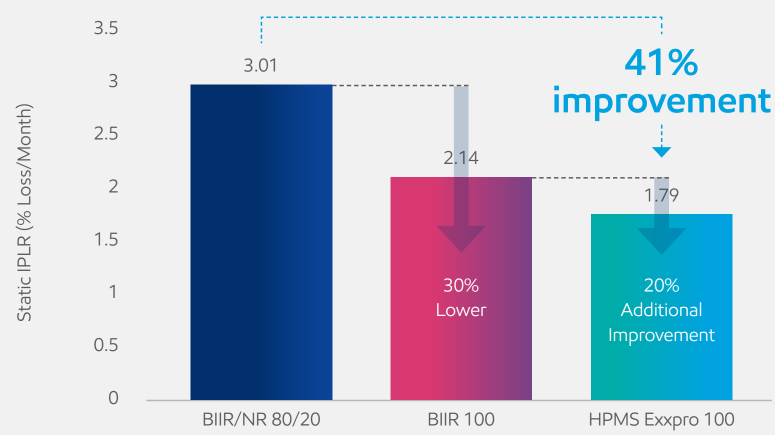
Figure 1:
Permeability of innerliner compounds used in study



In order to mimic real driving conditions, it is required to periodically measure rolling resistance values, subjecting the tire to real conditions over a period of time. In our studies, the three different tires were run on the roadwheel for a given number of miles per month (3000 miles/month) and subjected to natural deflation for the rest of the time.

This was repeated for almost 7 months (to simulate actual conditions the tire would be subjected to). Rolling resistance was measured initally before the start of the study, and then periodically at every month in accordance with ISO 28580 test method. Initial static IPLR was measured in accordance with ASTM 1112 test method, in a closed room at controlled conditions at 21°C + 1°C (**Figure 2**).

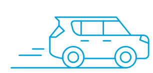
Figure 2:
IPLR of tires used in the study



In order to get a feel for the "in-use" IPLR that would be experienced in actual driving conditions, the IPLR was measured in 2 different ways.

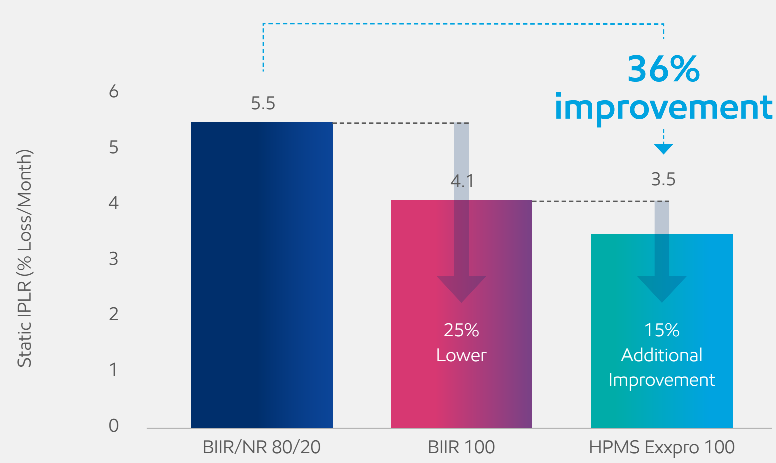
The results of the initial static inflation pressure loss rates are shown in **Figure 3**.

(a) on the road wheel simulating actual conditions



(b) an actual "on-road" driving test.

Figure 3:
IPLR after natural deflation on road wheel simulating actual driving conditions



The IPLR measured on the road wheel simulating actual conditions is shown in **Figure 4**.

These values closely mimic the inflation pressure loss rates obtained from real world driving conditions measured by the use of smart high precision sensors as shown in **Figure 5**.

The air loss of tires subjected to real world conditions were around twice as those obtained in static conditions in the laboratory (2X). Rolling resistance results as a function of time is shown in **Figure 5**. It can be seen that when pressure is lost, the rolling resistance increases.

For tires with conventionally used innerliner systems (80/20 BIIR/NR), the air loss over time is higher and this leads to an increase in rolling resistance by ~ 20% at the end of 7 months.

It is expected that the rolling resistance change for the tires with IPLR > 3.1% (BIIR/NR 80/20) is much higher than for the tires with IPLR < 1.8% (HPMS Exxpro 100).

For "in-use" efficiency, it is expected that there is minimal change to the rolling resistance over time. As shown in **Figure 5**, the tire with the lowest IPLR gives the lowest change to the RRC after 7 months of simulated "on-road" conditions.

Figure 4:
IPLR after "on road" testing of tires used in the study

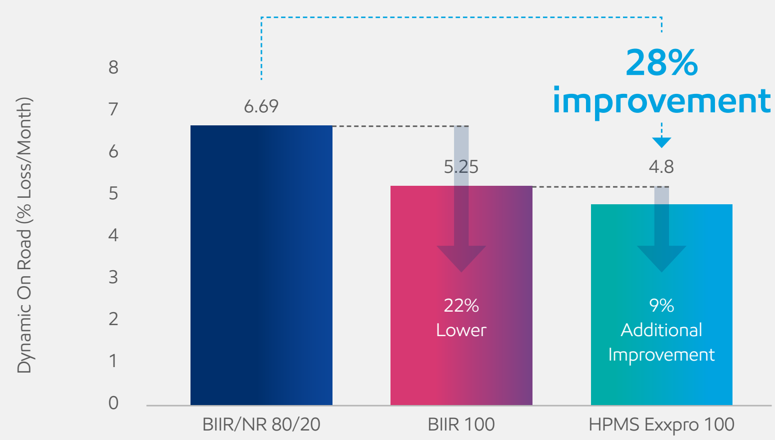
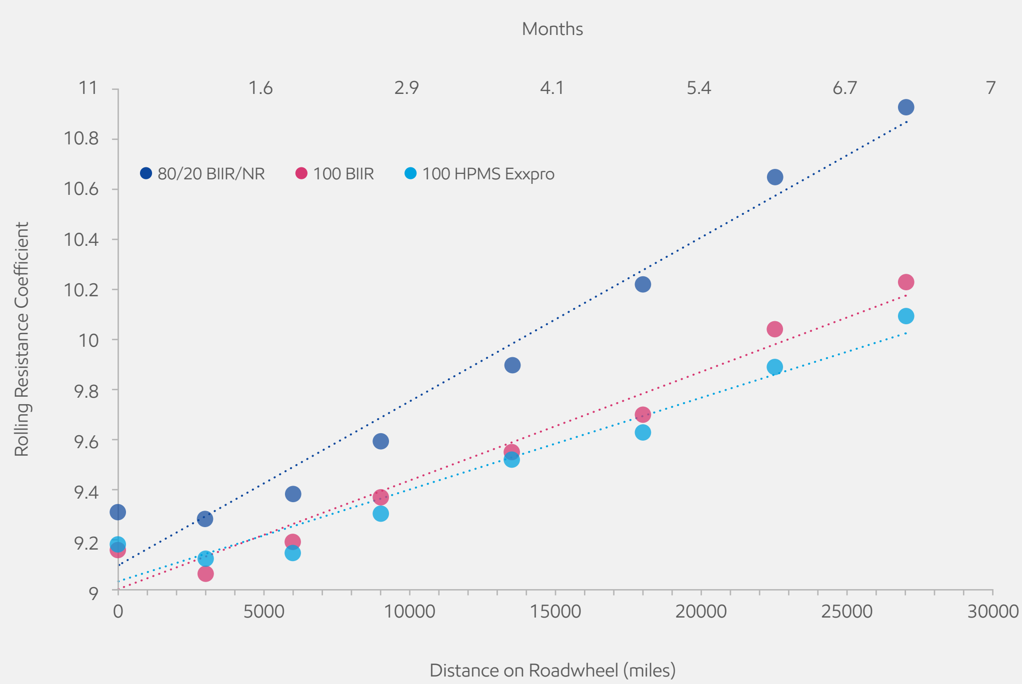


Figure 5:
Rolling resistance of tires used in the study as a function of time



In order to see the implications of rolling resistance and what it means on a macroscale, it is beneficial to conduct some calculations on fuel saved.

Studies conducted on 300 tires showed that 48% of the tires had an IPLR of ~ 3% and only 6% had an IPLR of ~1.68%. We will compare the fuel consumption difference at the book ends (extreme scenarios) using BIIR/NR 80/20 (IPLR ~ 3.1%) and HPMS Exxpro 100 (IPLR ~ 1.7%).

Details of the calculation is shown in **Table 2**.

The following assumptions are used in this calculation:
(a) average mileage = 25 MPG
(b) average distance travelled per month = 1000 miles/month (= 12000 miles/year)
(c) 10% RR increase = 1.5% decrease in fuel consumption.

The actual measured rolling resistance is used for month 0-7; RR for months 8-12 is calculated from the linear regression of the measured data from month 0-8. It can be seen that there is a difference of 4.5 gal/year in fuel consumption between vehicles using these two different sets of tires.

Table 2: Example monthly fuel consumption in a year with 2 different innerliner systems

Month	BIIR/NR 80/20 (IPLR = 3.1%)				HPMS Exxpro (IPLR = 1.7%)			
	RR	% Increase RR	% reduction FE	Extra Fuel (Gal)	RR	% Increase RR	% reduction FE	Extra Fuel (Gal)
0	9.3	0.0	0.0	0.0	9.2	0.0	0.0	0.0
1	9.3	0.0	0.0	0.0	9.2	0.0	0.0	0.0
2	9.4	1.1	0.2	0.1	9.2	0.0	0.0	0.0
3	9.6	3.2	0.5	0.2	9.3	1.1	0.2	0.1
4	9.9	6.5	1.0	0.4	9.5	3.3	0.5	0.2
5	10.2	9.7	1.5	0.6	9.6	4.3	0.7	0.3
6	10.7	15.1	2.3	0.9	9.9	7.6	1.1	0.5
7	11.0	18.3	2.7	1.1	10.1	9.8	1.5	0.6
8	11.2	20.4	3.1	1.3	10.2	11.3	1.7	0.7
9	11.5	23.6	3.5	1.5	10.4	13.3	2.0	0.8
10	11.8	26.8	4.0	1.7	10.6	15.3	2.3	0.9
11	12.1	30.0	4.5	1.9	10.8	17.3	2.6	1.1
12	12.4	33.2	5.0	2.1	11.0	19.3	2.9	1.2
Extra fuel consumed/year				11.7	Extra fuel consumed/year			6.3

If we assume that the total number of vehicles on the road globally is 1.2 billion units and 48% of these vehicles are operating on tires with IPLR > 3 (as shown in previous surveys), then the amount of fuel wasted by this fraction of vehicles would be 1.2 billion x 0.48 x 4.5 ~ 2.6 billion gals – which can be potentially saved by using tires with ultralow IPLR (~ 1.7%).

In the US, the energy consumption per year is 11000 KW-hr/year/household. The amount of energy difference consumed between tires with IPLR of almost 3.2% and IPLR of 1.7% is the annual energy consumed by 8.7 million households.

Reducing IPLR and "in-use" RRC enables the potential for Tier 1 suppliers and OEMs to maximize performance.

The above case study results show an IPLR < 1.8% would provide a benefit of reduced fuel consumption by 4.5 gal/year. In the future, it is not a stretch to expect that an IPLR < 1.8% will be the target IPLR specification for global OEM leaders in the next 5 years. It is beneficial for OEMs and tire makers to revise IPLR specifications to the next generation level of < 1.8%. In this way, we can improve customer experience and maintain consistent vehicle performance.

References:

1. "Government fuel economy standards for cars and trucks have worked" – The conversation, April 2018 (http://theconversation.com/government-fuel-economy-standards-for-cars-and-trucks-have-worked-94529)

2. National Highway Transportation & Safety Administration, "Corporate Average Fuel Economy" (https://www.nhtsa.gov/laws-regulations/corporate-average-fuel-economy)

3. Fuel Economy Guide 2019 (www.fueleconomy.Gov.)

4. The tire rolling resistance and fuel savings: A publication from Societe de technologie Michelin, 2003.

5. Picture (Image) reproduced from discount tire website (www.discounttire.com).

6. DOT HS 811154; NHTSA Tire Fuel Efficiency Consumer Information: Program Development – Phase 2: Effects of tire rolling resistance on traction, tread wear and vehicle fuel economy, August 2009.

7. Nair, S. "Evaluation of Exxpro in Tire Innerliners" ACS 198th Technical Conference, Cleveland, OH 2019

8. ExxonMobil Butyl Regulatory Fact Sheet, 2017, pp 2.

9. https://www.caranddriver.com/features/a26513421/tire-pressure-light-what-it-means/

10. https://www.edmunds.com/car-safety/tire-pressure-monitors-can-you-rely-on-them.html

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