"EVALUATION OF CHANGE IN TYRE ROLLING RESISTANCE (RR) WITH VIRTUE OF TYRE TREAD WEAR"

-COMPARING THE VALUES OF COEFFICIENT OF ROLLING RESISTANCE AND ROLLING RESISTANCE WITH RESPECT TO TYRE WEAR-

Dushyant Wazir[1]

[1]*International Centre for Automotive Technology, Plot No-1, Sector-M-11, HSIIDC, IMT Manesar, Gurugram-122050, Haryana(INDIA)*

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Abstract - *Rolling resistance is nothing but the rolling drag, which is the force resisting the motion when a body rolls on a surface. It is mainly caused by non-elastic effects like losing required energy into heat i.e. hystresis loss, energy lost in form of noise. It is recovered when the pressure is removed, within the sort of hysteresis losses and permanent deformation of the tyre surface. So, the rolling resistance contributes to the deformation of the roadbed as well as tyre surface of the vehicle. Factors contributing to rolling resistance are tyre inflation pressure, wheel diameter, speed, load on wheel, surface adhesion, sliding, and relative micro-sliding between the surfaces of contact. In this concerned paper, we are significantly working on the effect of tyre inflation pressure on rolling resistance and taking all other factors constraint.*

Key Words: Tyre Technology, Rolling Resistance, Tyre wear, Tyre Efficiency, Coefficient of Rolling Resistance.

1. INTRODUCTION

When Tyre rolls degradations occur on tyre Surface due to mechanical wear and chemical aging which affect both durability/running cycle and safety but along with affecting tyre properties like rolling resistance which contributes to inefficient rolling of tyres.

Narrowing down energy consumption and waste are the major goal for all nations and also the foremost demand for a better and sustainable future. Energy efficiency not just incorporates better economic development but is also essential for less environmental degradation. With the rising energy prices, consumers and businesses are getting affected negatively, and have contributed to exalting in the Consumer Price Index in recent years. A vehicle's fuel economy is suffering from Tyre rolling resistance; therefore, fuel-saving might be achieved by reducing Tyre rolling resistance. Low-rolling-resistance original equipment (OE) Tyres are employed by auto manufactures to assist meet the Federal fuel economy standards for brand spanking new passenger cars and lightweight trucks.
Rolling Resistance and its coefficient are the parameters that are not independent of other tyre properties like traction, tyre pressure, material compounding, shape, design, and Tyre wear rate. So, to understand the effect of tyre wear on rolling resistance and its coefficient ICAT's TTL is conducting this study in the ISO and NABL accredited Lab to corroborate the best results and can simulate the actual conditions for the tests. By, this study we can lead to a solution, whether tyre wear plays a major role in influencing the tyre rolling resistance or not.

This paper presents a study that shows the effect of tyre wear on the rolling resistance of the tyre. Five numbers of radial car tyres of different sizes, Speed symbols, and load indexes were selected for the study which was worn using a machine that simulates the actual road condition. The tyres wear is conducted in steps by running the tyre in the cycle of 10000 km. Before and after each step rolling resistance of tyres was measured on the Rolling Resistance Test Machine aligned with the reference laboratory as per regulation ECER 1222/2009. To simulate the same test conditions for all the tyres the temperature was kept within the tight range of 25 ±5°C.

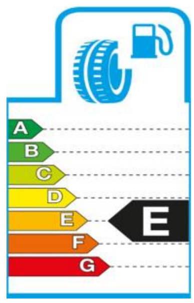

Figure-1 EC Regulation 1222/2009, Tyre Rating on the bases of Cr.

C1 Tyres		C2 Tyres		C3 Tyres	
RRC in kg/t	**Energy Efficiency class**	**RRC in kg/t**	**Energy Efficiency class**	**RRC in kg/t**	**Energy Efficiency class**
RRC ≤ 6.5	A	RRC ≤ 5.5	A	RRC ≤ 4.0	A
6.6 ≤ RRC ≤ 7.7	B	5.6 ≤ RRC ≤ 6.7	B	4.1 ≤ RRC ≤ 5.0	B
7.8 ≤ RRC ≤ 9.0	C	6.8 ≤ RRC ≤ 8.0	C	5.1 ≤ RRC ≤ 6.0	C
Empty	D	Empty	D	6.1 ≤ RRC ≤ 7.0	D
9.1 ≤ RRC ≤ 10.5	E	8.1 ≤ RRC ≤ 9.2	E	7.1 ≤ RRC ≤ 8.0	E
10.6 ≤ RRC ≤ 12.0	F	9.3 ≤ RRC ≤ 10.5	F	RRC ≥ 8.1	F
RRC ≥ 12.1	G	RRC ≥ 10.6	G	Empty	G

Figure-2 EC Regulation 1222/2009 Cr values for energy efficiency

2. DEFINATIONS

Rolling Resistance (Fr) (ISO 28580 : 2018) – Loss of energy (or energy consumed) per **unit of distance travelled, in hysteresis loss** and permanent roadbed and tyre wear.

Rolling Resistance Coefficient (C_r) (ISO 28580: 2005) – Ratio of the rolling resistance, in newtons, to the load form of on the tyre, in kilo-newtons.

3. MACHINES AND METHODOLOGY

To analyze the effect of Tyre wear on Rolling Resistance, five numbers radial tyres were selected having different tyre designations and properties. To simulate the tyre wear on the real road condition the tyres are mounted on commercial rims and are then rotated against a metal roller having grit surface texture comparatively equivalent to the road surface. The tyres were then rotated in a cycle of 10000 km to keep the conditions realistic the tyres were stopped for a break of 30 min after completion 6 hours of the testing cycle for the tyre to cool and then again rotated against the drum until the completion of 10000 kilometers. For more accurate results the ambient conditions were kept under a very tight range. To evaluate the tyre wear, tread depth was measured before and after the cycle of 10,000 kilometers using a calibrated digital depth gauge.

The coefficient of Tyre Rolling Resistance was evaluated taking reference standard ISO 28580 before and after running the tyre, using the Tyre Rolling Resistance Machine aligned with European reference laboratory

Tyre Wear Machine and Paramenters:

1) **Machine** : Tyre Endurance Machine
2) **Drum Diameter** : 1.7 Meter, Textured Grit roller surface.
3) **Tyre Load** : 75% of maximum marked load.
4) **Tyre Speed** : 81 Kmph.
5) **Ambient Temp.** : 25±5°C.

Figure-3 Tyre Rolling Endurance Machine.

Tyre Depth Measurement:

1) **Gauge** : Depth Gauge.
2) **Nos. of Readings** : 06.
3) **Scale Range** : 20 mm.
4) **Least Count** : 0.01mm.

Figure-4 Tyre Depth Gauge.

Tyre Rolling Resistance Machine and Parameters:

1) **Machine** : Tyre Rolling Resistance Machine
2) **Drum Diameter** : 1.7 Meter.
3) **Reference Standard** : As per ISO 28580
4) **Tyre Load** : As per ISO 28580.
5) **Tyre Speed** : As per ISO 28580.
6) **Ambient Temp.** : 25±5°C.
7) **Skim Load** :100-200 N
8) **Test Duration** : 30 min

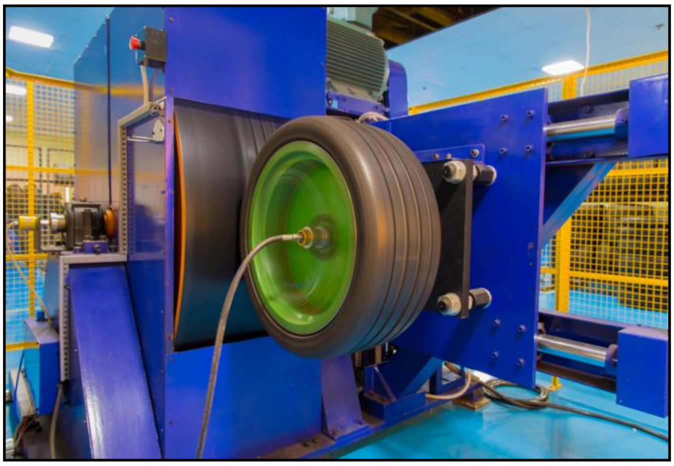

Figure-5 Tyre Rolling Resistance Test Machine (C1 Category).

The machine used in this test process is the Tyre Rolling Resistance test machine (C1 category) aligned with **UTAC France Laboratory**. This Machine is specially procured to evaluate/calculate Rolling Resistance and coefficient of Rolling Resistance of Passenger Car Radial Tyres (C1 category). The machine uses **Torque method** algorithms to evaluate the tyre RRC results. The Test process can be carried out as per various national and international standards i.e. **ISO 28580:2018, ISO 18164:2005, AIS 142 ECE R117:2017.**

Candidate tyres that are used in this study are only Passenger Car Tyre.

1) **235/70 R16 106T-C - PCR**
2) **165/65 R14 79T-A - PCR**
3) **205/65 R16 95W-A - PCR**
4) **185/65 R15 88H-C - PCR**
5) **175/70 R14 88T (XL)- A - PCR**

4. FORMULA USED

General Formula

$F_r = C_r W$ (1)

F_r = Rolling Resistance or Rolling Friction (N)
C_r= Rolling Resistance Coefficient (dimensionless)

W = m a_g = Normal Force or Weight of the Body (N)
m = Mass of Body (kg)
a_g = Acceleration of Gravity (9.81 m/s^2)

Formulas as per ISO 28580 and ISO 18164

$Fr = F_t[1+(r_L/R)]-F_{pl}$ **- Force method** (2)

$Fr = T_t/R-F_{pl}$ **-Torque method*** (3)

F_t is Tyre spindle Force
r_L is Tyre radius at steady state
R is Test wheel radius
F_{pl} is parasitic loss
T_t is Drum Torque

$F_r = 3.6V \times A/U_n - F_{pl}$ **- Power method** (4)

V is Electric Potential applied to the Machine Drive
U_n is the test drum speed.

***Calculation carried out as per Torque method.**

✓ **Temperature Correction (at 25°C):**

$F_{r25} = F_r[1+K_t(t_{amb}-25)]$ **(5)**

F_{r25} is the rolling resistance at 25°C
K_t is the Temperature correction Factor
0.008 for Passenger Car Tyres ;
0.010 for Truck and Bus Tyres;
0.006 for Larger Truck and Bus Tyres;
t_{amb} is the test ambient Temperature.

✓ **Drum diameter correction**

$F_{r02} \cong K_r F_{r01}$ **(6)**

$K_r = \{(R_1/R_2)(R_2+r_T) / (R_1+r_T)\}^{1/2}$ **(7)**

K_r is Drum diameter correction factor
R_1 is the radius of drum 1, in meters;
R_2 is the radius of drum 2, in meters;
r_T is the nominal tyre radius, in meters;
F_{r02} is the rolling resistance value measured on drum 1, in Newton
F_{r01} is the rolling resistance value measured on drum 2, in Newton

Formula used for finding Coefficient of Rolling Resistance

$C_r = F_{net}/W$ **(8)**

C_r is Coefficient of Rolling Resistance
F_{net} is Rolling Resistance at 25°C

$C_{r\,net} = 0.045 \times C_r$ **(9)**

$C_{r\,net}$ is Coefficient of Rolling Resistance value aligned with the Reference laboratory value.

5. EFFECT OF TYRE WEAR ON ROLLING RESISTANCE

1) Tyre Sze : 235/70 R16 106T

Tyre Wear Parameters

S.NO	Tyre Running Distance (km)	Tyre Inflation Pressure (kPa)	Tyre Tread Depth before wear (mm)	Tyre Tread Depth after wear (mm)	Tyre Wear After Every Cycle
1)	**0**	180	-	6.37	**0**
2)	**10000**	180	6.35	5.93	**0.44**
3)	**20000**	180	5.98	5.43	**0.94**
4)	**30000**	180	5.41	4.78	**1.59**
5)	**40000**	180	4.83	4.17	**2.2**

Note: The tyre depth was measured from tyre wear indicator (TWI).

Test Rim	Conditioning Time (hrs)	Test Speed (km/h)	Test Load (KN)
7 J " X 16"	3	81	5.59

Initial Temperature*	Final Temperature*	Relative Humidity*	Skim load (N)
23.6°C	24.5°C	27%	100-200

*Taking Mean of absolute values

Tyre Rolling Resistance Parameters and Results as per ISO 28580

S.NO	Tyre Running Distance (km)	Tyre Inflation Pressure (kPa)	Tyre RRC Value before wear	Tyre RRC Value after wear	Difference in RRC value after every cycle
1)	**0**	210	-	8.40	**0.00**
2)	**10000**	210	8.40	8.48	**0.08**
3)	**20000**	210	8.46	8.53	**0.13**
4)	**30000**	210	8.51	8.60	**0.20**
5)	**40000**	210	8.61	8.68	**0.28**

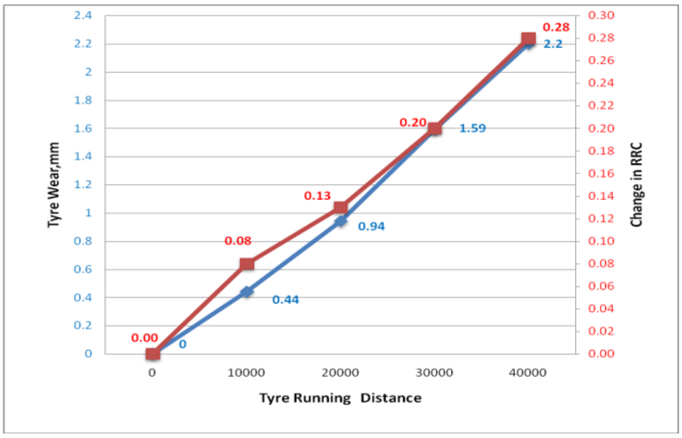

Figure-6 Distance clocked vs Change in RRC vs Tyre Wear

2) Tyre Sze : 165/65 R14 79T-A

Tyre Wear Parameters

S.NO	Tyre Running Distance (km)	Tyre Inflation Pressure (kPa)	Tyre Tread Depth before wear (mm)	Tyre Tread Depth after wear (mm)	Tyre Wear After Every Cycle
1)	**0**	180	-	5.63	0
2)	**10000**	180	5.64	5.42	0.21
3)	**20000**	180	5.45	5.09	0.54
4)	**30000**	180	5.13	4.64	0.99
5)	**40000**	180	4.65	4.05	1.58

Note: The tyre depth was measured from tyre wear indicator (TWI).

Test Rim	Conditioning Time (hrs)	Test Speed (km/h)	Test Load (KN)
5 J " X 14"	3	81	2.56

Initial Temperature*	Final Temperature*	Relative Humidity*	Skim load (N)
22.3°C	24.8°C	25%	100-200

*Taking Mean of absolute values

Tyre Rolling Resistance Parameters and Results as per ISO 28580

S.NO	Tyre Running Distance (km)	Tyre Inflation Pressure (kPa)	Tyre RRC Value before wear	Tyre RRC Value after wear	Difference in RRC value after every cycle
1)	**0**	210	-	9.36	0.00
2)	**10000**	210	9.37	9.44	0.08
3)	**20000**	210	9.46	9.57	0.21
4)	**30000**	210	9.55	9.62	0.26
5)	**40000**	210	9.62	9.71	0.35

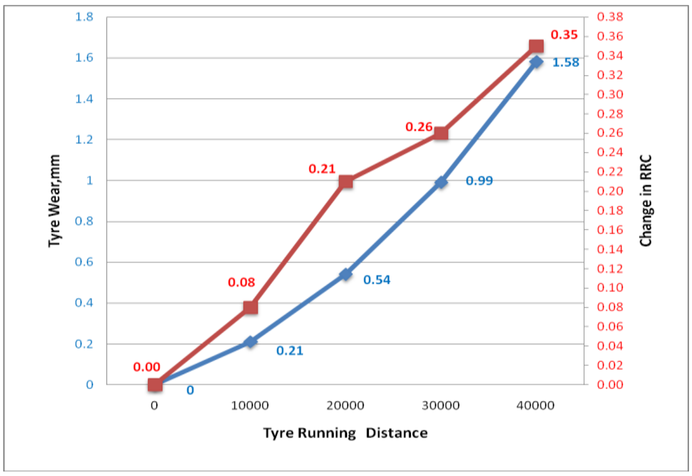

Figure-7 Distance clocked vs Change in RRC vs Tyre Wear

3) Tyre Sze : 205/65 R16 95W-A

Tyre Wear Parameters

S.NO	Tyre Running Distance (km)	Tyre Inflation Pressure (kPa)	Tyre Tread Depth before wear (mm)	Tyre Tread Depth after wear (mm)	Tyre Wear After Every Cycle
1)	**0**	180	-	4.96	**0**
2)	**10000**	180	4.95	4.73	**0.23**
3)	**20000**	180	4.73	4.29	**0.67**
4)	**30000**	180	4.27	3.84	**1.12**
5)	**40000**	180	3.86	3.50	**1.46**

Note: The tyre depth was measured from tyre wear indicator (TWI).

Test Rim	Conditioning Time (hrs)	Test Speed (km/h)	Test Load (KN)
6 J ” X 16”	3	81	4.06

Initial Temperature*	Final Temperature*	Relative Humidity*	Skim load (N)
21..4°C	25.8°C	32%	100-200

*Taking Mean of absolute values

Tyre Rolling Resistance Parameters and Results as per ISO 28580

S.NO	Tyre Running Distance (km)	Tyre Inflation Pressure (kPa)	Tyre RRC Value before wear	Tyre RRC Value after wear	Difference in RRC value after every cycle
1)	**0**	210	-	7.23	0.00
2)	**10000**	210	7.24	7.36	0.13
3)	**20000**	210	7.35	7.43	0.20
4)	**30000**	210	7.45	7.48	0.25
5)	**40000**	210	7.50	7.53	0.30

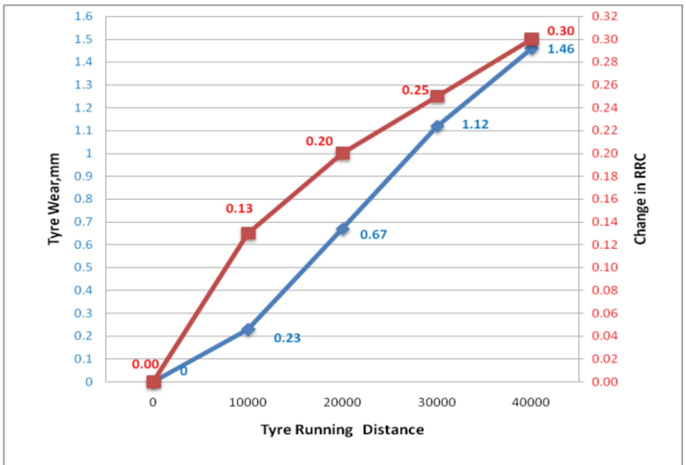

Figure-8 Distance clocked vs Change in RRC vs Tyre Wear

4) Tyre Sze : 185/65 R15 88H-C

Tyre Wear Parameters

S.NO	Tyre Running Distance (km)	Tyre Inflation Pressure (kPa)	Tyre Tread Depth before wear (mm)	Tyre Tread Depth after wear (mm)	Tyre Wear After Every Cycle
1)	**0**	180	-	**5.54**	**0**
2)	**10000**	180	5.54	**5.02**	**0.52**
3)	**20000**	180	5.00	**4.67**	**0.87**
4)	**30000**	180	4.65	**4.13**	**1.41**
5)	**40000**	180	4.16	**3.70**	**1.84**

Note: The tyre depth was measured from tyre wear indicator (TWI).

Test Rim	Conditioning Time (hrs)	Test Speed (km/h)	Test Load (KN)
5.5 J ” X 15”	3	81	3.3

Initial Temperature*	Final Temperature*	Relative Humidity*	Skim load (N)
21°C	24.8°C	21%	100-200

*Taking Mean of absolute values

Tyre Rolling Resistance Parameters and Results as per ISO 28580

S.NO	Tyre Running Distance (km)	Tyre Inflation Pressure (kPa)	Tyre RRC Value before wear	Tyre RRC Value after wear	Difference in RRC value after every cycle
1)	**0**	210	-	**10.23**	**0.00**
2)	**10000**	210	10.23	**10.28**	**0.05**
3)	**20000**	210	10.28	**10.35**	**0.12**
4)	**30000**	210	10.35	**10.44**	**0.21**
5)	**40000**	210	10.44	**10.51**	**0.28**

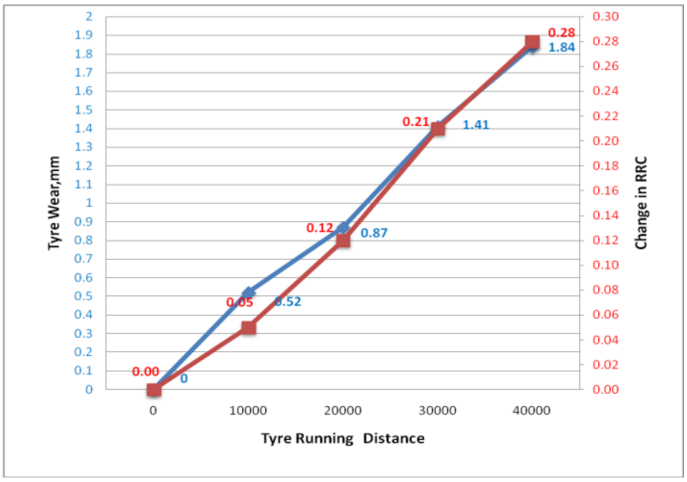

Figure-9 Distance clocked vs Change in RRC vs Tyre Wear

5) Tyre Sze : 205/65 R16 95W-A

Tyre Wear Parameters

S.NO	Tyre Running Distance (km)	Tyre Inflation Pressure (kPa)	Tyre Tread Depth before wear (mm)	Tyre Tread Depth after wear (mm)	Tyre Wear After Every Cycle
1)	**0**	180	-	**5.56**	**0**
2)	**10000**	180	5.55	**4.94**	**0.62**
3)	**20000**	180	4.96	**4.58**	**0.98**
4)	**30000**	180	4.59	**3.91**	**1.65**
5)	**40000**	180	3.91	**3.24**	**2.32**

Note: The tyre depth was measured from tyre wear indicator (TWI).

Test Rim	Conditioning Time (hrs)	Test Speed (km/h)	Test Load (KN)
5 J " X 14"	3	81	3.30

Initial Temperature*	Final Temperature*	Relative Humidity*	Skim load (N)
16°C	23.5°C	18%	100-200

*Taking Mean of absolute values

Tyre Rolling Resistance Parameters and Results as per ISO 28580

S.NO	Tyre Running Distance (km)	Tyre Inflation Pressure (kPa)	Tyre RRC Value before wear	Tyre RRC Value after wear	Difference in RRC value after every cycle
1)	**0**	210	-	**9.84**	**0.00**
2)	**10000**	210	9.84	**9.91**	**0.07**
3)	**20000**	210	9.91	**9.97**	**0.13**
4)	**30000**	210	9.97	**10.06**	**0.22**
5)	**40000**	210	10.06	**10.14**	**0.30**

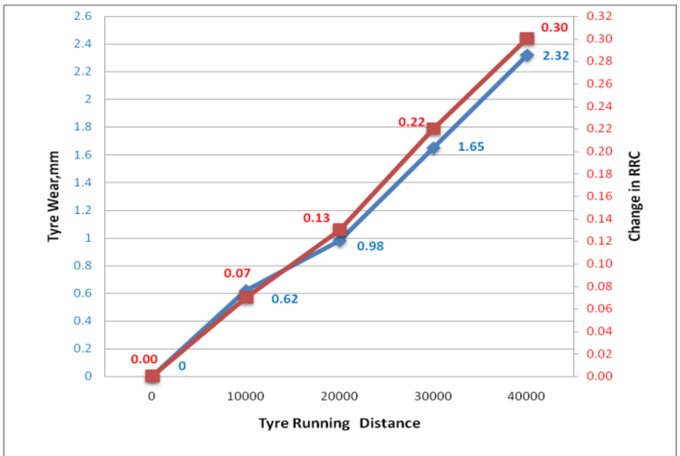

Figure-10 Distance clocked vs Change in RRC vs Tyre Wear

6. STUDY ANALYSIS

This study shows the effect of tyre wear along with distance traveled by tyre on tyre Rolling Resistance and in terms of Rolling Resistance Coefficient. As it is clear from the study that different tyre sizes with different compounding and structures have different wear rates and eventually the variable value of RRC. The analysis of this study shows that an average of **0.81%** increase in the value of the Rolling Resistance Coefficient had been observed in each interval of **10,000 km**.

The study also shows that the average of percentage change in RRC value after running the tyre for **40,000 km** is **3.36 %** **(***refer below tables***)** which is quite significant.

Table showing % change in RRC value after every cycle

S.NO	Tyre Size	Tyre Running Distance (km)	Tyre Wear After Every Cycle	Difference in RRC value after every cycle	% change in RRC after every cycle
1)	**235/70 R16 106T**	0	-	-	**-**
		10000	0.44	0.08	**0.9**
		20000	0.94	0.13	**1.5**
		30000	1.59	0.20	**2.3**
		40000	2.2	0.28	**3.3**
2)	**165/65 R14 79T**	0	-	-	**-**
		10000	0.21	0.08	**0.8**
		20000	0.54	0.21	**2.2**
		30000	0.99	0.26	**2.7**
		40000	1.58	0.35	**3.7**
3)	**205/65 R16 95W**	0	-	-	**-**
		10000	0.23	0.13	**1.7**
		20000	0.67	0.20	**2.7**
		30000	1.12	0.25	**3.4**
		40000	1.46	0.30	**4.1**
4)	**185/65 R15 88H**	0	-	-	**-**
		10000	0.52	0.05	**0.4**
		20000	0.87	0.12	**1.1**
		30000	1.41	0.21	**2.0**
		40000	1.84	0.28	**2.7**
5)	**175/70 R14 88T(XL)**	0	-	-	**-**
		10000	0.62	0.07	**0.7**
		20000	0.98	0.13	**1.3**
		30000	1.65	0.22	**2.2**
		40000	2.32	0.30	**3.0**

Table showing mean of % Change in RRC value

S.NO	Tyre Size	Mean of % change in RRC after every Step			Mean of % of wear after each cycle/step	Average Increase in RRC Value After each Step
		W1	W2	W3		
1)	235/70 R16 106T	0.6	0.8	1.0	**0.80**	**0.81**
2)	165/65 R14 79T	1.4	0.5	1.0	**0.96**	
3)	205/65 R16 95W	1.0	0.7	0.7	**0.80**	
4)	185/65 R15 88H	0.7	0.9	0.7	**0.76**	
5)	175/70 R14 88T(XL)	0.6	0.9	0.8	**0.76**	

Table showing mean of % Change in RRC value before and after Wear.

S.NO	Tyre Size	Mean of % change in RRC by running tyre from 0 Km to 40000 Km	% Mean
1)	235/70 R16 106T	**3.3**	**3.36**
2)	165/65 R14 79T	**3.7**	
3)	205/65 R16 95W	**4.1**	
4)	185/65 R15 88H	**2.7**	
5)	175/70 R14 88T(XL)	**3.0**	

Figure-11 Photographs of same tyre before and after wear (after running for 40000 Km, Tyre Size: 205/65 R16 95W-A).

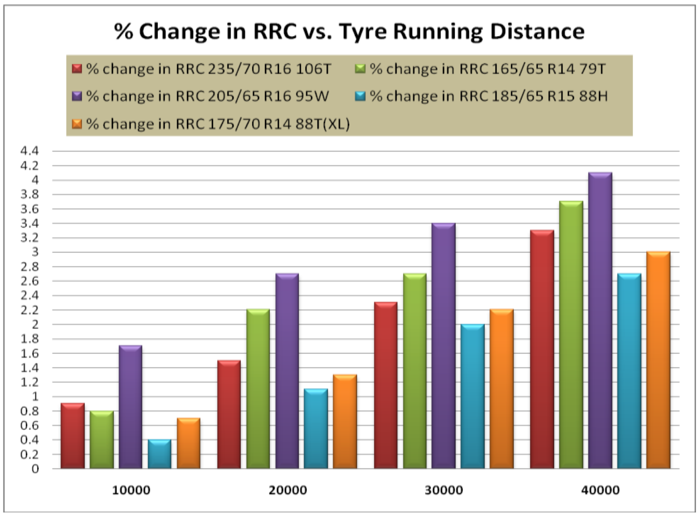

Figure-12 Percentage change in RRC values with respect to Tyre Running Cycles

7. CONLUSION

It is briefly scrutinized in this study, the effect of Tyre Wear concerning the distance traveled by Tyre on Rolling Resistance and its Coefficient. So, this study shows that with an increase in the tyre wear the Rolling Resistance increases simultaneously between tyre surface and the contact surface, while the Rolling Resistance also depends on other parameters like Tyre compound and construction, in this study we have taken various tyres of different brands and tyre sizes and conclude that RRC increases with increase in Tyre Wear. Hence, the derived conclusion is that tyre wear parameter plays an important role in defining the Rolling Resistance of Tyre. Though, this doesn't mean we have to change tyre frequently to maintain the same RRC values. This study could intrigue Industry to find better solutions through which we can develop new Tyres which show low deformation against the actual load and long endurance period and hence which will results in better hysteresis resistance even after running or covering a reasonable amount of distance which will eventually minimize the difference in RRC values.

8. REFERENCES

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