Indian Journal of Engineering & Materials Sciences
Vol. 11, October 2004, pp. 406-412

Effect of tyre overload and inflation pressure on rolling loss (resistance) and fuel consumption of automobile and truck/bus tyres

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Received 4 July 2003; accepted 1 July 2004

The effect of rolling resistance R on fuel consumption of radial passenger and truck tires is discussed in this paper. The model equation for the rolling loss R was directly proportional to tire load W (R α W) and inversely proportional to inflation pressure p (R α $1/p^x$). These relationships were experimentally quantified. Using manufacturer's recommended values for load W and pressure p as reference points the R values for different overload conditions (from +10 to +100%) at constant p were estimated. Similarly, the required p values to support 10 to 50% additional load to maintain original R were also estimated. Then the estimated R values for different overload/inflation pressure conditions were combined with the fuel saving factor F (obtained from published literature results). Then the relative change in fuel consumption of truck/bus tires for different load/pressure combinations vis-a-vis the fuel use for the manufacturer's recommended W and p values was evaluated. The present analysis showed that for the same amount of fuel use a truck carrying a 100% overload and making one round trip would correspond to slightly more than two round trips by a truck of same size carrying the recommended load. Finally, a possible method of optimizing fuel use by adjusting the tire load/pressure conditions was suggested. All these estimates were obtained for radial tires. The author feels that the same methodology is applicable for bias tires also.

IPC Code: Int. Cl.[7] B60C 17/00, G01L 17/00

Tire rolling loss can be defined as the energy dissipated as heat by a rolling tire moving unit distance. Based on simple physics principles (conservation of energy) rolling loss *R* can be written as

R = (Energy input into a tire – Energy output by tire)/ speed
= Energy lost in tire/speed, W/m/s

The unit of *R* is watt per meter per second, which is equivalent to *N*. Though the unit of *R* is expressed in terms of *N* the rolling loss does not represent 'force' but 'energy/unit distance'. Generally, rolling loss and rolling resistance are considered equivalent terms and are used interchangeably. Energy loss in a tire includes hysteresis loss, aerodynamic drag, friction between tire and road surface and wind resistance. Hysteresis loss is the major factor and contributes about 90-95% of rolling loss.

Rolling loss or rolling resistance is an ever-important property for the tire and automotive industries because of its practical implication. Tire scientists and engineers have conducted rolling resistance research from differing perspectives for over three decades. Some of the major research activities included the effect of material properties and tire construction[1-9], effect of rolling resistance on fuel consumption[10-12], effect of road/vehicle interaction[13,14] and finite element analysis method[15,16]. Schuring and Futamura[17] published an extensive review covering all aspects of rolling loss.

Fuel consumption and tire rolling loss in all types of automobiles have become increasingly important because of adverse environmental effects (air pollution and global warming) and economic costs (high petroleum price). During the last couple of decades many government departments especially in the U.S. passed laws and regulations requiring improved fuel efficiency for automobiles. The automobile industry in collaboration with the supplier industries has been implementing many programs to accomplish this goal. Improving the efficiency of internal combustion engine, hybrid engine, lighter automobiles, reducing aerodynamic drag, reformulated gasoline and solar powered car are some of the methods implemented by the automobile industry. Tire industry for its part has developed fuel-efficient tires by reducing tire rolling loss. Tire load and pressure, vehicle speed, stop and go driving and vehicle styling (aerodynamic shape versus box type) are some of the parameters that influence the rolling resistance. Nature of road surface is an external factor. This paper essentially confines to the effect of tire load W and inflation pressure p on rolling loss that influences fuel use. An extensive discussion of load/pressure combinations with corresponding fuel consumption through respective R value changes is also presented.

Tire Operating Parameters and Rolling Loss

Load and inflation pressure are two tire operating parameters. Rolling loss changes when these parameters change. The lower the rolling resistance, the better the fuel economy, i.e., reduced fuel use. It is obvious from first principles that as W increases R increases; as p increases R decreases. These are only qualitative statements and are not useful for quantitative evaluation. Quantitative expressions between R and these operating parameters W and p are established first so that meaningful practical application of these relationships can be attempted.

Using standard load/pressure conditions of truck tires as reference points relative rolling loss values were determined for few overload conditions, typically +10 to +100% of recommended load at different inflation levels. These overload/pressure conditions seem to correspond with the situations obtained in the field. The fleet operators have direct control over these parameters (tire over load and pressure). Therefore, the effect of these parameters on tire rolling loss is examined here from a service point of view. Increase in fuel consumption due to tire overload is estimated. A simple method to optimize fuel use by adjusting tire-operating conditions (load and inflation pressure) is suggested for the benefit of truck/bus operators.

Estimating Quantitative Relationships

R versus W relation

Using an energy balance approach Pillai and Fielding-Russell[18] developed a general equation for rolling resistance R in terms of tire load W at constant inflation pressure p as

$$R = (h.\ d.\ w/A).\ W \qquad \ldots\ (1)$$

where h, d, w, and A are whole tire hysteresis ratio, deflection, footprint width and area respectively. As a corollary to this relation, Pillai[19] has shown that about 95% of the rolling loss could be explained by the hysteresis behaviour of the whole tire (materials and structure). The R values of three typical P195/75R14 size passenger tires and a radial medium truck tire 11R22.5 at three different load values at constant p were measured and plotted. All R versus W plots were linear; a typical plot was shown in Fig. 1. This linear relation indicated that Eq. (1) could be simplified as

$$R = C_1\ W \qquad \ldots\ (2)$$

where $C_1 = (h.\ d.\ w)/A$ was a constant (the slope of the line). The mean slope C_1 was found to be 0.010 and 0.0078 for truck and passenger tire respectively. It is known that the tire deflection d increases with W; but at the same time, the footprint terms w and A also change simultaneously so that the ratio $(d.w)/A$ remains fairly constant. The h values of the passenger and truck tire were nearly independent of the load range used here[20]. This analysis indicated that the rolling resistance R was directly proportional to load W (see Eq. (2)).

R versus p relation

Though it is obvious from first principles that R and p are inversely related the exact nature of this relationship is not known. A general relation between R and p can be expressed as

$$R = C_2\ 1/p^x \qquad \ldots\ (3)$$

where C_2 is a constant including h and W values[20]. The pressure exponent x has to be estimated to quantify Eq. (3). This was done by a direct experimental method and by an indirect regression analysis method.

Experimental method—The R data for a number of different passenger tires (P175/80R13, P195/75R14, P205/75R15, and P225/60R15) and truck tires (11R22.5 and 295/75R22.5) were obtained as a function of inflation pressure p at constant load. The R versus p plots of all the tires were made and the corre-

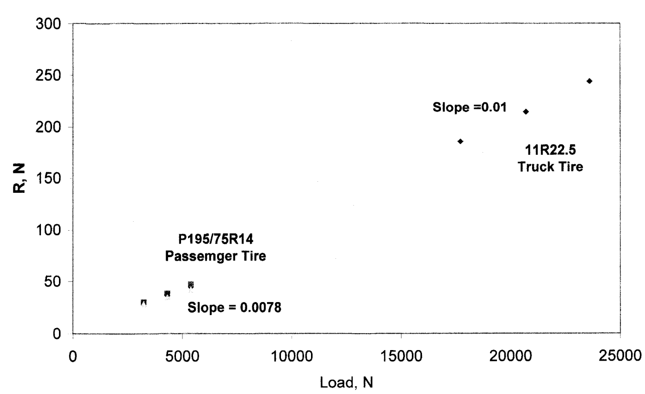

Fig. 1—Rolling loss versus load plot for passenger and truck tires

sponding exponent x values were determined and tabulated in Table 2. The exponent values were nearly identical and the mean was found to be about 0.5. A typical R versus p plot for 295/75R22.5 truck tire and a P195/75R14 passenger tire was shown in Fig. 2.

Regression method—Eq. (1) does not explicitly include the inflation term p. Therefore, Eq. (1) was modified to include the p term through its relation to tire deflection d. Pillai and Fielding-Russell[21] obtained an empirical equation for tire footprint area A as

$$A = 1.85\, d^{2/3}\, r^{1/3}\, s \quad \ldots (4)$$

where r and s are tire radius and section width. The footprint width w is approximately equal to 75% of the section width s. Hence, Eq. (4) can be rewritten as

$$A/w = 2.50\, d^{2/3}\, r^{1/3} \quad \ldots (5)$$

Defining pressure normalized spring rate parameter K as $K = W/d.p;$ deflection d can be written as

$$d = W/(K\, p) \quad \ldots (6)$$

Substituting for d, Eq. (5) is rewritten as

$$A/w = 2.50\, (W/K\, p)^{2/3}.\, r^{1/3} \quad \ldots (7)$$

Then Eq. (1) is modified as

$$R = C_3/(K\, p\, r)^{1/3} \quad \ldots (8)$$

which can be rewritten as

$$R = C_4/p^{\,0.33} \quad \ldots (9)$$

where $C_4 = C_3/(K\, r)^{1/3}$ is a constant.

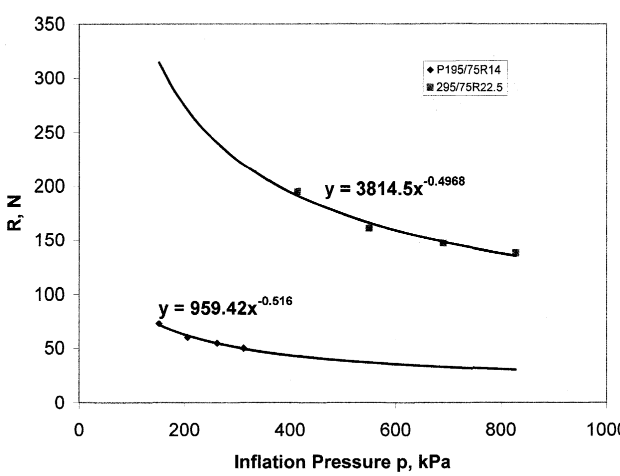

Fig. 2—Rolling loss versus inflation pressure

The pressure exponent x was nearly equal to 0.5 and 0.33 by the experimental method and by multiple regression analysis method respectively. The latter empirical approach involved multiple approximations and regressions; hence this x value was only approximate. The exponent x obtained by the experimental method for each of the passenger and truck tires was nearly the same equal to 0.5 (see Table 2). This observation agreed with the results obtained by Elliott *et al.*[22] and Barbin[23].

Therefore the general expression for R versus p in the form of

$$R = C_2\, 1/p^{\,0.5} \quad \ldots (10)$$

was used for further analysis.

Experimental Procedure

Typically a tire is loaded against a 1.7 m diameter dynamometer wheel. Adjusting the starting load and pressure conditions to W_1 and p_1 the rolling resistance R_1 was measured according to SAE procedure J1269[24]. This is the standard procedure for measuring the rolling resistance of different types of pneumatic tires under steady state and free rolling conditions at zero slip and zero inclination angles. In summary, the R values of P175/80R13, P195/75R14, P205/75R15 and P225/60R15 passenger tires and 295/75R22.5 and 11R22.5 truck tires were measured at initial load and incremental loads of +16%, 33% and +70% higher. Also R measurements were obtained at high incremental load conditions (+200 to +300%) for 295/75R22.5 tire. All these measurements were done at constant pressure p. A typical R versus W plot for a 11R22.5 and a P195/75R14 tires was linear as shown in Fig. 1. As this study included different size and types of tires the increase in load and rolling resistance values were normalized for each tire. Percentage increase values of rolling loss and load, rather than absolute values, were given in Table 1 for comparison. The percentage increase in rolling loss of each tire agreed with that of the increase in load. These relative percentage values were generally independent of tire construction and size and hence applicable to different tire types.

The R values of all the above tires were also measured as a function of p at constant load. The pressure exponent x for each tire was determined and the data presented in Table 2.

Table 1 – Incremental load and percentage increase in rolling resistance values of passenger and truck tires

Tire size	Reference conditions			Increase in W%	Increase in R%
Passenger tire	W_1, N	p_1, kPa	R_1, N		
P175/80R13	2736	207	36.0	+33%	31%
				+67%	+64%
P195/75R14	3238	207	28.6	+33%	+30%
				+67%	+62%
P205/75R13	3705	207	42.2	+33%	+33%
				+67%	+68%
P225/60R16	3678	207	33.9	+33%	+34%
				+45%	+47%
				+67%	+67%
Truck tire					
11R22.5	17700	586	185.1	+17%	+16%
				+33%	+32%
295/75R22.5	12620	828	81.3	+200%	+195%
	6310	483	44.2	+300%	+307%

Table 2 – Inflation pressure exponent x values for passenger and truck tires

Tire size	Exponent 'x' value
P175/80R13	0.5237
P205/75R14	0.5140
P205/75R15	0.4902
295/75R22.5	0.4968
11R22.5	0.5326

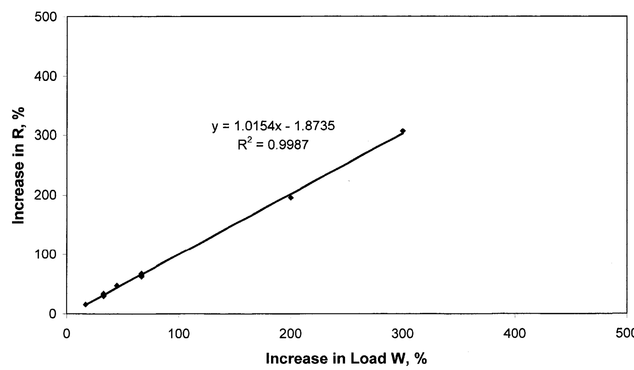

Fig. 3—Percentage increase in R as a function of percentage increase in W for passenger and truck tires

Results and Discussion

Quantitative relations

These two equations

$$R = C_1 W \quad \ldots (2)$$

and

$$R = C_2\, 1/p^{\,0.5} \quad \ldots (10)$$

are general quantitative expressions that relate R independently to load W and pressure p. These relations are used for further discussion of the points raised above, viz., rolling resistance change due to overloading and over-inflation of bus and truck tires and its effect on fuel consumption.

Sample calculations and detailed analysis

Experimentally R has been found to be linear with W for up to about 70% increase in W for most of the tires studied; for one truck tire the linearity extended all the way to +300% increase in load. The relative increase in tire overload and the corresponding percentage increase in rolling resistance are used in the present analysis. Percentage increase in R was plotted against the percentage increase in W for the above passenger and truck tires and is shown in Fig 3. The regression line corresponded to the equation Y = 1.0154X–1.87 with correlation coefficient R^2 = 0.9987 showing very good agreement. The X intercept also would be nearly +1.87% because the X-Y plot is almost a 45° line. The X intercept can be considered as a measure of tire weight. This intercept method estimated the weight of a P195/75R14 tire to be about 62, N that agreed roughly with the actual weight of a similar but a different tire. A small positive load in addition to the structural weight has to be applied on the tire so that a small measurable rolling resistance value may be registered on the load cell.

The linear R versus W relation seems to be general for all types and sizes of tires as mentioned earlier. A sample calculation of R for different load and pressure for a 11R22.5 truck tire was shown below. Manufacturer's recommended load W_1, inflation pressure p_1 and the corresponding R_1 values for this tire were used as the starting reference points – W_1 = 17700, N; p_1 = 580, kPa; and R_1 = 185, N. The relative percentage change in rolling resistance for few typical overload conditions was presented earlier in Table 1. Say 70% increase in load corresponds to 70% increase in rolling loss, i.e., 1.7 W_1 corresponds to 1.7 R_1. Let the load be increased to 2 $W_1 = W_2$, i.e., 100% overloaded condition then the rolling resistance increases by 100% to $R_2 = 2R_1$ at constant p_1. This raises the question: if the overload condition is maintained at W_2 what should the inflation pressure p_2 be so that the rolling resistance would be equal to the original value R_1? The p_2 value in relation to p_1 was found to be equal to 4 p_1 by using the R versus p relation (Eq. (10)). A corollary question: what should the corresponding inflation pressure p_3 be that would produce a rolling resistance equal to $R_2 = 2R_1$ at W_1 load. Similarly, p_3 was found to be equal to $p_3 = 0.25\ p_1$. These extreme pressure values of 4 p_1 at one end and 0.25 p_1 at the other end are not practical as tire operating pressures. Normally, a tire cannot operate at 4 times its recommended pressure because this pressure level is likely to be higher than the burst pressure and is not safe. Similarly, a tire is not durable at a pressure level of ¼ the recommended inflation and may shred completely and damage the rim in a short time. These extreme pressure conditions are based on theoretical calculation and are not feasible in real service situation. Let us consider an intermediate inflation pressure level p_4 equal to say 1.5 p_1. Applying the same analysis the rolling resistance R_3 corresponding to a tire load of $2W_1$ and an inflation pressure equal to 1.5 p_1 would be nearly equal to 1.63 R_1. In other words, at a revised load equal to 2 W_1 and tire pressure equal to 1.5 p_1 then the rolling loss would reduce by about 37% from R_2 to 1.63 R_1. Similarly, corresponding to a 150% load (1.5 W_1) the tire pressure would be equal to 2.25 p_1 so that the rolling resistance would be equal to R_1. Rolling resistance values corresponding to different load/pressure combinations are summarized in Table 3a. The extent of overload and over-inflation levels should be below the tire safety limits. Overloading the tire and/or varying the tire pressure would drastically affect the tire rolling loss. This in turn adversely affects the vehicle fuel consumption.

Table 3a – Relative Inflation pressure and rolling resistance values at different overloaded conditions

Load, N	Inflation, kPa	Rolling loss, N
W_1	p_1	R_1 (Initial reference conditions)
$W_2 = 2\ W_1$	p_1	$R_2 = 2\ R_1$
$W_2 = 2\ W_1$	$p_2 = 4\ p_1$	R_1
W_1	$p_1 = 0.25\ p_1$	R_2
$W_2 = 2W_1$	$p_4 = 1.5\ p_1$	$R_1 = 1.63\ R_1$
$W_3 = 1.5\ W_1$	$p_3 = 2.25\ p_1$	R_1

Table 3b – Overload condition/required inflation pressure values to maintain rolling loss at R_1

Load, N	Overload condition	Rolling loss, N	Required inflation pressure, kPa
W_1		R_1	p_1 (initial condition)
1.1 W_1	+10%	R_1	1.21 p_1
1.2 W_1	+20%	R_1	1.44 p_1
1.3 W_1	+30%	R_1	1.69 p_1
1.4 W_1	+40%	R_1	1.96 p_1
1.5 W_1	+50%	R_1	2.25 p_1

As mentioned earlier, the rolling loss is inversely related to inflation pressure. This implies that increasing the inflation pressure can partially or fully compensate the effect of limited overload condition on rolling loss. Let the load be increased to 1.1 W_1, what should the pressure be so that the rolling resistance is maintained at the original R_1 value? This pressure was calculated to be about 1.21 p_1 using Eq. (10). Required pressure values were determined for 10%, 20%, 30%, 40% and 50% overload conditions to maintain the rolling loss value at R_1.These results were also given in Table 3b. Increasing the inflation pressure might be an inexpensive and convenient method of lowering the rolling resistance when tire load is increased. These pair of load/inflation pressure conditions would likely maintain the fuel consumption at the original level because the initial R_1 value was maintained. The vehicle operator should be aware that higher inflation would make the ride harder and uncomfortable.

Fuel saving factor

In addition to rolling loss, fuel use depends on vehicle characteristics, the nature of driving, frequent starts and stops and driving in congested streets. The present study concerns only with rolling loss reduction and fuel saving. Over the last couple of decades about 70% reduction in rolling resistance has been accomplished for a pneumatic tire by switching from bias to radial construction[23,25]. The primary question raised here is: How much fuel can be saved by a certain percentage change in rolling resistance? The fuel saving factor F is defined as

F = Fuel consumption change %/Rolling loss change %

Glemming and Powers[11] presented experimental details of trailer tire method of estimating fuel use against rolling loss change. Schuring[10,25] published a detailed experimental study of this concept using different size passenger and truck tires. His results showed some variability in F value: for a truck tire about 3-4% reduction in rolling loss saved about 1% fuel use while for a passenger tire the respective values were about 5-7% versus 1%. These numbers are for radial construction.

Rolling resistance change versus fuel consumption

The effect of the increase in rolling resistance on the fuel consumed by a truck or bus is analyzed here. Table 1 shows that when a tire gets overloaded by +70%, its rolling resistance increases by about 70%. It can be assumed that when a tire gets overloaded by 100%, its rolling resistance also increases by 100% at the same inflation $p_{1.}$ This increase is per tire. Applying Schuring's rolling loss versus fuel consumption results it can be concluded that a 100% increase in rolling loss of a truck tire would cause about 25-30% increase in fuel consumption. Normally, a truck or bus may ride on 4 or 6 tires. So when a vehicle carries a 100% overload its total fuel consumption increases by nearly 100-180%. This implies that the truck operator can make more than two trips at the load (W_1) at the standard inflation p_1 for the same volume of fuel. In other words, the above analysis leads to the conclusion that two trips with normal load would consume slightly less fuel than one trip carrying 100% overload. Equal amount of total load would be transported in both cases. Case 1 (normal load and two trips) and case 2 (100% overload and one trip) are compared. A negative factor for case 1 is the additional time and expenses involved in completing two trips. For tire wear and tear the latter case may be more damaging because of the heavy overload though in the former case the tires have to travel twice the distance.

A typical calculation above showed that $2W_1$ load the rolling resistance increased by 100% to R_2 which caused a 25-30% increase in fuel consumption. It was shown that by increasing the pressure by 50% to 1.5 p_1 the rolling resistance decreased by about 63%; the fuel consumption decreased by about 8-10%. A fleet operator has to consider all these factors. Fuel use is a major factor in the operating cost of a truck or bus. Knowing the rolling loss values at different overload /inflation pressure conditions the respective fuel consumption might be estimated and possibly optimized. It might be possible for the operator to work the truck/bus at some intermediate overload and slightly higher inflation pressure so that the total operating cost (fuel cost + tire cost) might be minimized. The operator has to be aware of the practical limitation of the overload/over inflation combinations shown in Table 3b. This analysis implies that it would be beneficial for fleet operators to adjust the load/pressure conditions under which a vehicle is operated so that fuel consumption can be minimized.

Additional comment—This study has been performed for radial tire construction. In India only a very small percentage (about 2% in 2001-2002) of truck/bus tires is of radial construction while nearly 98% is of bias type[26]. In general, bias tires have higher rolling loss than the radial tire. Tire literature suggests material and compound modification[17] and design changes[27,28] for reducing rolling loss. Even a small decrease in rolling loss of these truck/bus tires would be beneficial for fleet operators in particular and for the economy in general. The basic methodology discussed above is applicable to bias tire construction also. The slope term relating R versus W and the pressure exponent relating R versus p might be different and therefore have to be estimated for bias tire. The slope constant C_1 for R versus W relation for the bias tire though likely to be different would not affect the ongoing analysis. The pressure exponent x would be different and does influence the inflation pressure analysis. The fuel saving factor has to be estimated for the bias tire. The amount of fuel consumption by the bias tire for different load/pressure combination can be calculated as explained above

Especially in India where the bus and truck (lorry) tires are heavily overloaded the rolling loss penalty is high. Another point to note is that the square and box type body shape of Indian buses and trucks increases aerodynamic drag and is not conducive for rolling loss reduction. It was estimated that $1.00 increase in price per barrel of oil costs Indian economy about Rs 3000 crores. This additional cost makes it imperative to reduce fuel consumption. One method of accomplishing this is by reducing tire rolling loss and improving the aerodynamic styling of truck and bus body shape. In the technology ladder scenario one of the steps that Indian tire industry has to climb up is to develop an energy efficient tire.

Conclusions

The direct proportionality between R and W and the inverse relationship between R and p were quantified as $R = C_1 W$ and $R = C_2 1/p^{0.5}$ respectively. The relative change in rolling resistance of a typical truck tire at different overload and inflation pressure conditions (10-100% overload and 10-50% over-inflation) has been evaluated. Fuel saving factor has been defined in terms of percentage change in rolling resistance. Additional fuel use due to increased rolling resistance has been estimated for different load/pressure conditions.

A truck or bus carrying 100% overload would consume more than twice the amount of fuel compared to normal load. Fleet operators have direct control over tire overload and inflation levels. Hence, the effect of these direct parameters on relative change in rolling resistance and thus on fuel consumption were evaluated.

A possible method of optimizing fuel consumption by adjusting tire operating load/pressure conditions was suggested. Increasing tire pressure is a convenient and inexpensive method of partially or fully compensating for rolling resistance increase. Some fuel saving might be accomplished by this method.

Overload/over-inflation combination values were estimated so as to maintain initial rolling loss value and thus maintain the same amount of fuel use.

Percentage increase in R plotted against percentage increase in W was a 45° line with very high correlation coefficient. The X intercept was a measure of the structural weight of the tire. For a typical P195/75R14 tire the structural weight estimated by this method agreed approximately with that of a similar tire.

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