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ROLLING RESISTANCE OF PNEUMATIC TIRES

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16. Abstract

Potential improvements in tire power transmission efficiency are worth seeking for gaining improved automotive fuel economy. Summaries herein of tire rolling resistance as influenced by tire construction and design, tire materials, and tire operating conditions indicate clearly that current trends towards smaller, lighter automobiles and increasing usage of radial tires, in addition to reduced speed levels are positive contributions in their effort. Difficulties in obtaining accurate and relevant data are discussed, including the capabilities existing and new testing machinery, and the necessity for adopting standardized testing methods for tire rolling resistance.

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PREFACE

This report, submitted to the Transportation Systems Center under the agreements of Contract DOT-TSC-316, was prepared in connection with the Component Evaluation Subproject of the Auto Energy Efficiency Project (AEEP), Harold S. Miller, Project Manager. The AEEP is sponsored by the Office of the Asst. Secretary for Systems Development and Technology (TST) of OST, Mr. Richard Strombotne, Program Manager.

The basic objective of the Auto Energy Efficiency Project is to evaluate the capability of the automobile industry to make substantial improvements in the fuel economy of the vehicles it manufactures. The Component Evaluation Subproject provides a continuing fuel economy assessment of the performance of current and projected automotive components. Automobile tires, a major automobile component, are directly attributed to approximately one-fourth of automobile power losses and thus substantially impact automobile fuel consumption. This report's intent is to present the many factors that affect the rolling resistance of present day pneumatic tires and to make recommendations believed important to reduce rolling resistance.

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1. INTRODUCTION

It is useful to think of the tires on the drive wheels of an automobile or truck as power transmission devices, since they transmit power from the engine to the roadway in order to propel the vehicle. This is accomplished with an efficiency which may vary from nearly 100% to zero, although under normal conditions of good traction and steady-state running the efficiency of the pneumatic tire is quite high, being of the same order of magnitude as that of other power transmission components in the vehicle. The unpowered or free rolling wheels on a vehicle may be thought of as a special case of powered wheels, but now with zero torque applied from external sources.

The construction of a tire with zero rolling loss would still leave the typical passenger car vehicle with comparable or greater power losses associated with other drive train components, with accessories appended to the engine and with the aerodynamic forces. For example, Roberts [70] estimates that only about 25% of total vehicle losses can, on the average, be attributed to tire power loss, and while this conclusion is heavily dependent on speed and driving cycle details, it has nonetheless been widely accepted. Walter and Conant [86] give similar results. Thus, improvements in tire mechanical efficiency can, at best, improve total passenger car vehicle efficiency by only a relatively limited amount. These conclusions give some rough measure of the importance of tire rolling losses to the total automobile loss picture. Similar conclusions for trucks do not seem to be available.

The assessment of the mechanical efficiency of a tire, and particularly a pneumatic tire, is made difficult by the interaction of tire losses with a variety of other factors, such as velocity, pressure, and temperature. This interaction may be partially clarified by the following set of considerations:

(a) It is generally agreed bv all who have studied the problem that the total mechanical loss incurred in a pneumatic tire is made up of three components:
  (i) Friction between the road and tire surface due to slipping at the tire road interface.
  (ii) Windage or aerodynamic losses in the tire itself.
  (iii) Hysteretic losses within the tire due to the action of the rubber and cord components of the tire, both of which have their individual loss characteristics.

(b) Under conditions of free rolling or steady state driving, where external torque applied to the wheel is not large, it is generally conceded that the hysteretic component of the total tire loss is the dominant one, making up something more than 90% of the total mechanical losses in the tire. Aerodynamic drag of the tire itself and friction between the tire and roadway are minor components.

(c) The hysteretic loss characteristics of most of the materials used in the tire construction, namely rubber and polymeric cord, are quite sensitive to the temperature level at which the loss characteristics are measured. Steel and glass cords are less sensitive to temperature effects.

(d) Starting from rest at ambient temperature, the temperature of the rolling tire begins to rise as the vehicle starts in motion due to the fact that the hysteretic losses inside the material generate heat. Due to the poor thermal conductivity of rubber it takes a relatively long time for the tire to come into temperature equilibrium. For example, a normal passenger car tire under passenger car vehicle loads requires at least 30 minutes to reach steady-state temperature beginning from rest. Eventually this equilibrium is attained. This higher temperature is not uniform throughout the tire body but varies according to geometric and material design. Due to mixing, the air inside the tire cavity will have a higher average temperature than at the beginning of the rolling process. This results in a higher pressure than the original inflation pressure of the tire, due to the increased temperature of the trapped air. This rise in pressure causes a reduction in the deflection of the tire. Since the following loss is strongly dependent upon the tire deflection as well as upon the material temperatures in the tire body, then these factors both influence the equilibrium state rolling loss value.

(e) From this discussion it may be seen that an unambiguous description of the rolling loss of a pneumatic tire requires the complete specification of its operating characteristics. For example, one must specify temperature state and inflation state, both of which depend not only on the length of time of running, but also upon detailed running history and ambient temperature, as well as the various other operating parameters that enter the picture such as speed, power transmitted through the wheel, and suspension influences including the fraction of vehicle weight carried and camber settings. Many possibilities exist for interaction between variables.

In order to discuss the problem of tire rolling loss concisely it is necessary for the reader to have a clear picture of the forces and moments acting on a tire as it rolls forward. In order to introduce these concepts simply, Figure 1 shows a self-powered vehicle moving to the right with velocity V and being retarded by an aerodynamic force labeled F and by the front wheel rolling resistance R_o. Force equilibrium is maintained by the net forces N at the rear wheels. The balance or equilibrium between the retarding force and the driving wheel forces allows the vehicle to run at velocity V. We now examine in more detail the rear wheel.

Figure 2 shows the rear wheel carrying a portion of the vehicle dead weight, denoted here by W_r. The pressure distribution in the contact area between tire

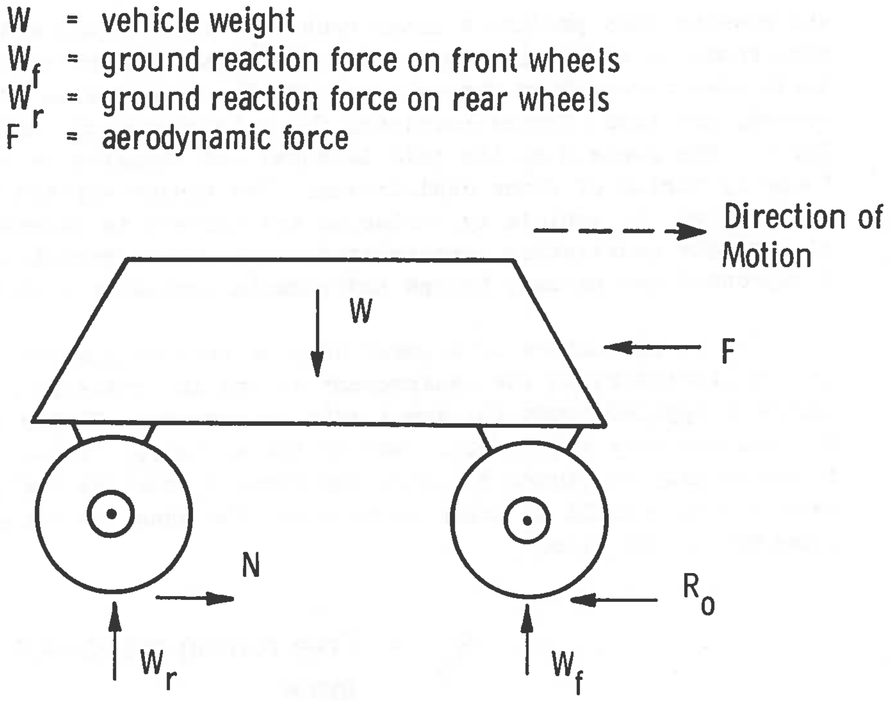


FIGURE 1. FORCES ACTING ON A VEHICLE

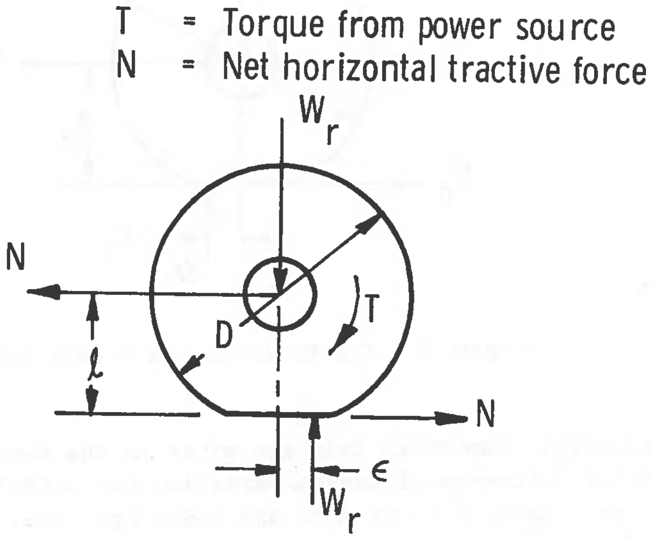


FIGURE 2. FORCES ACTING ON A DRIVEN TIRE

and roadway must produce a total resultant force equal and opposite to this, also shown in Figure 2. That force is offset forward by a dimension ε. The horizontal forces N at the axle and at the contact area of the tire with the roadway are those forces necessary for maintenance of the overall vehicle velocity V. The force N at the axle is equal and opposite to the roadway tractive force by virtue of force equilibrium. The torque applied to this wheel causing it to drive the vehicle by virtue of the force N is denoted by T. In the case of a simple nonsteering, noncambered wheel, these variables as shown in Figure 2 represent the primary forces and moments acting on a rolling wheel.

Due to the nature of a great deal of test equipment, not much data exist in the literature on the measurement of rolling resistance of tires when the torque T applied about the wheel axis is nonzero. It has been much more common to consider only the special case of the so called free-rolling wheel, shown schematically in Figure 3. Here the force R_o must be applied to the wheel axle by the vehicle in order to maintain the wheel at velocity V, due to losses inherent in the tire.

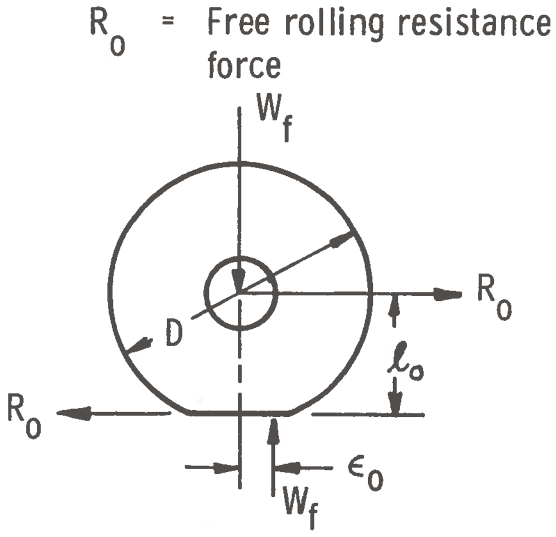


FIGURE 3. FORCES ACTING ON A FREE ROLLING TIRE

Considerable numerical data are given in the subsequent sections of this report on the influence of design variables and operating conditions on tire rolling loss. Most of those data are based upon test information obtained from the free rolling tire, such as shown in Figure 3. More data are needed on the rolling loss of tires under conditions of power transmission.

In the sections of this report immediately following we examine data collected from the literature on the rolling resistance of tires. This can be conveniently split into two parts. The first deals with the question of the influence of tire size, design, and material selection on the rolling resistance. Data are presented on the three major types of tires which have been common in the American market, the bias, the bias-belted, and the radial. Data are also given outlining some approximate numerical values of improvements in rolling resistance which can be obtained by design changes, by using different types of reinforcing cords and by using lower loss rubber compounds.

It is also possible to consider the tire as an accessory of the vehicle, subject to considerable control by the automobile designer and by the driver. The changes they can bring to bear on tire rolling resistance are outlined. The most important of these are load on the tire, its inflation pressure and its speed, although others can be cited. The relative importance of these variables on tire rolling loss is also discussed.

2. THE INFLUENCE OF TIRE CONSTRUCTION AND DESIGN ON ROLLING RESISTANCE

In this section we consider the influence of tire construction, design and material selection on the phenomenon of rolling loss. There are three fundamental types of tire construction now in use in this country. These are:

(a) The bias tire, characterized by the fact that alternate layers of its textile reinforcing cords lie at a substantial angle with respect to one another.

(b) The bias-belted tire, similar in construction to the bias tire but now with an added reinforcing belt under the tread region.

(c) The radial tire, so named because its carcass plies run in a purely radial direction, from bead to bead. This tire is heavily reinforced by a belt running circumferentially around it, approximately the width of the tread.

The bias tire developed in this country primarily due to the fact that its production could be semi-automated. It was dominant for many years, until pressure for longer wear and better handling characteristics forced the adoption of first the bias-belted tire, which was an interim measure, and finally the radial tire which only within the last two or three years has come into the commercial market in large numbers. The radial tire is already widely used in Europe and will undoubtedly become the dominant tire construction in the United States within a short period of time.

Generally speaking, radial tires exhibit lower rolling resistance than either bias or bias-belted tires. Partly this is due to the materials normally used in them, but it is also partly due to their detailed tire design characteristics such as belt stiffness and cord angles.

With regard to tire material selection, two major components must be discussed here. The first of these is the tire cord, which may range all the way from rayon or nylon, both relatively high loss materials, to glass or steel, both of which perform as nearly linearly elastic materials when used in pneumatic tire service. The choice of cord materials is not generally considered to be a major influence in determining tire rolling loss, in most cases.

The choices of rubber compounds used in the tire seem to be more important than the choice of tire cord. A number of different rubber compounds are used inside a pneumatic tire for different specific purposes. The two most important from the point of view of tire rolling loss are the carcass compounds, used to encase and insulate the reinforcing cords from mechanical contact with one another, and the tread compound which is used to provide scuff protection for the tire carcass as well as to give optimum traction and wear characteristics. It is hardly surprising that different rubber compounds would be used for service conditions which are so different from one another. Generally speaking, one could conclude that the choice of low loss rubber compounds would be beneficial in reducing the rolling loss of the pneumatic tire, and this is indeed true.

As can readily be imagined, the relative importance of the reinforcing cords and the rubber compounds in contributing to tire rolling loss is the subject of considerable interest. Willett [89] and Collins et al. [16], have both attempted to define the role of various tire component materials in the overall hysteretic heating process. Since this process is so intimately tied to tire rolling resistance, the conclusions applying to one will apply to the other. Both writers approach this problem from the point of view of selective compounding and construction, that is to say, by building tires using rubber or textiles of varying loss characteristics while all other materials were held constant. Free rolling losses were then measured in these tires in an effort to define the role of each of the tire components in the overall loss process. The data of both Collins and Willett are combined in Table 1. Both writers conclude that approximately 20 to 40% of the total loss in a pneumatic tire may be attributed to losses in the cord reinforcing system.

TABLE 1.-LOSS CONTRIBUTION OF TIRE COMPONENTS

	9.00-20 Truck Tire	2.25-8 Industrial Tire	6.95-14 4-Ply Bias Passenger Car Tire
Rubber:			
Tread	59%	51%	72%
Other	12%	9%	11%
Cord:	29%	40%	17%
Reference	[16]	[16]	[89]

Unfortunately these two authors do not agree closely in their quantitative assessments, but the general conclusion seems to be that the cord component is not the predominant factor in the rolling loss process of the pneumatic tire. This is confirmed by other numerical data which will be presented subsequently in this section.

The data of both Collins and Willett were obtained for bias-ply tires. No comparable data seem to exist for radial tires at this time.

2.1 Construction Type

There is some information in the literature comparing rolling loss characteristics of bias, bias-belted, and radial tires for the same size and load carrying abilities. Representative data for passenger car tires are given by Elliott [24] in Figure 4. This figure shows that the radial tire exhibits lower rolling resistance than either the bias-belted or bias tire up to about 90 to 100 mph, at which time its rolling resistance tends to become greater than either of the other two types. In view of the fact that this is considerably above normal speed ranges, one may conclude that for passenger car service the radial design is most efficient, the bias-belted next and the bias tire least efficient.

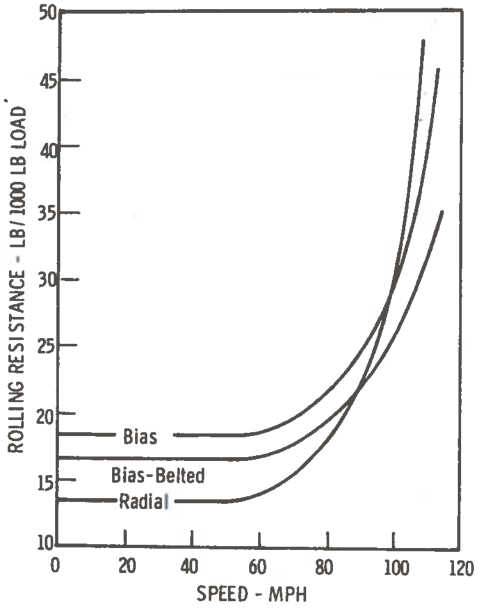


FIGURE 4. ROLLING RESISTANCE VS. SPEED FOR DIFFERENT TIRE CONSTRUCTION TYPES (PASSENGER CAR TIRES)

Similar conclusions have been reached for truck tires. Davisson [20] has given rolling loss information for typical truck tires showing that the radial tire is also more efficient in that case than a similar bias-ply design. This is uniformly true within the limited speed range with which he deals. These data are given in Figure 5.

Finally, Curtiss [19] has presented rolling loss data for several different tire constructions, including a low-profile tire. These are presented in Figure 6 and are of particular interest since they illustrate improvements which can be obtained by changing tire cross-section dimensions. Both the conventional bias and low-profile bias tires which are illustrated in Figure 6

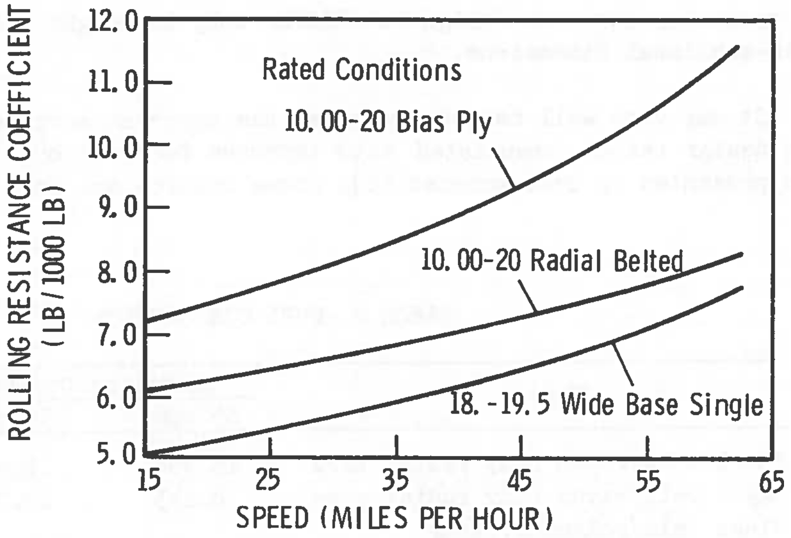


FIGURE 5. ROLLING RESISTANCE VS. SPEED FOR DIFFERENT TIRE CONSTRUCTION TYPES (TRUCK TIRES)

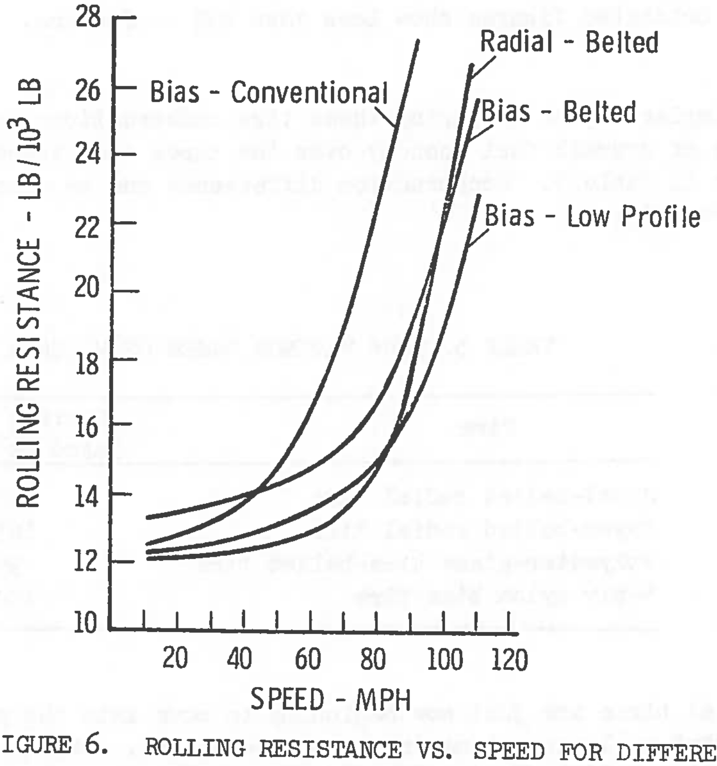


FIGURE 6. ROLLING RESISTANCE VS. SPEED FOR DIFFERENT TIRE CONSTRUCTION TYPES (PASSENGER CAR TIRES)

are basically the same design but differ only in height and width of their cross-sectional dimensions.

It may very well be asked whether the apparent advantages of the radial tire design can be translated into improved fuel economy. Data on this have been presented by Bezbatchenko [3], whose results are shown in Table 2.

TABLE 2.-FUEL CONSUMPTION

Tire	Gasoline Consumption, mpg		
	35 mph	50 mph	75 mph
Steel belt/rayon body radial tire	18.758	18.403	13.681
Rayon belt/rayon body radial tire	18.143	17.718	(13.298)
Glass belt/polyester body bias-belted tire	(17.614)*	(17.068)	(13.024)
4-ply nylon body bias tire	(17.636)	(17.207)	(13.102)
Limits for significant difference at 95% confidence	0.408	0.462	0.376

*The bracketed figures show less than 95% confidence.

A simpler way of comparing these tire constructions is to rate them on the basis of overall fuel economy over the three test speeds. These results are shown in Table 3. Construction differences can be clearly seen in these mileage results.

TABLE 3.-TIRE RATINGS BASED ON MILEAGE

Tire	Overall Rating Based on Mileage
Steel-belted radial tire	106
Rayon-belted radial tire	103
Polyester-glass bias-belted tire	99
4-ply nylon bias tire	100

Radial tires are just now beginning to move into the passenger car and truck market in large volume in the United States. If the experience in the European tire market can be taken as a precursor of what will come here in the United States, we will find in a few years that the radial tire design will represent the major fraction of tires manufactured and sold in the United States for both the passenger car and commercial vehicle market. This market shift will in itself do a great deal to reduce the rolling resistance characteristics of the total American vehicle population, probably more than any other single factor.

Tire design is an evolutionary process. Due to the very large number of units produced, and due to the fact that feedback on field experience is difficult to obtain in adequate quantity until after a substantial number of units have been manufactured and put into service, there is strong economic pressure to confine engineering changes to relatively small perturbations which can be closely monitored for reliability and durability. For these reasons the industry now finds itself fully occupied with the process of bringing acceptable radial tires to the American tire market. There has not yet been time for the direction of the next major design change of the future to become at all clear. Even in the European passenger car market, which is considerably more advanced than ours in the use of radial tires, there has been no clear move as yet from the radial to more advanced designs. For that reason it must be concluded that we will be living with some version of the radial tire in this country for a number of years, and that the primary study of rolling resistance characteristics should be directed to that design.

2.2 Design

Tire size—There is need to examine the role of the overall tire size on the rolling loss process. This must be conditioned, however, by the need for the tire to carry a specified load. It is this load carrying requirement which is primary both in passenger car vehicles and in trucks or other commercial vehicles. Within that restriction, however, different sizes of tires may indeed be used to carry greater or lesser loads, depending upon their design, construction, and inflation pressure. Aircraft tires are an excellent example of this, where in extreme cases loads in excess of the weight of a complete passenger car may be carried by a single tire substantially smaller than any tire presently in use on passenger cars. In general this kind of tire requires the use of heavy multi-ply tire casings and extremely high inflation pressures. Such tires are expensive and suffer from the decided disadvantage of having extremely high vertical spring rates, so that their cushioning effect on both the vehicle and its occupants is dramatically reduced.

There are some data in the literature on modern aircraft tires, such as that given by Horne and Leland [39] and by Skele [80]. They give free rolling resistance figures for large aircraft tires on the order of 10 to 15 pounds of drag per 1000 pounds of vertical load. This would indicate that, generally speaking, total rolling resistance of these very highly loaded tires is not any lower than that of any conventional automobile tire, and no dramatic improvements could be expected by using very small high-pressure tires in vehicular service.

Some general information on this subject was presented by Evans [25] who studied the loss characteristics of the solid rubber tire whose dimensions are shown in Figure 7. He shows that for this tire the free rolling loss is given by

$$R_o = K \frac{W^2}{D} \left(\frac{h}{w}\right)^{1/2}$$

where K is a constant containing the loss and elastic characteristics of the tire material and W is the load on the tire.

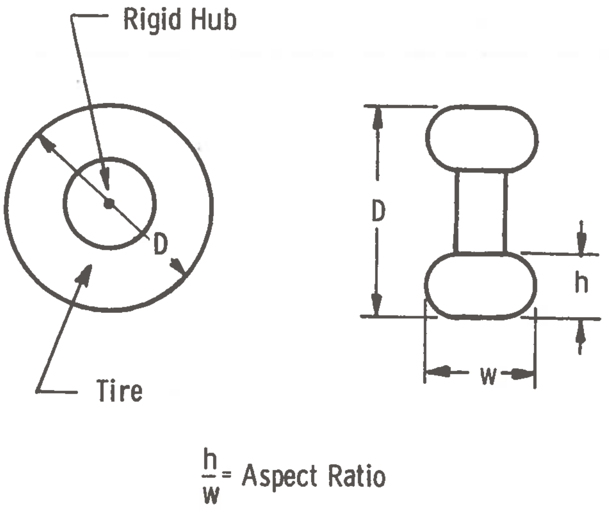


FIGURE 7. DEFINITION OF ASPECT RATIO

Assuming that the results of Evans may be applied to pneumatic tires as well, one may conclude that the important factors governing rolling resistance are, in the order of their importance:

(a) The load on the tire should be kept as small as possible.

(b) The diameter of the tire should be kept large.

(c) The aspect ratio of the tire should be kept low.

These tentative conclusions should be confirmed by more detailed theoretical studies.

Some confirmation of the general conclusions reached by Evans has appeared in the literature from studies of the rolling resistance of conventional passenger car tires of different sizes under the same load conditions. Curtiss [19] presents data taken at constant load on a variety of tires of fixed rim diameter but varying section width. His results, given in Figure 8, illustrate the influence of aspect ratio on tire rolling drag as derived by Evans.

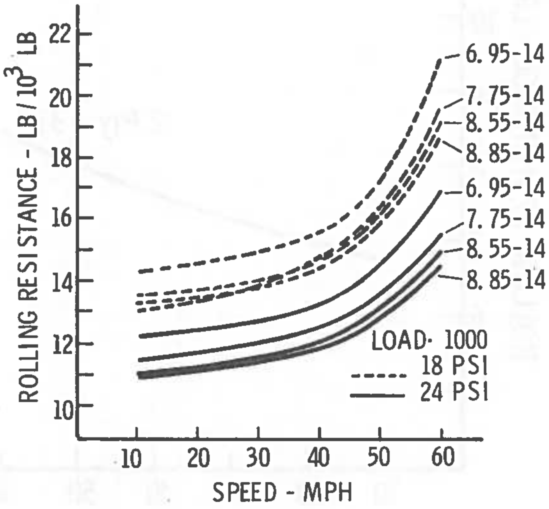


FIGURE 8. ROLLING RESISTANCE VS. SPEED FOR DIFFERENT TIRE SIZES (ASPECT RATIOS)

Number of Plies—Generally the rolling resistance of a pneumatic tire increases as the number of plies increases. Billingsley [4] reported that 6-ply tires had a 7% greater rolling resistance than 4-ply tires, both tested at 30 mph and under conditions of the same load and inflation pressure. At 60 mph the difference had reduced to 4% between the 6-ply and 4-ply tires.

This phenomenon has been observed by others. Curtiss [19] shows this clearly in Figure 9, given for passenger car tires, while Rekitar [68] gives similar data for truck tires in Figure 10. Rekitar also gives data on truck tires running in thermal equilibrium, which confirms the fact that those with larger numbers of plies exhibit higher rolling resistance values. These data are presented in Figure 11.

The only data available in the literature which do not agree with the conclusion that an increasing number of plies results in increasing rolling resistance are presented by Seki [78] who found a constant value of rolling resistance with number of plies in passenger car tires. His data are presented in Figure 12.

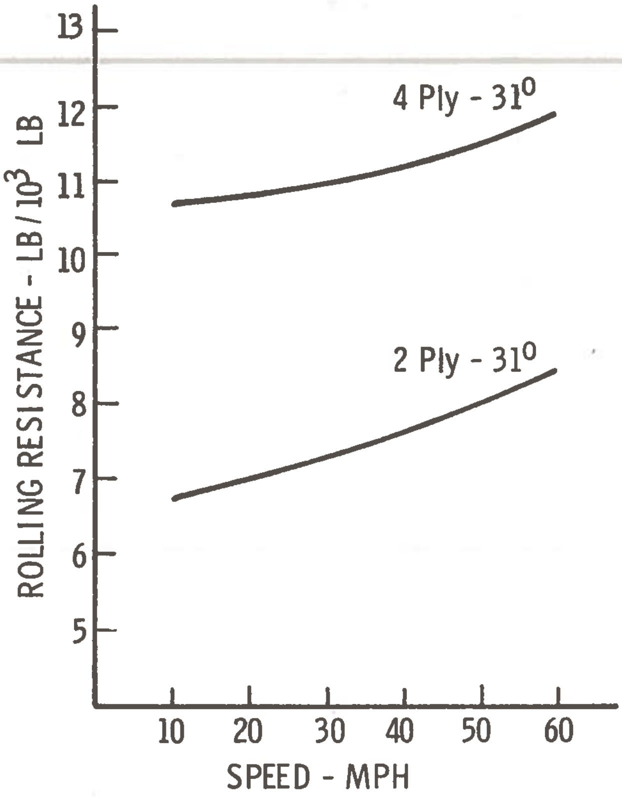


FIGURE 9. ROLLING RESISTANCE VS. SPEED FOR A 2-PLY AND A 4-PLY PASSENGER CAR TIRE

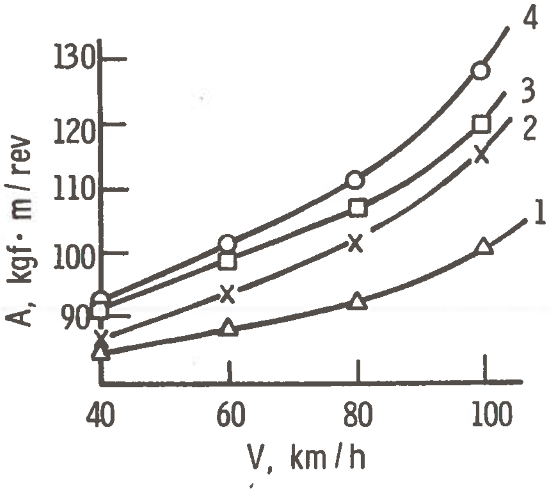


FIGURE 10. A (PROPORTIONAL TO ROLLING RESISTANCE) VS. V (SPEED) FOR TRUCK TIRES OF THE SAME SIZE WITH 4-PLIES (1), 6-PLIES (2), 8-PLIES (3), AND 10-PLIES (4)

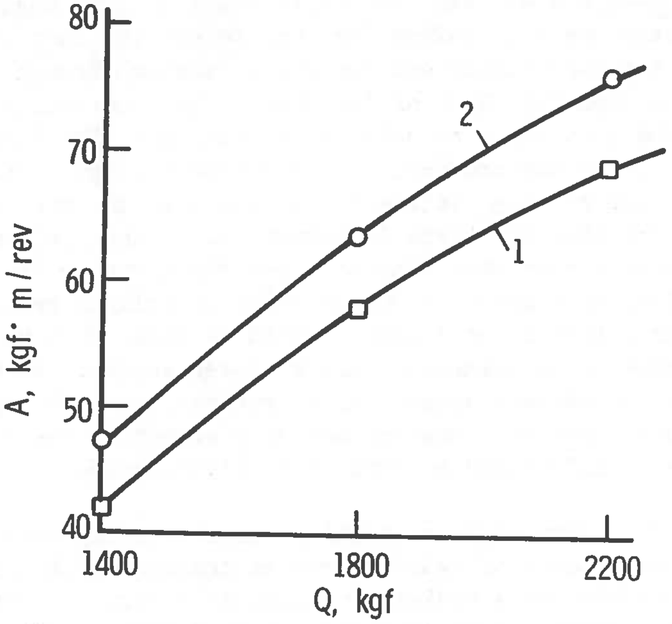


FIGURE 11. A (PROPORTIONAL TO ROLLING RESISTANCE) VS. Q (VERTICAL LOAD) FOR TRUCK TIRES OF THE SAME SIZE WITH 4-PLIES (1) AND 10-PLIES (2)

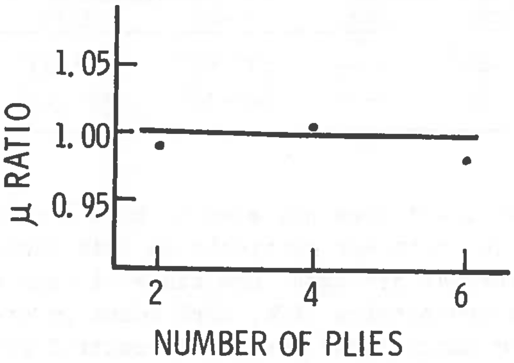


FIGURE 12. μ RATIO (PROPORTIONAL TO ROLLING RESISTANCE) VS. NUMBER OF PLIES

Cord Angle—Since at least two definitions of cord angle are prevalent in the tire industry, we will define for this report the cord angle as that angle lying between the cord itself and the plane passing through the mid-surface of the tire and through the plane of the wheel. All information available on the influence of the cord angle on rolling resistance is for bias-ply tires whose constructions lie in the moderate- to large-angle range. Walter and Conant [86] conclude that rolling resistance increases as the cord angle increases. This is shown for bias-ply tires in Figure 13. Evans [26] concurs with this result, and further concludes that for bias-ply tires in the range of acceptable cord angles, only about an 8% variation in rolling resistance can be achieved by variations in cord angle. Both of these writers caution, however, that this conclusion is clear-cut only at lower speeds. At higher speeds, above the range of present speed limits, reversals in rolling resistance may occur due to the onset of vibratory and wave effects. These latter phenomena are also markedly influenced by cord angle distribution.

The effect of cord angle on rolling resistance may account partly for the lower rolling resistance of radial tires as compared with bias tires since much of the cord body in a radial tire lies at a very low cord angle. It is interesting to compare the distribution of cord angles in typical tire constructions. These are given here in Table 4 from data originally published by Walter and Conant [86].

TABLE 4.-CORD ANGLES USED FOR BODY AND BELT PLIES

Tire Condition	Bias		Belted-Bias		Radial	
	Body	Belt	Body	Belt	Body	Belt
Unvulcanized	54°-64°	—	57°-61°	55°-59°	85°-90°	17°-26°
Vulcanized	26°-36°	—	32°-36°	28°-32°	85°-90°	15°-24°

Cord Count—Cord count does not seem to have a marked effect on rolling resistance although few data are available on this factor. Since count is intimately tied to carcass strength, and since minimum strengths are necessary for adequate fatigue and service life, cord count generally does not appear to be a factor which can be manipulated readily to control rolling resistance. Curtiss [19] has presented what are probably the most recent data on the direct influence of cord count on rolling resistance in Figure 14. In spite of the fact that the two cords discussed by Curtiss, polyester and rayon, seem to have opposite effects in terms of exhibiting a maximum or a minimum, nevertheless the variation in rolling resistance which can be achieved within a single cord material seems to be relatively small, being of the order of 5% or less.

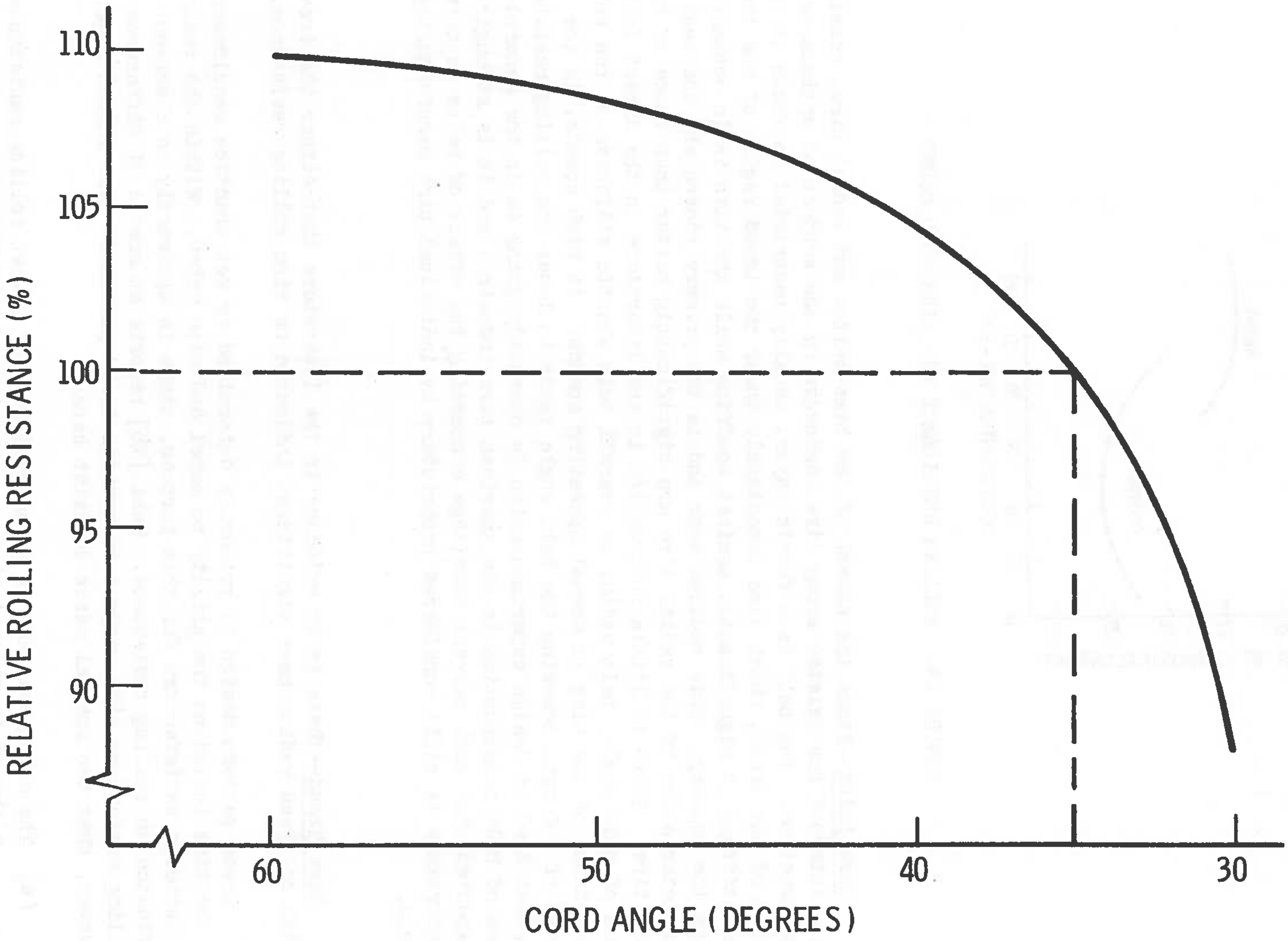


FIGURE 13. RELATIVE ROLLING RESISTANCE VS. TIRE CORD ANGLE

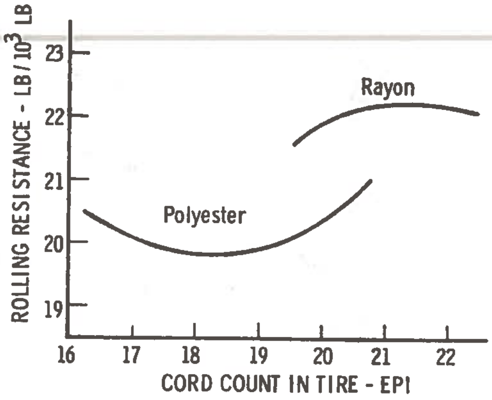


FIGURE 14. ROLLING RESISTANCE VS. TIRE CORD COUNT

Tire Belts—Since the advent of the bias-belted and radial tire, considerable interest has existed among tire engineers on the subject of optimum belt construction. The belt is a fabric layer, usually restricted in width to the width of the tread, which lies immediately under the tread region of the tire and stiffens it significantly against scuffing while the tire is in contact with the roadway. This reduces wear and is the primary reason why the wear characteristics of the radial tire are significantly better than those of the bias tire. There is little information in the literature on the direct influence of belt angle, belt width, or overall belt elastic stiffness on the rolling resistance of the tire at normal operating speeds. At high speeds, in the order of 100 mph, lowering the belt angle tends to lower the rolling resistance. A great deal of design experimentation is currently going on in the general area of belt construction in the American tire industry, and it is strongly suspected that much current knowledge concerning the effect of belts on tire performance is still considered proprietary by individual tire manufacturing firms.

Tire Tread—There is no evidence in the literature that either the tread width or tread radius have significant influence on tire rolling resistance.

Tread pattern design is primarily determined by wet traction requirements of the tire including the ability to expel and wipe water. Within the realm of patterns satisfactory for this purpose, there is apparently no clear-cut influence on rolling resistance. Seki [78] reports at most a 5% difference in rolling resistance with respect to various tread patterns. One should note, however, that two special cases do exist here:

(a) The completely smooth tread exhibits the lowest rolling resistance, although in general it is completely unacceptable from a wet traction point of view.

(b) Tread patterns become relatively more important in determining overall rolling resistance for high pressure tires.

As would be expected, thinner treads generally reduce the rolling resistance of tires. This was pointed out in Table 1 where the tread rubber was shown to be an important factor in rolling loss. Curtiss [19] has examined the rolling loss of the same tires but with variable tread thickness by buffing off portions of the treads of these tires. His data are given in Figure 15, and confirm the role of thicker treads in causing higher rolling loss. The only surprising result is that at very high speeds radial tires exhibit lower rolling loss with thicker treads. This is due to suppression of vibratory effects at these speeds.

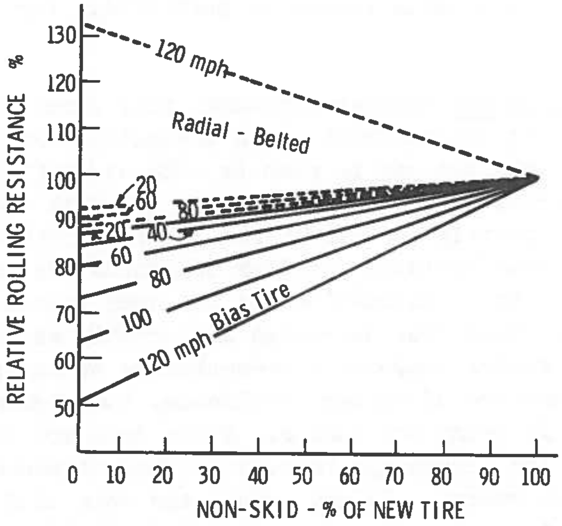


FIGURE 15. RELATIVE ROLLING RESISTANCE VS. TREAD THICKNESS

All of these reports on the influence of tread thickness on rolling resistance must be tempered by the realization that they are quite speed dependent. The primary reason for this is temperature. A tire with thin tread will tend to run at lower equilibrium temperatures at high to moderate speeds than will a tire with a thicker tread. Under these lower equilibrium temperatures the hysteretic characteristics of the materials used in the tire will cause a higher loss per unit stress cycle than at higher temperatures. Thus one has the counterbalancing effects of lower running temperature for tires with thin treads but of less material being stressed. The net direction of these two effects seems generally to be a decrease in rolling resistance for the tire with thin tread, but the effect is certainly not as large as it would be were it not for the opposite effect of changing equilibrium temperature.

2.3 Tire Materials

The role of tire materials in the overall rolling loss characteristics of the pneumatic tire is extremely complex. It is complex because the selection of materials is not governed solely by consideration of rolling loss. The tire must not only transmit power with relatively low loss characteristics, but must also provide acceptable shock cushioning between highway roughness and the vehicle, must provide cornering forces and tractive forces in both wet and dry conditions, and must do so at reasonable cost and relative durability. These factors dictate that the rubber compound and textile cord selection be compromises between a number of factors desired in overall tire performance. Therefore, the comments which follow on tire materials will be restricted to those lying in reasonable ranges of possibility for current pneumatic tire service.

Rubber Compounds—Rubber compounds play a relatively large role in controlling the loss characteristics in pneumatic tires. The influence of compounds on rolling loss may be seen in both aircraft and truck tire construction. In aircraft tires, where high deflection and high speed are the rule, natural rubber is used heavily because of its low hysteresis characteristics and subsequent small heat buildup. Similar compounds are used, but to a lesser extent, in truck tire construction for the same reason. Curtiss [19] shows that the relative rolling loss decreases measureably as the percentage rebound increases for a rubber compound representative of an entire tire. The percentage rebound is a measure of rubber resilience, the higher the percentage rebound the more elastic being the rubber. These data are given in Figure 16. Another definition of the percentage rebound is that it represents a direct measure of the recoverable energy. In any event, the data of Figure 16 must be treated with some caution since they represent information obtained from relatively low speed tests. At moderate and higher speeds the influence of the rubber compound on rolling resistance is less dramatic. This phenomenon also was reported by Curtiss, who gives data on two tires identical in all repsects except for their rubber compounds. This is shown in Figure 17, where it is seen that at higher speeds the high-hysteresis material (low rebound) exhibits a lower rolling loss than the low-hysteresis material (high rebound). This is undoubtedly because of the onset of dynamic and vibratory effects, which are more efficiently suppressed by a high damping material than by a low damping material. Nevertheless, the conclusion seems to be that within the normal speed range significant improvements can be made by variations in rubber compounding in a tire. Some absolute data on this have been obtained by Collins [16], who reports variations in tire drag associated with different values of the tread compound loss modulus. These were determined for a series of different tire deflections, and are presented in Figure 18. From these data one would conclude that the influence of tread hysteresis characteristics is more important for large tire deflections than for low tire deflections, but that there seems to be a direct correlation between rolling resistance and tread hysteresis under all conditions.

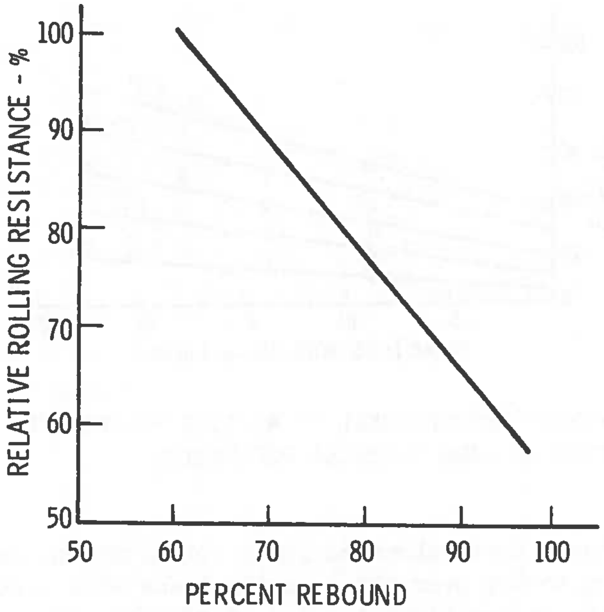


FIGURE 16. RELATIVE ROLLING RESISTANCE VS. PERCENT REBOUND FOR MODERATE SPEEDS

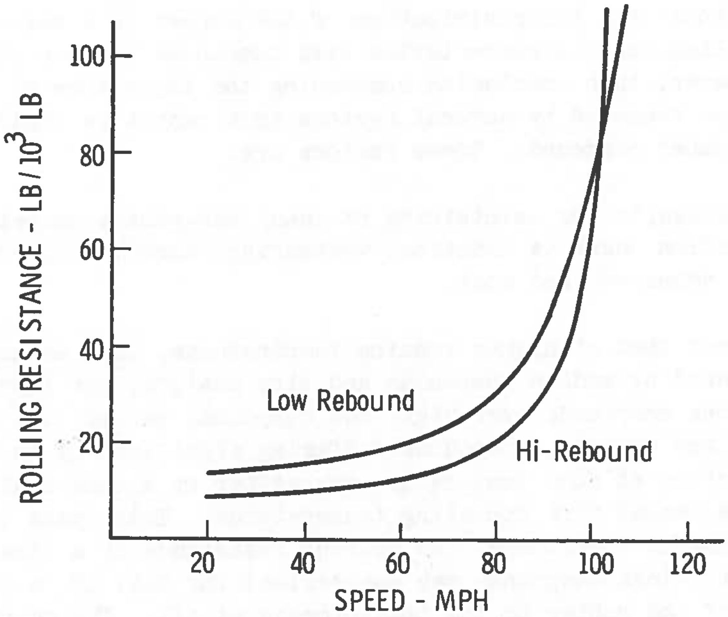


FIGURE 17. ROLLING RESISTANCE VS. SPEED FOR HIGH- AND LOW-HYSTERESIS COMPOUNDS

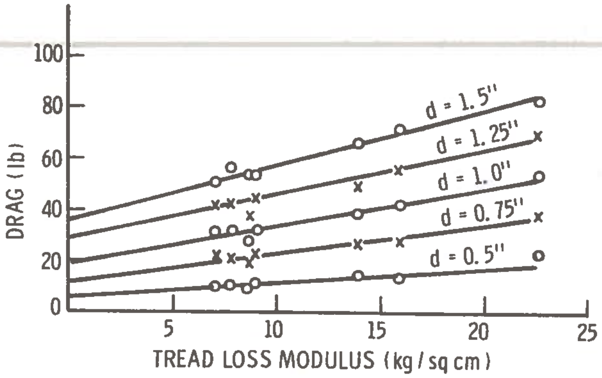


FIGURE 18. DRAG FORCE (PROPORTIONAL TO ROLLING RESISTANCE) VS. TREAD LOSS MODULUS AS A FUNCTION OF TIRE VERTICAL DEFLECTION

Curtiss [19] states that rubber compound substitutions can decrease rolling resistance by up to 40% over the same tire made with high-hysteresis compounds. This seems to be the highest value of possible improvement which has been reported due to compound substitution alone.

Generally speaking the decrease in rolling resistance with increasing resilience (decreasing hysteresis) of a typical rubber compound is to be expected since Table 1 shows that the contribution of the rubber in a pneumatic tire to its overall rolling loss characteristics lies somewhere between 60 and 80% of the total. However, this conclusion concerning the importance of the rubber component must be tempered by several factors that cannot be neglected in the choice of the rubber compound. These factors are:

(a) The necessity for maintaining at least acceptable values of other properties such as traction, weathering, durability, cut resistance, wear, adhesion, and cost.

(b) The fact that at higher running temperatures, such as are being encountered by modern compounds and tire designs, the improvements of low-loss compounds over high-loss compounds become less and less, so that, for example, compounds differing significantly in hysteresis properties at room temperature may differ by a much smaller degree at the actual tire operating temperatures. This means that under equilibrium conditions, the rolling resistance of a tire with particular low-loss compounds may not reflect the full 60 to 80% contribution of the rubber to the loss process at all. The contribution or the difference may be substantially smaller, and usually is.

(c) Figure 17 shows that at higher speeds the differences in rolling resistance between tires made with high-loss and low-loss compounds may also become blurred. The high-loss compounds, while giving higher rolling resistance at lower speeds, also provide greater damping and suppress the onset of dynamic or vibratory effects so that at higher speeds the low-loss compounds may actually result in a tire with higher overall total drag characteristics, due to the fact that wave phenomena exist in that tire which do not exist in a more highly damped tire. Thus the interaction with speed may mitigate the beneficial effects of compound substitution.

The general conclusion that seems to be drawn from information available in the literature, such as the review papers of Curtiss [19], Walter and Conant [86] and Roberts [70] is well summarized by the data of Roberts given in Figure 19. These show that for three sets of tires made with high- and low-loss compounds, the initial or room temperature rolling resistance values differ markedly, probably by close to a factor of 2 to 1 or 2.5 to 1. However, their equilibrium temperatures under running conditions also tend to be different, with the higher loss compound running at a higher equilibrium temperature. Under these conditions of equilibrium the comparative loss values of the two tires differ by not more than 20%. From this it must be concluded that while fundamental improvements are possible by the use of low-hysteresis rubber compounds, care must be taken in assessing the magnitudes of the potential gains. They will certainly not be as large a factor as might be anticipated by consideration of their room temperature hysteretic properties and by consideration of their overall contribution to the total tire loss problem.

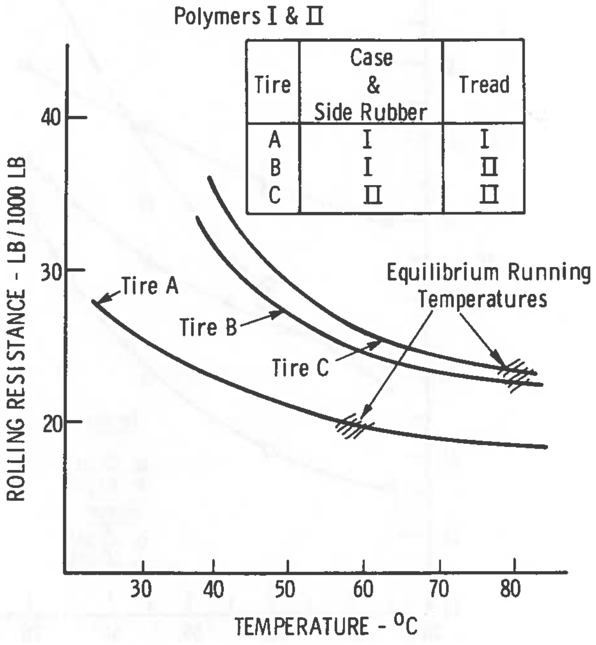


FIGURE 19. ROLLING RESISTANCE VS. TEMPERATURE FOR A PRODUCTION POLYMER (I) AND AN EXPERIMENTAL HIGH-HYSTERESIS POLYMER (II)

Cord Materials—Generally speaking, experiences with a wide range of textile cord materials have demonstrated that cord changes do not have, by themselves, major influence on the rolling loss characteristics of tires. Curtiss [19] has concluded that this is the case, as have other authors, and overall experience with bias, bias-belted, and radial tires shows that the use of extremely low-loss textile cords has not remarkably altered the rolling resistance characteristics of present day pneumatic tires. For example, the substitution of glass and steel in the belts of radial tires has not significantly reduced the rolling resistance over those values which are obtainable from fabric belts such as rayon. Some advantages may be obtained by the subsitution of low-loss textiles in tire carcass sidewall construction, but this practice is currently restricted to truck tires and is not yet available in passenger car tire production.

Some typical data have been given by Stiehler et al. [81], who compare nylon and rayon cords in a typical bias passenger car tire, and find that the differences in rolling resistance between these two types of tires seem to be somewhat ambiguous. These data are reproduced in Figure 20, which illustrates

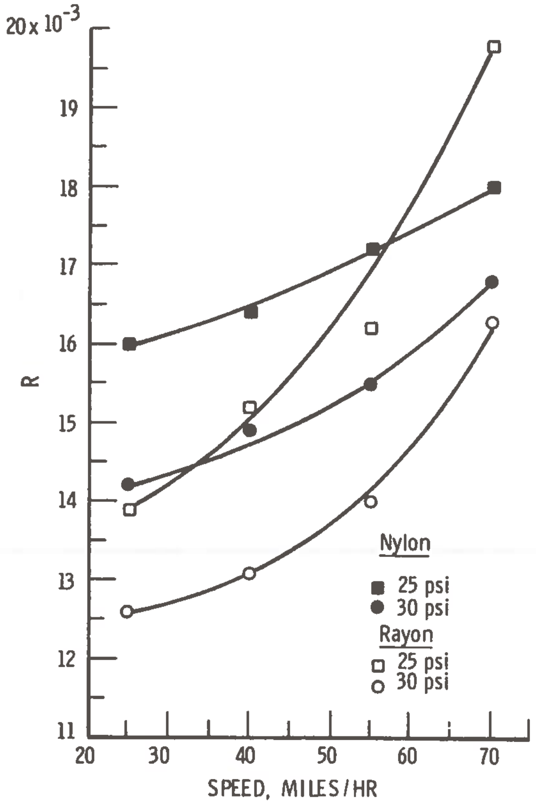


FIGURE 20. R (PROPORTIONAL TO ROLLING RESISTANCE) VS. SPEED AS A FUNCTION OF CORD TYPE

the fact that differences in inflation pressure and speed apparently cause changes in rolling resistance greater than those observed by differences in cord materials. The data of Figure 20 must further be qualified, as must many of the data presented in this report, by inadequate knowledge of the exact test conditions under which they were obtained. For example, it is not known whether these tires were at equilibrium conditions or at other conditions when the data were taken.

As was previously pointed out, the work of Collins et al. [16], indicates that the cord plays a smaller role in determining overall rolling resistance than does the rubber used in the tire. This information was given quantitatively in Table 1. The influence of the tire cord in overall power loss can be discerned but is not as great as that of the rubber itself. This conclusion has been confirmed by Evans [26] who states that "it is clear that their (cords) attributes and characteristics have some bearing on the overall level of power consumption of the finished tire...As between any one of these materials (nylon, rayon, steel) and each of the others the direct effect on rolling resistance of the tire is not great; certainly it is much less than the effect on certain other aspects of performance of the respective tire."

Tire Temperatures—The temperature of the tire is a dependent variable. Its value is determined by all of the design, construction, and operating characteristics of the tire including its running history. Nevertheless it is of general interest to understand the direct influence of temperature on the rolling resistance of the tire so that this factor may be more clearly delineated.

A number of references in the literature allude to the problem of temperature rise of a tire as it starts from rest. This is shown from the work of Evans [26] given in Figure 21 and from the work of Floyd [27] given in Figure 22, both of whom dealt with passenger car tires of conventional size and construction. Both conclude that times of the order of 30 to 60 minutes are needed for complete temperature equilibrium to be obtained prior to determining an equilibrium value for rolling resistance at a given velocity.

This type of time-temperature behavior was also confirmed for truck tires by the work of Kainradl [43] who found that almost 2 hours was needed to reach equilibrium temperatures in a truck tire. These data are shown in Figure 23. Curtiss [19] also measured this effect but did not report the existence of steady-state equilibrium conditions even after running for over 1 1/2 hours. His data are shown in Figure 24 and indicate temperatures continuing to rise even at the end of his test period.

Previous measurements done by the writer of this report using direct thermocouple measurements in passenger car tires running on the highway tend to confirm the data of Evans and Floyd just reported in Figures 21 and 22. We find equilibrium times of the order of 20 to 30 minutes to be the case in

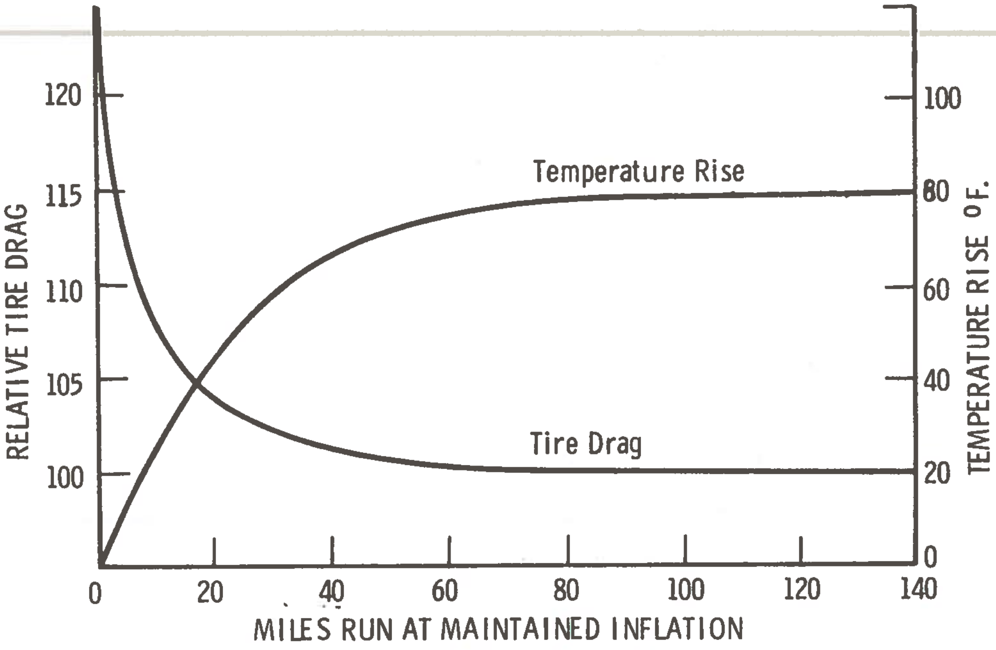


FIGURE 21. RELATIVE TIRE DRAG (PROPORTIONAL TO ROLLING RESISTANCE) AND TIRE TEMPERATURE INCREASE VS. MILES TRAVELED

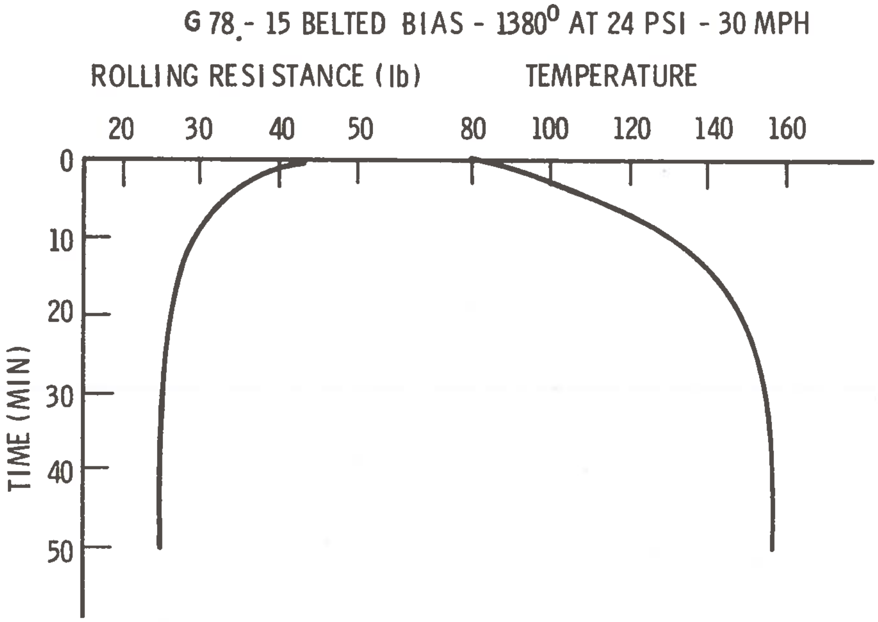


FIGURE 22. ROLLING RESISTANCE AND TEMPERATURE VS. TIME FOR WARM-UP

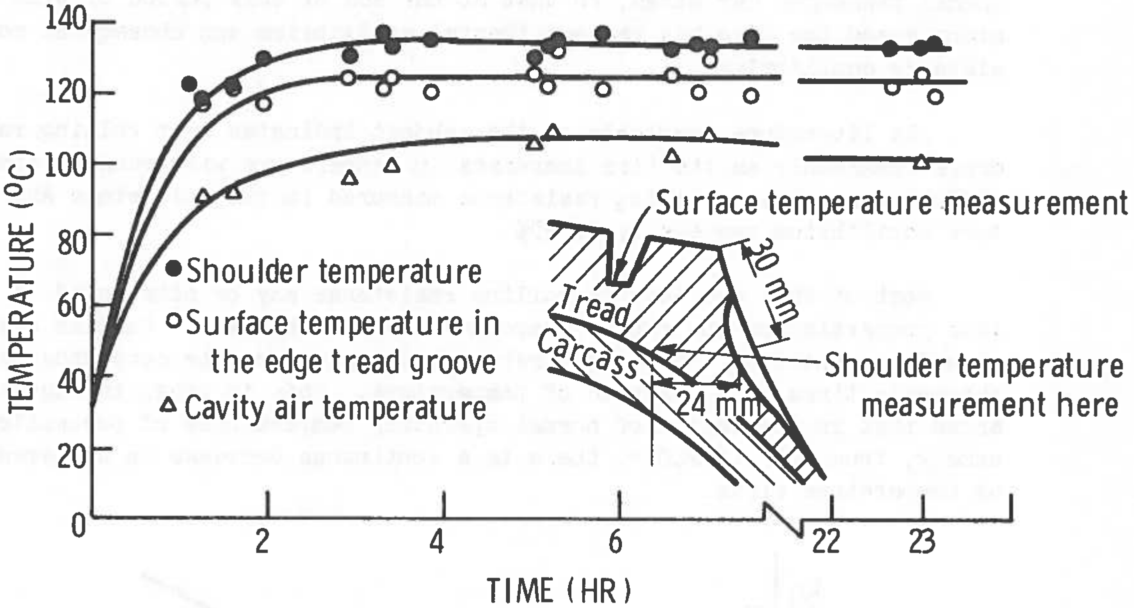


FIGURE 23. TIRE TEMPERATURE AT THREE POSITIONS VS. TIME IN A CONSTANT SPEED TEST

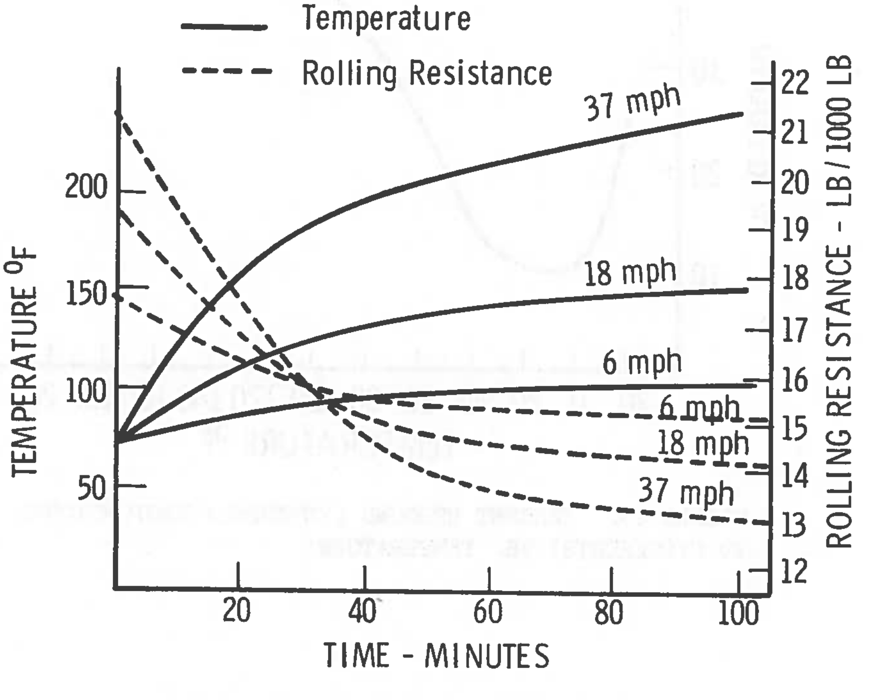


FIGURE 24. TEMPERATURE AND ROLLING RESISTANCE VS. TIME FOR THREE SPEEDS

normal passenger car tires, so that at the end of this period of time at constant speed the tire has reached thermal equilibrium and consequent rolling resistance equilibrium.

All literature available on the subject indicates that rolling resistance drops remarkably as the tire increases in temperature with running time. The differences between rolling resistance measured in the cold state and temperature equilibrium may easily be 25%.

Most of this decrease in rolling resistance may be attributed to the lower loss properties of the rubber compounds used in the tire. Curtiss shows this clearly by plotting the percent rebound of typical rubber compounds used in pneumatic tires as a function of temperature. This is given in Figure 25 and shows that in the region of normal operating temperatures of pneumatic tires, namely, from 60°F to 200°F, there is a continuous decrease in hysteresis loss as temperature rises.

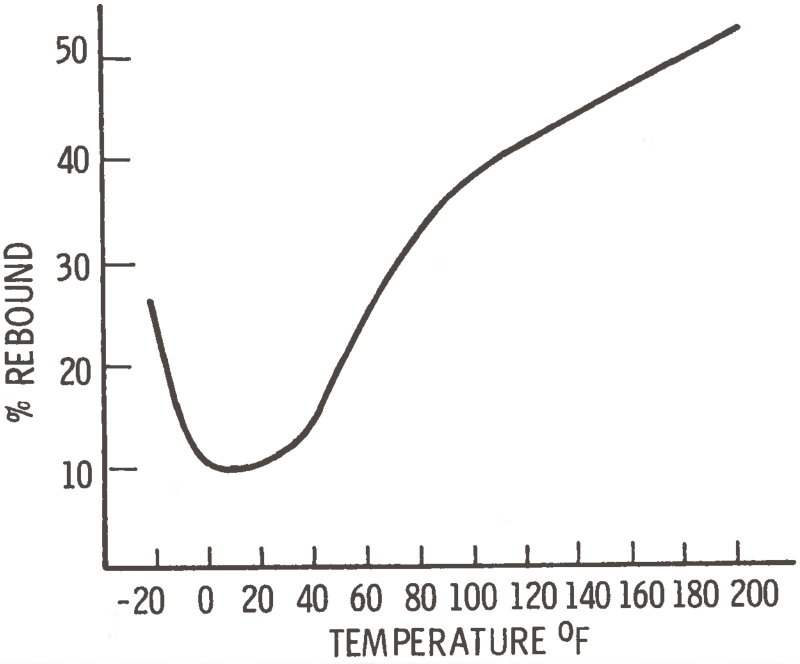


FIGURE 25. PERCENT REBOUND (INVERSELY PROPORTIONAL TO HYSTERESIS) VS. TEMPERATURE

3. THE INFLUENCE OF TIRE OPERATING CONDITIONS ON ROLLING RESISTANCE

Once the tire is designed and manufactured it passes into the hands of the automotive engineer and the ultimate consumer. The automotive engineer decides the load which the tire is to carry and recommends inflation pressures for it. He decides upon the suspension system camber, toe-in, and roll bar settings. To that extent he defines many of the external variables which control the rolling resistance of the tire. The vehicle owner, on the other hand, controls such characteristics as tne inflation pressure, the vehicle speed, the state of wear, and the type of driving cycle to which the tire is subjected. In this section we attempt to determine the influence of these variables on the overall tire rolling resistance.

3.1 Tire Speed

It is generally agreed in the literature that tire rolling resistance either increases with increasing speed or remains constant with speed in the moderate speed ranges. All investigators further agree that at higher speeds the rolling resistance increases at a faster rate. Typical data on this phenomenon have been presented by Curtiss [19], whose results are given in Figure 26. These results indicate the average or idealized response to be expected over a variety of tire types. Detailed information on specific tires was also given in the same paper and this information is given in Figure 27.

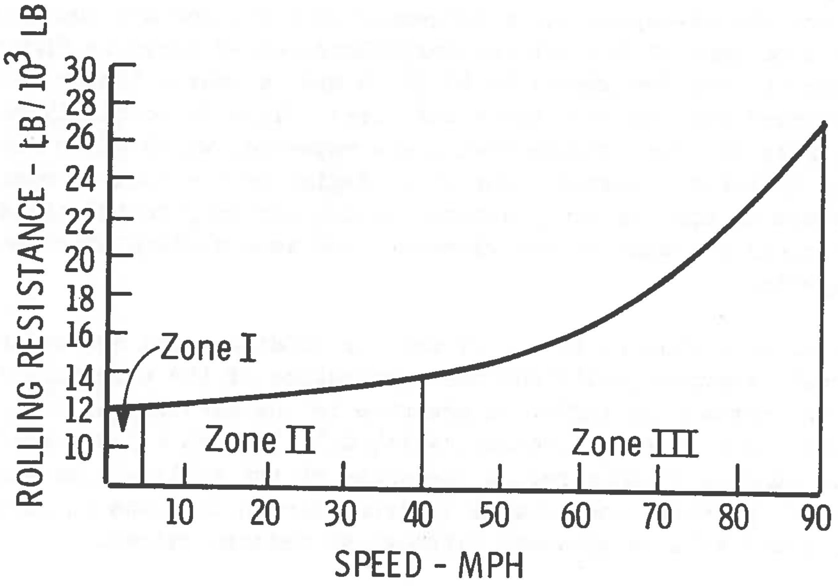


FIGURE 26. ROLLING RESISTANCE VS. SPEED

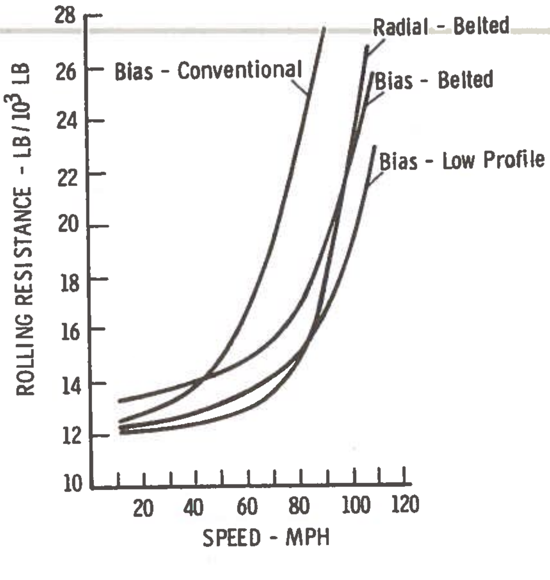


FIGURE 27. ROLLING RESISTANCE VS. SPEED
FOR DIFFERENT CONSTRUCTION TYPES

From Figure 26, it can be seen that the rolling resistance-speed relationship is divided into three regions. The first is a speed independent portion which is primarily due to the compression of the rubber in the contact patch and to the shearing action in the rubber between adjacent plies of textile reinforcing material. Figure 27 shows that the speed independent part of the rolling resistance—speed curve is nearly constant for all common tire designs. In the second part of the rolling resistance—speed curve in Figure 26, spanning a region from low speeds to 40 to 50 mph, a nearly linear relationship exists between rolling resistance and speed. This is primarily due to the increasing rate at which stress cycles are repeated, which gives rise to an increase in hysteretic losses. The third region of the rolling resistance—speed curve, above 50 mph, is nonlinear and is due not only to the hysteresis of the tire materials but also to the vibratory and wave actions which occur at these higher speeds.

The data in Figures 26 and 27 are for constant load and inflation pressure. Under actual service conditions the temperature of the tire will increase, causing an increase in inflation pressure in the air trapped in the tire. This will result in a lower deflection, which will lead to a lower rolling loss. This will tend to further reduce the slope of the rolling loss—speed curves just given. However, the general tendency for an increase in rolling loss with velocity still will be present, although at reduced values.

3.2 Tire Vertical Deflection

All the information reported in the literature agrees that the larger the tire deflection the greater the rolling resistance. This is primarily due to the fact that from 90 to 95% of the power consumption in the rotating tire is caused by hysteresis of the materials and of the tire structure, and that both of these effects are proportional in some fashion to the deformation state of the tire. Figure 28 shows the influence of vertical deflection for a passenger car tire, taken from data first presented by Willett [89]. Collins [16] has given similar data for truck tires, and a typical set of this is presented in Figure 29.

3.3 Tire Inflation Pressure

Increasing tire inflation pressure decreases the rolling resistance at all speeds on smooth hard surfaces. This occurs because the deflection at a fixed load is less at higher pressure, therefore reducing the hysteresis loss which is partly tire deformation dependent. This also increases the effective spring rate of the tire sidewalls, which reduces inertia losses at higher speeds. Walter [86] has presented data showing the effects of inflation pressure on rolling resistance for passenger car tires. These are given in Figure 30. Curtiss [19] gives similar data over a range of speeds, and these are presented in Figure 31. Finally, similar truck tire data have been published by Davisson [20], and he finds results yielding the same trends, as shown in Figure 32.

3.4 Tire Vertical Load

At fixed speed and inflation pressure the rolling resistance of a pneumatic tire increases with increasing vertical load. This is mostly due to the increased deflection resulting from the increased load. Curtiss [19] has obtained some general information relating rolling resistance to vertical load which is presented here in Figure 33. Elliott [24] gives quantitative results for passenger car tires at different speeds, and these are illustrated in Figure 34. Figure 35 gives similar data from the work of Stiehler et al. [81], for truck tires.

All of the data given in Figures 33, 34, and 35 were obtained on dynamometer wheels. Although curvature effects were present, these data appear to be consistent in that they show linear relationships for rolling resistance with vertical load. This is apparently partly explained by the fact that the inflation pressure was held constant during these tests. If the inflation pressure

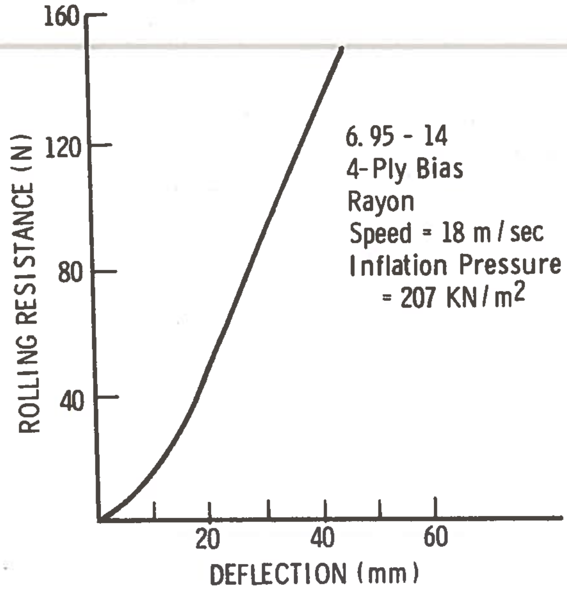


FIGURE 28. ROLLING RESISTANCE VS. DEFLECTION

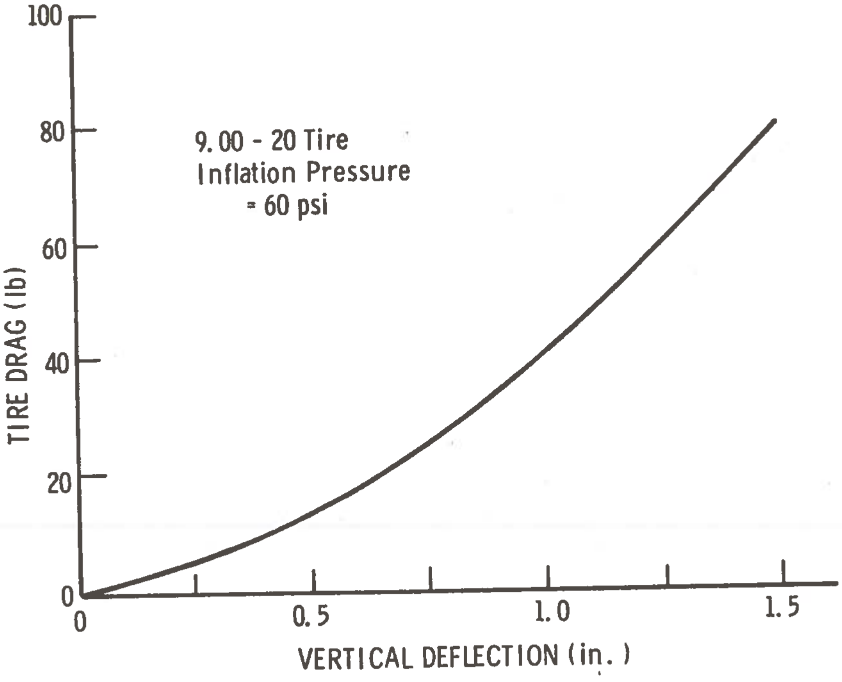


FIGURE 29. TIRE DRAG (PROPORTIONAL TO ROLLING RESISTANCE) VS. VERTICAL DEFLECTION

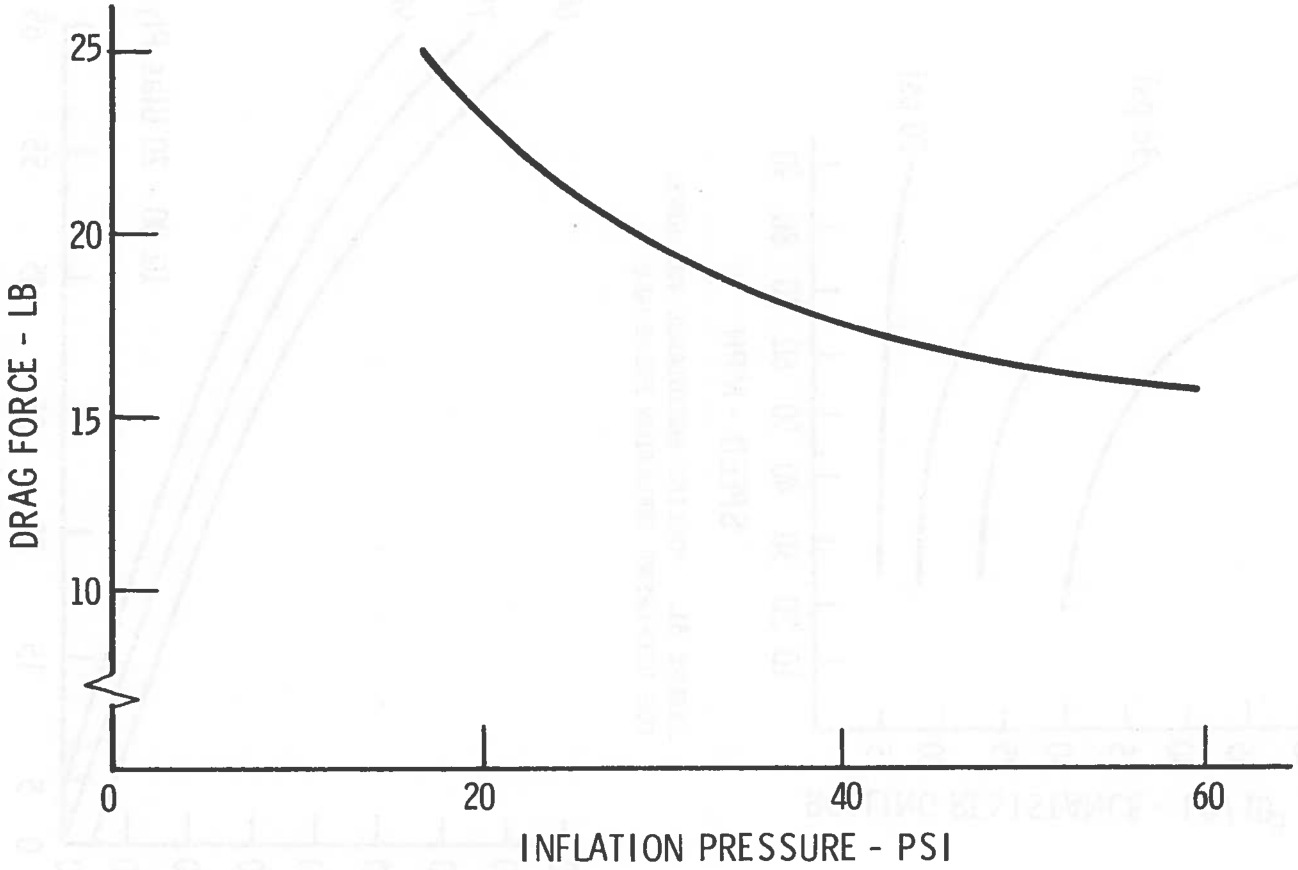


FIGURE 30. DRAG FORCE (PROPORTIONAL TO ROLLING RESISTANCE) VS. INFLATION PRESSURE

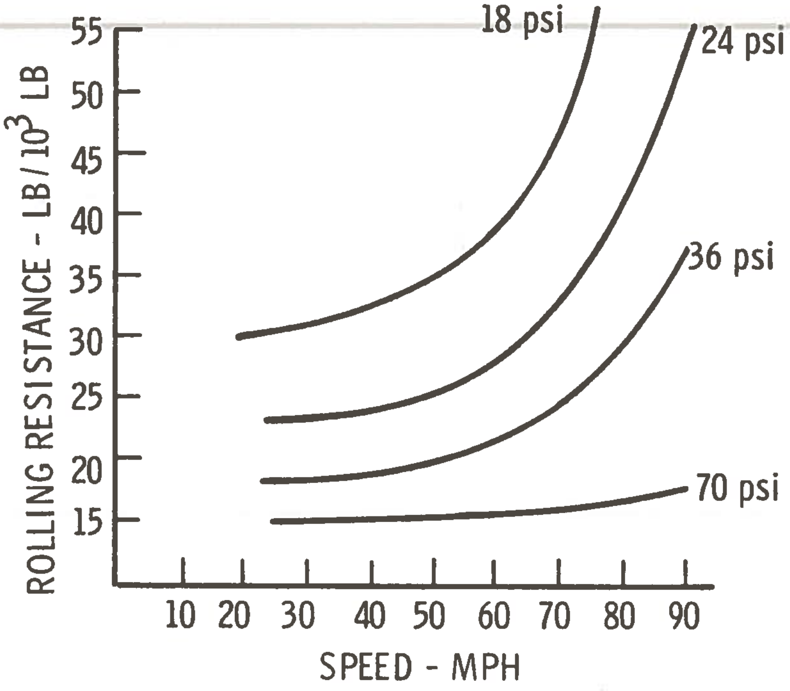


FIGURE 31. ROLLING RESISTANCE VS. SPEED FOR DIFFERENT INFLATION PRESSURES

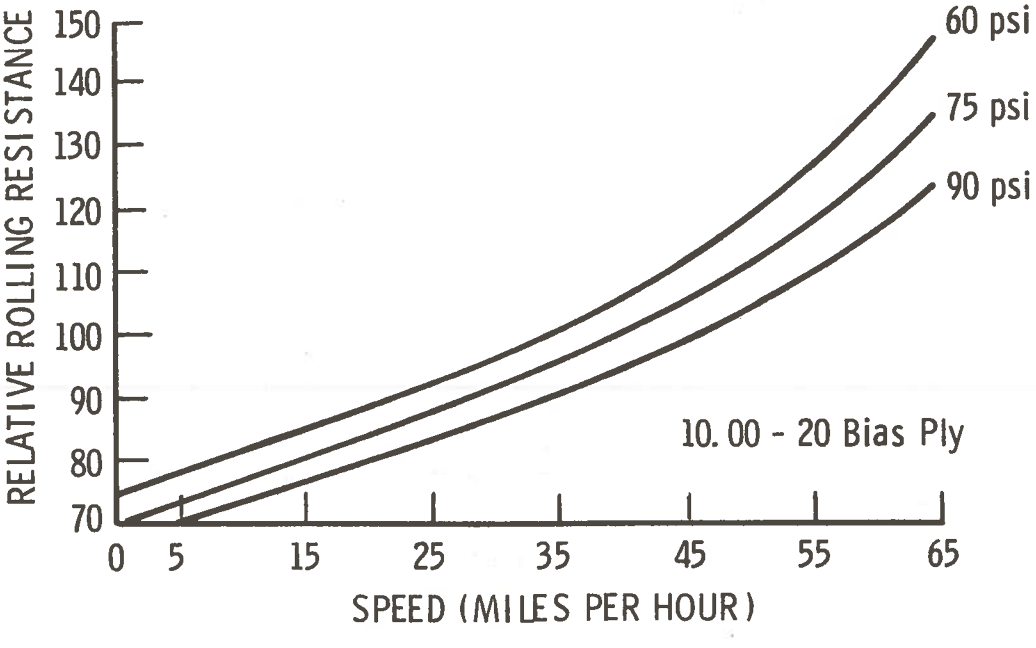


FIGURE 32. RELATIVE ROLLING RESISTANCE VS. SPEED FOR DIFFERENT INFLATION PRESSURES

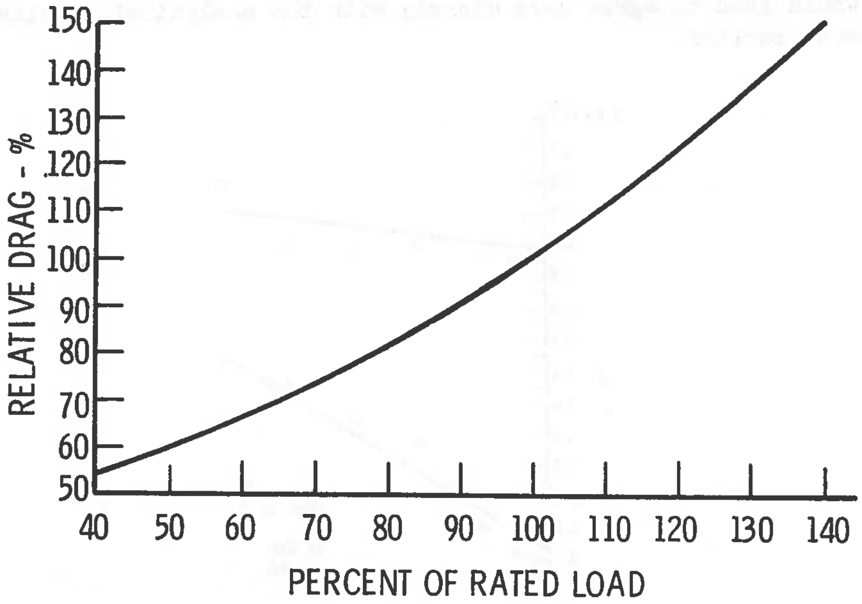


FIGURE 33. RELATIVE DRAG (PROPORTIONAL TO ROLLING RESISTANCE) VS. PERCENT OF RATED LOAD

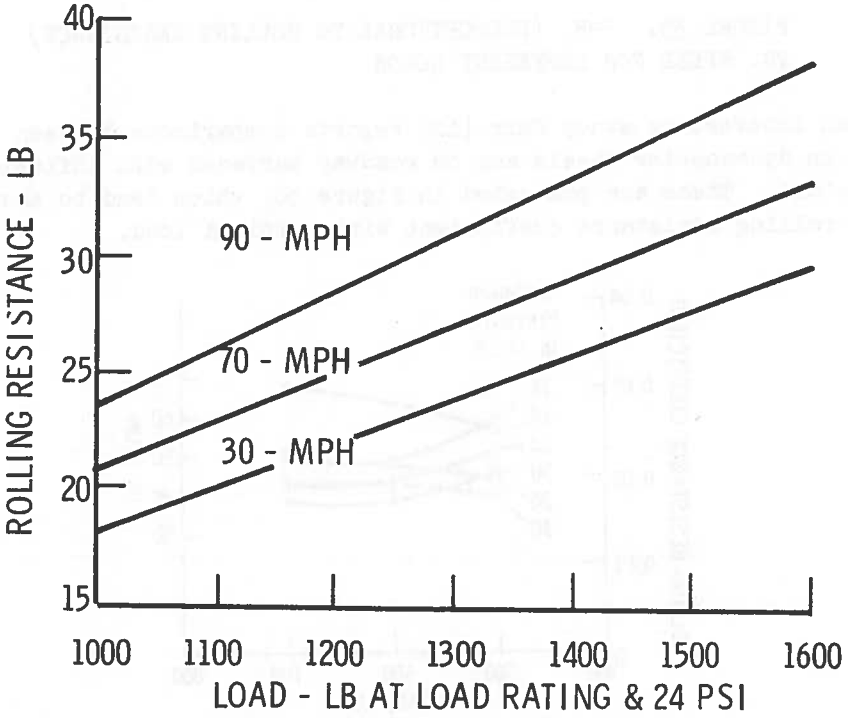


FIGURE 34. ROLLING RESISTANCE VS. LOAD FOR DIFFERENT SPEEDS

were allowed to build up such as occurs in field experience, the results probably would tend to agree more closely with the analytical results of Evans [25] discussed earlier.

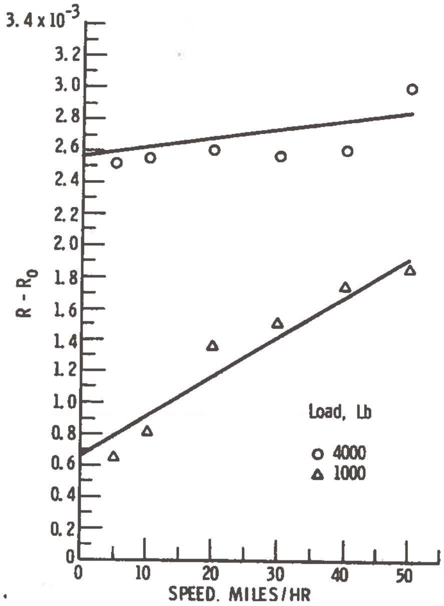


FIGURE 35. R-R$_0$ (PROPORTIONAL TO ROLLING RESISTANCE) VS. SPEED FOR DIFFERENT LOADS

In an interesting study Carr [12] reports comparisons between rolling loss obtained on dynamometer wheels and on roadway surfaces with inflation pressure held constant. These are presented in Figure 36, which tend to show nearly constant rolling resistance coefficient with vertical load.

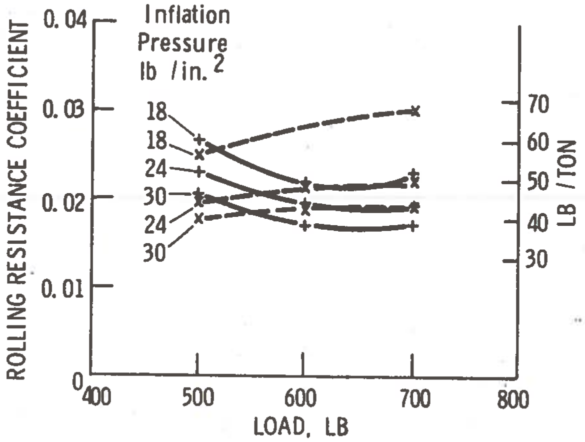


FIGURE 36. ROLLING RESISTANCE COEFFICIENT AND ROLLING RESISTANCE VS. LOAD FOR DYNAMOMETER (DASHED LINES), ROAD (SOLID LINES), AND DIFFERENT INFLATION PRESSURES

3.5 Summary of Speed, Load, Deflection and Inflation Effects

Carr [12] has presented a series of curves illustrating the combined effects of speed, load, deflection, and inflation pressure on the rolling resistance of tires for both dynamometer and road tests, using a 5.20-13 bias-ply tire. This information is given in Figure 37. From it we see that, generally speaking, dynamometer tests give higher rolling resistance values than road tests except at very low loads. These data also illustrate clearly that as inflation pressure rises, rolling resistance decreases while rolling resistance increases as the load increases.

3.6 Tread Wear

Tread wear has exactly the same effect on the rolling resistance of the tire as manufacturing the tire with a thinner tread, a condition discussed in the previous section. As the tread wears and becomes thinner, the rolling resistance at moderate speeds decreases because of the reduced mass of rubber which is stressed during each cycle of rolling. Roberts [70] confirms that when two-thirds of the tread of a passenger car tire is worn off, the rolling resistance is reduced to about 85% of its value at full tread. A convenient rule of thumb is sometimes quoted as stating that a loss of 1 mm of tread thickness reduces rolling resistance approximately 1%.

The same interaction between tread thickness and tire equilibrium temperature holds for a worn tire as for a tire manufactured with a thinner tread. This interaction was also discussed in the previous section. The worn tire with thinner tread runs at a lower equilibrium temperature since its cross sectional dimensions are less. The lower equilibrium temperature results in a higher hysteresis loss per unit mass of material, so that the two effects tend somewhat to cancel each other. The reduced mass results in a lower total hysteresis but the lower temperature results in a higher hysteresis per unit mass. The net effect still favors the worn tire in terms of lower rolling resistance, however, as has been reported by Walter and Conant [86]. Their data are given in Figure 38. These data indicate about as large a difference in rolling resistance between new and worn tires as any reported in the literature, being about 50%. Smaller differences have been reported by Roberts [70], who states that a passenger car tire tested at 30 mph will exhibit a 10 to 20% reduction in rolling resistance when one-half to two-thirds of the tread depth is worn away. He further reports that truck and bus tires exhibit about a 20% reduction in rolling resistance when the tread is fully worn, based on test data taken at 20 mph. Seki [78] and Floyd [27] both report that the rolling resistance of passenger car tires decreases about 15% from new to fully worn condition.

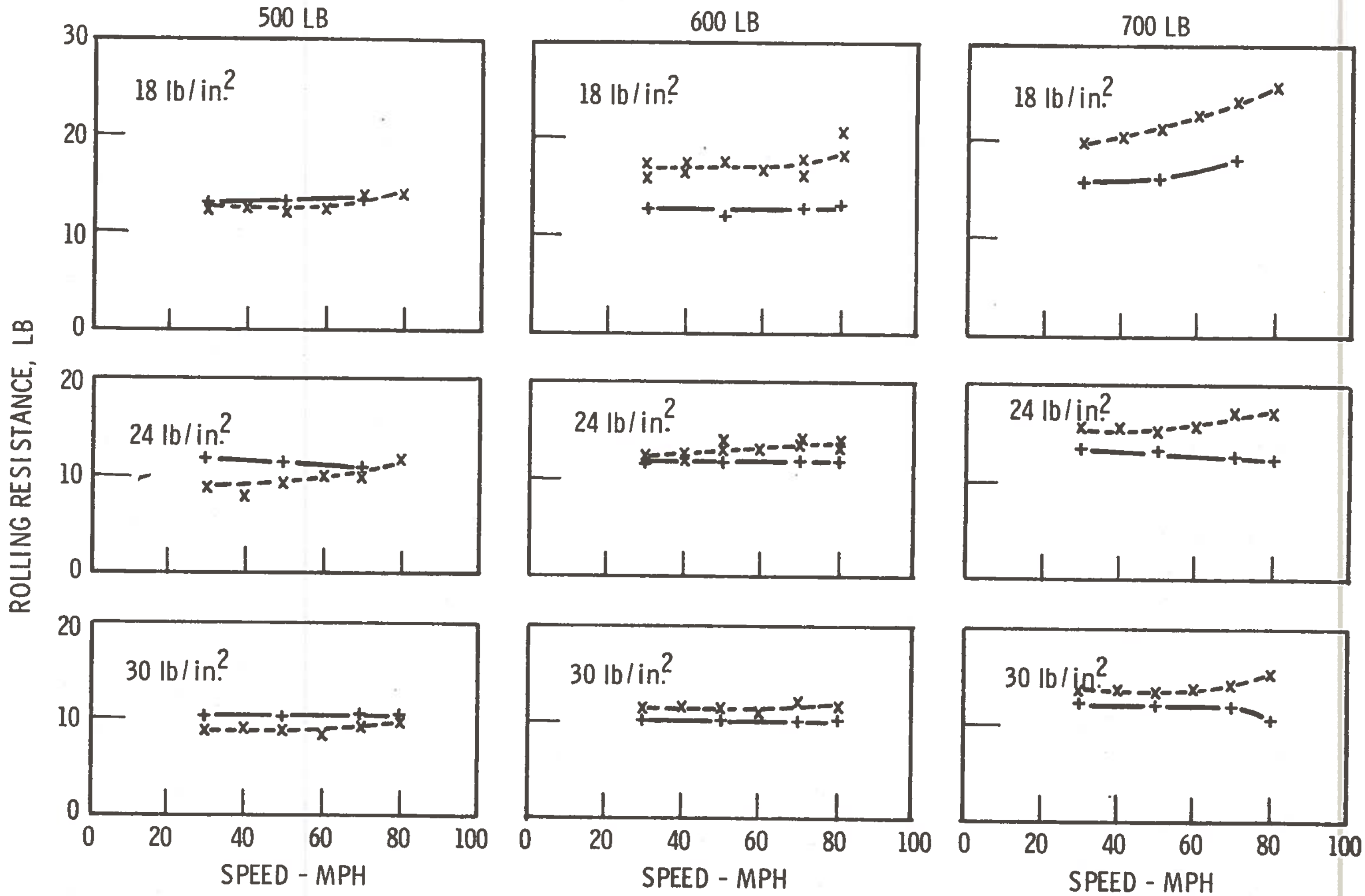


FIGURE 37. ROLLING RESISTANCE VS. SPEED FOR DYNAMOMETER (DASHED LINES), ROAD (SOLID LINES), AND DIFFERENT LOADS AND INFLATION PRESSURES

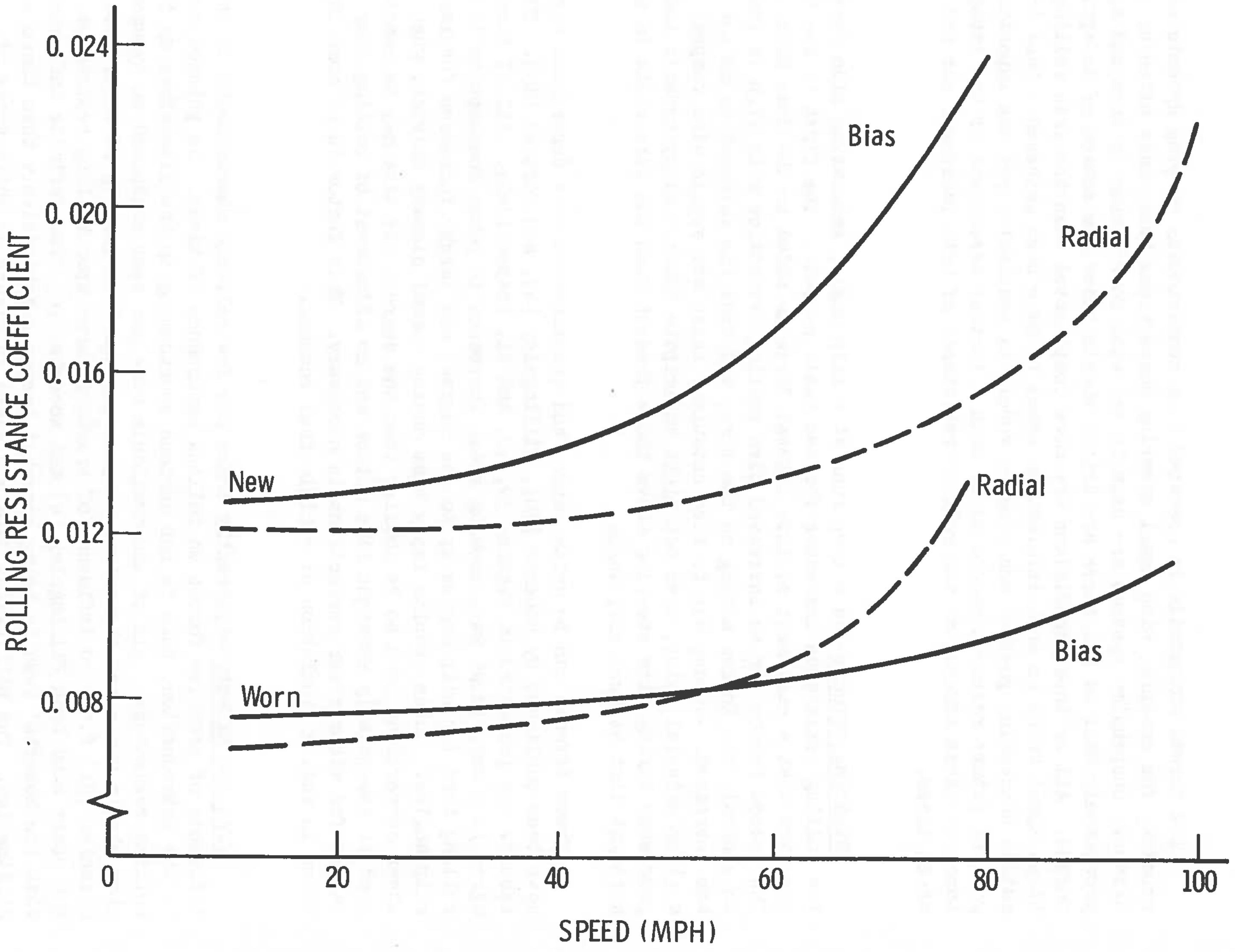


FIGURE 38. ROLLING RESISTANCE COEFFICIENT (PROPORTIONAL TO ROLLING RESISTANCE) VS. SPEED FOR NEW AND WORN TIRES

3.7 Steering and Tractive Effects

The normal automobile is operated in a continuously varying dynamic environment, for example, with small steering corrections being made often by the driver. Suspension systems are usually set with some camber in them and approximately half of all tires are driven wheels under the action of an applied torque. All of these conditions are more complicated than the free rolling tire, about which so much information seems to have been gathered. Less information concerning powered and steered wheels is available, and one important goal of future research should be to gain a further assessment of the importance of these effects on the rolling resistance of both passenger car and truck tires.

Steering Effects—As a tire runs at a slip angle, generating side force, the rolling resistance increases for two basic reasons. The first is due to the fact that a component of this lateral force is added to the drag force. The second reason for an increased tire rolling resistance with slip is that, in general, the forces acting on the tire, and thus the deformation of the tire, are increased. Since, due to tire rotation, these are cyclic with respect to a given material point, then one might anticipate additional hysteretic loss processes during tire steering above those present when the tire rolls in a straight line at zero slip angle.

These effects can be quite large, and quantitative data describing them have been published by Roberts [70], Billingsley [4], and Curtiss [19]. Their results are presented in Figures 39, 40, and 41, respectively. All of these agree in a very rough way, showing small increases in power consumption in a rolling tire for slip angles up to one degree, and larger increases for larger slip angles. These results imply that during normal highway driving, when steer corrections tend to be smaller than one degree, the tire may be considered in essentially straight line motion and no adjustment of rolling loss values for minor steer corrections is necessary. This factor is of some importance in analog simulation of vehicle fuel economy.

Traction Effects—Apparently there are few reliable measurements on the influence of tractive forces on rolling resistance of tires. As pointed out in the introduction, this is one serious shortcoming in the literature on tire rolling resistance. All of the available work has been conducted on dynamometer wheels which are themselves suspect in regard to quality of their data. Stiehler [81] finds no influence of tractive force upon rolling resistance. On the other hand both Billingsley [4] and Roberts [70] find definite influences, with the Roberts' results being somewhat larger quantitatively than those of Billingsley. The Billingsley data are given in Figure 42 while those of Roberts are given in Figure 43.

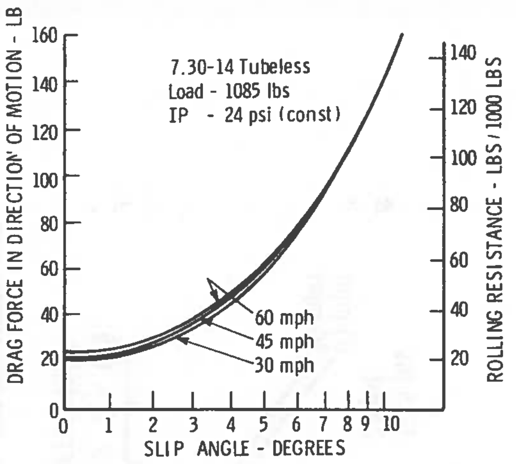


FIGURE 39. DRAG FORCE IN DIRECTION OF MOTION AND ROLLING RESISTANCE VS. SLIP ANGLE FOR DIFFERENT SPEEDS

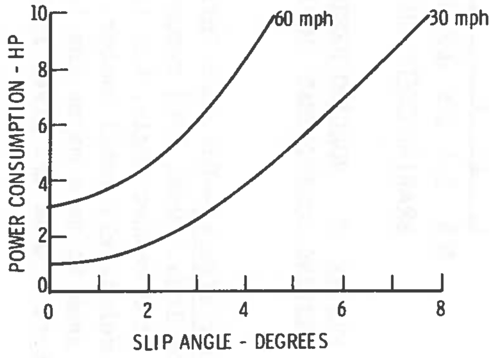


FIGURE 40. POWER CONSUMPTION (PROPORTIONAL TO ROLLING RESISTANCE) VS. SLIP ANGLE FOR DIFFERENT SPEEDS

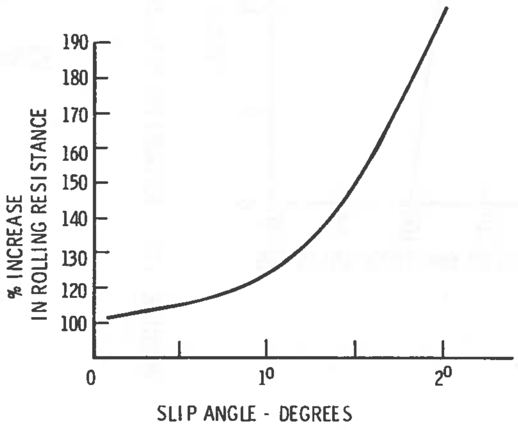


FIGURE 41. PERCENT INCREASE IN ROLLING RESISTANCE VS. SLIP ANGLE

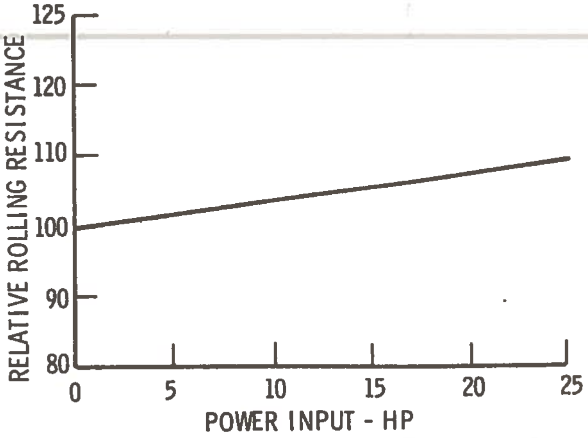


FIGURE 42. RELATIVE ROLLING RESISTANCE VS. POWER INPUT

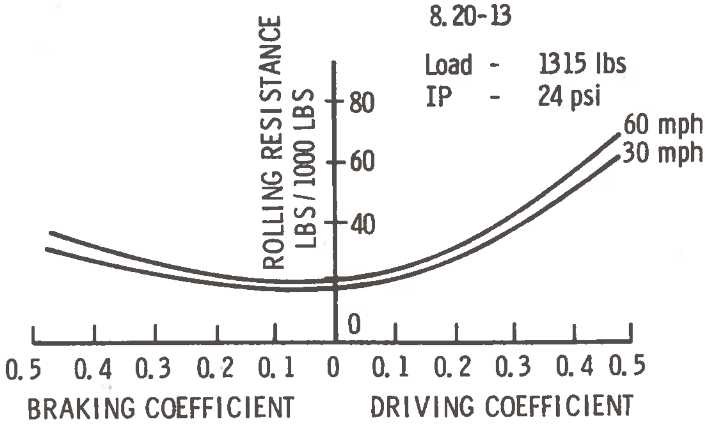


FIGURE 43. ROLLING RESISTANCE VS. BRAKING COEFFICIENT AND DRIVING COEFFICIENT (MEASURES OF TRACTIVE FORCE MAGNITUDE)

Camber Effects—Not much information is available on the effect of camber on rolling loss. Seki [78] reports some increase in the value of rolling resistance with camber angle, but in view of the fact that most suspensions are set with relatively small camber, at least in American vehicles, that factor does not seem to be a major one in determining a final value of rolling resistance. Seki's data are given in Figure 44.

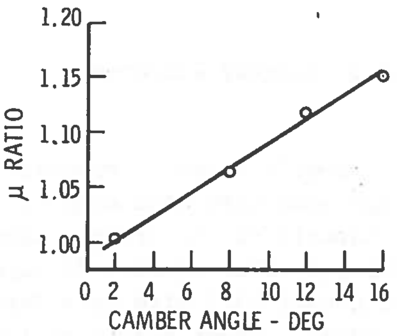


FIGURE 44. μ RATIO (PROPORTIONAL TO ROLLING RESISTANCE) VS. CAMBER ANGLE

3.8 Wheel and Rim Design

Rim width and diameter have a small effect on the rolling resistance of a pneumatic tire. One would anticipate that in general the use of wider rims would tend to reduce the rolling resistance of a tire and within limits this apparently is true. In fact, it is possible and permissible to mount the same tire on rims of different widths, and to have that tire operate quite satisfactorily under those conditions.

Curtiss [19] has examined this phenomenon for a single specific tire and his data are given in Figure 45. It shows that there exists a rim width for which the rolling resistance is a minimum, at least for the tire which he studied. This conclusion should be carefully qualified since there is no assurance that such a minimum exists for other tires. It is worthy of some consideration since it is one way to influence the rolling resistance of a tire without markedly changing its other properties.

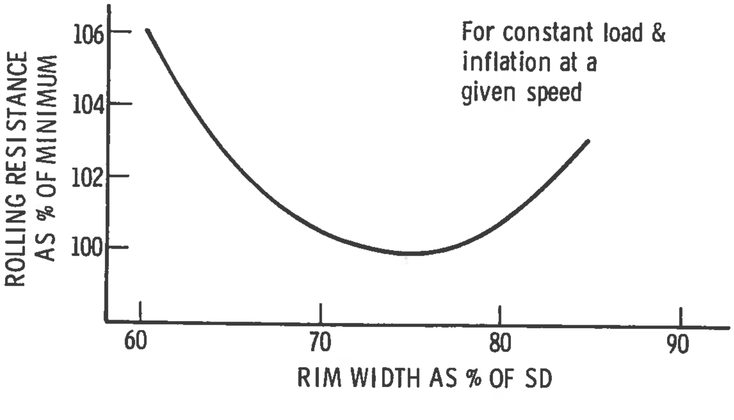


FIGURE 45. ROLLING RESISTANCE AS A PERCENT OF MINIMUM VS. RIM WIDTH AS A PERCENT OF SD

3.9 Roadway Surfaces

The rolling loss of pneumatic tires is essentially independent for all hard surface roads, although some test data seem to indicate a slight increase in rolling resistance for asphalt vs. concrete. Clearly, rolling loss is substantially greater for vehicles which operate on unpaved roads and for off-the-road vehicles. Walter and Conant [86] give data for typical rolling loss values for several common surfaces. These are given in Table 5. The ranges of values given here are so broad that no specific detailed conclusions can be made about rolling resistance as influenced by road surface type.

TABLE 5.-ROLLING RESISTANCE ON DIFFERENT ROAD SURFACES

Surface	Lb/1000 Lb Vehicle Weight
Concrete	10-20
Asphalt	12-22
Dirt	25-37
Sand	60-150

4. MEASUREMENT METHODS FOR TIRE ROLLING RESISTANCE

A variety of methods exists for the measurement of tire rolling resistance. In view of the fact that each of these methods tends to give somewhat different results, it is worthwhile to discuss them briefly so that their strengths and shortcomings are evident. In theory it should be possible to measure rolling resistance accurately independent of test method, provided that sufficient data are available to understand completely the correlation of one method with another. Unfortunately the mechanisms of rolling resistance are complex enough so that this information has not yet become available, and good correlation methods do not exist. For the most part the tire manufacturing industry has used both dynamometer and test vehicle methods, the former to conduct experiments which define the role of individual construction variables in tires, while the highway vehicle methods have been used primarily to attempt to demonstrate the role of rolling resistance in reducing gasoline consumption. Several other specialized test methods have been tried but these are not as widely available as the dynamometer and the test vehicle techniques. A brief description of each of these methods will be given in this section.

4.1 Direct Measurements of Tire Rolling Resistance

Road Vehicle—Probably the most desirable method for determining rolling resistance of a tire is to mount it on a vehicle whose wheel, axle and transmission are so instrumented that all six forces and moments acting on the tire are recorded. It is also necessary to determine the linear and angular velocities of the wheel and its orientation in space. This has proven to be so difficult that it has not yet been accomplished.

The easiest approach to this problem is to measure only the drive shaft torque on a road vehicle as, for example, Davisson [20] has done. The results of such measurements must then be adjusted by compensating for other losses, such as chassis friction, aerodynamic drag and the power curve of the engine. Direct force measurements on a rolling tire are difficult since the front axle of a rear drive vehicle may be steered, and generally operates at a camber angle and with a toe-in. Any force transducer used to measure rolling resistance should be free to move with the vehicle suspension, so that without fixed orientation in space the interpretation of the results becomes quite complicated.

The second approach prompted by Novopolsky [62] and used by Masaki [55] is to measure tire pressure, deflection and speed only. A laboratory experiment correcting for drum curvature can be carried out which relates tire pressure, deflection and speed to a measured value of rolling resistance. Thus, on the road vehicle, an instrumented wheel in which pressure, deflection and velocity are measured can be converted to a measure of rolling loss of the tire [57,58]. It is clear that this method must be used with considerable caution.

Road Trailer—Since it is so difficult to measure the appropriate variables on a standard automobile wheel, specially instrumented wheels and axles have been produced for towed trailers. In this way the tire can be located in space very accurately and most of the variables can be controlled or measured. Table 6, taken from Glemming and Bowers [32], gives a summary of the advantages and disadvantages of rolling resistance trailer techniques.

TABLE 6.-ADVANTAGES AND DISADVANTAGES OF ROLLING RESISTANCE TRAILER

Advantages	Disadvantages
Isolates a single wheel	Free rolling only
Controlled speed, load, and inflation	Sensitive to:
Direct output F_r	Transducer alignment vehicle-yaw, pitch, roll acceleration
No aerodynamic drag	Road irregularities
No chassis friction	Road slope
	Wind gusts
Tire tested on roadway	Camber
Isolates F_z and F_r	Slow recovery from dynamic inputs
Operates in natural tire environment	Steady-state testing only
Not sensitive to changes in R_ℓ	Productivity is low

The rolling resistance trailer technique can provide data on tire loss with brake torque but is usually used only for free rolling measurements. Other methods must be used to determine the influence of brake or driving torque on the tire.

Many such trailers having varying degrees of sophistication are in use [10,24,28]. Some measure only the force required to tow the trailer in steady motion. In one case a whole car was towed [28]. Others have transducers attached to the axle or wheel mounts to measure all pertinent forces and moments.

Excellent quality trailer equipment for measurement of rolling loss is available at the Hodges Transportation Company, Carson City, Nevada.

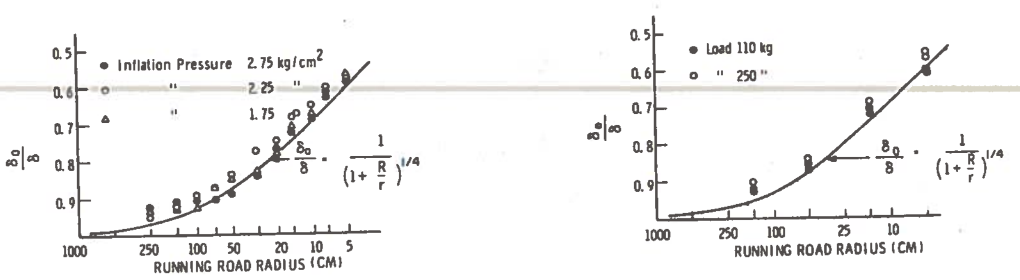
Roadwheel or Dynamometer—From the point of view of the tire manufacturer, the most convenient method of measuring rolling loss is in the laboratory on a dynamometer. This is a large diameter steel wheel against which tires are run under loads for durability studies. Without major adaptations in instrumentation, rolling loss work may be done on these machines. Laboratory conditions can be controlled and reproducibility is excellent for the data which are obtained. Torque can be measured at the drive system to the dynamometer wheel by either a "Torque Reaction Method" or a "Torque Shaft Method" [70], using a photoelectric torque meter [30] or magnetic pickup [70]. Many instrumented wheels and axles have been designed to measure rolling loss on tires.

Unfortunately the tire deformation pattern on a roadwheel is quite difleremt from that experienced by a tire running on a flat roadway, due to roadwheel curvature. Roadwheel data give good comparative results for studies of different tire construction methods but do not correlate well with highway data. Such correlation must be carried out by experimentally determined factors, which are difficult to obtain.

Some studies have been made to relate rolling loss data from dynamometers to actual road data, using as a variable the curvature of the roadwheel [45,55, 58]. The general result is that rolling resistance increases with increasing curvature (decreasing radius of curvature). However, rolling resistance is simultaneously a function of wheel speed and equilibrium temperature. Masaki [58] and Khromov [45] show that rolling resistance increases significantly as roadwheel radius decreases. Their data are shown in Figure 46. It should also be noted that this effect can be different for different tire constructions.

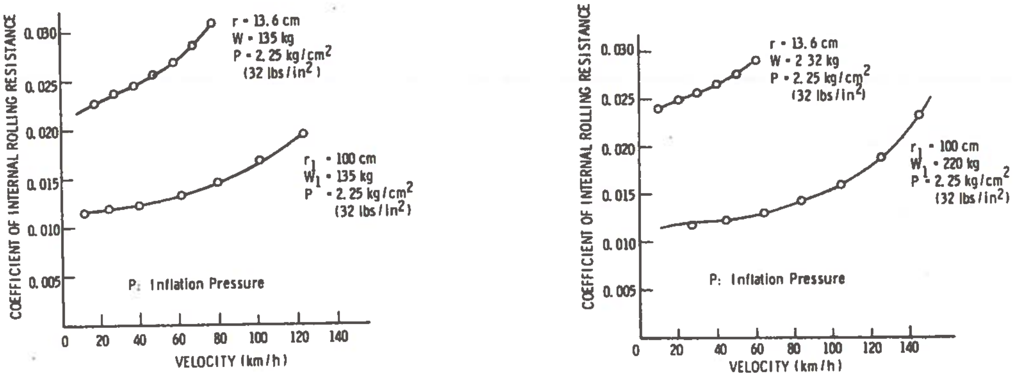
There are many different designs of test apparatus utilizing dynamometers. The basic design is a large steel dynamometer wheel with one tire loaded against it for rolling resistance measurements. Other designs include measuring various forces and moments, or using two tires on one dynamometer, or two small rollers supporting one tire. The Dunlop circulating power machine [70] simulates both driving and braking torques on the two tires in tests simultaneously.

Moving Belt Machine—Due to curvature effects, it appears that a moving flat surface would be best for a laboratory measurement of rolling resistance. Flat plank machines having fixed length are not used for this purpose since they have start up and stopping problems associated with plank inertia. The length of the plank becomes prohibitive, even at low speeds, and it is not



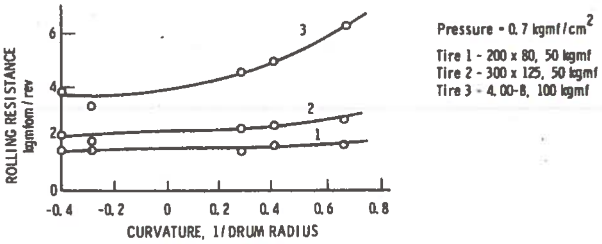
(a) Fixed load of 215 kgmf (b) Fixed pressure of 2.25 kgmf/cm²

Ratio of deflection of a tire on a flat surface to its deflection on a curved surface vs. road radius



(c) (d)

Rolling resistance coefficient (RR/W) vs. velocity for the same tire at different loads on two different roadwheels



(e) Rolling resistance (RR) dependence on curvature for three different tires

FIGURE 46. RELATIONSHIPS AMONG CURVATURE OF ROAD SURFACE, TIRE DEFLECTION, VELOCITY AND ROLLING RESISTANCE

possible to reproduce correct temperature effects in the tires.

There are two moving belt machines now in use for obtaining tire data, and both of these are capable of measuring tire rolling resistance. The General Motors Corporation has a segmented track machine which is driven by two large pneumatic tires and is supported by urethane-clad rollers to provide a flat test section. Due to track vibrations this device is used only for low speed work. Ritter [69] has a description of this apparatus.

A newer facility for laboratory testing at speeds up to 200 mph is the Calspan Corporation's TIre Research Facility. TIRF is a continuous steel belt under high tension mounted on two large steel wheels and supported by air bearings under the test section. The installation includes a wheel mount capable of measuring all six force and moment components acting on the tire. It is hoped that this device will be particularly useful in the measurement of rolling loss phenomena [5,32,77,82,83].

4.2 Coastdown Measurement of Tire Rolling Resistance

Road Vehicle—A coastdown or inertia test is one in which the time taken to pass between two speeds or the distance traveled in that time is related to the tire rolling resistance. The farther the distance traveled or the greater the time taken, the less the decelerating force and hence the lower the rolling loss. The method requires little test equipment, is the least complicated and provides a good ranking procedure when compared with other methods. It is relatively easy and can provide dramatic results. Some of these are illustrated in Figure 47, from Glemming and Bowers [32].

It is generally conceded that a road vehicle coastdown test is the least accurate of the various methods used for measurement of rolling resistance. There are many losses in a vehicle other than the rolling resistance of the tires, some of which are nearly uncontrollable. Examples of these are wind gusts, minor variations in following the same path from one time to another and the control of initial car velocity. In addition, chassis friction, aerodynamic drag, road grade, and road surface all affect the results and the reproducibility. Small changes in rolling loss may be completely masked by these factors and multiple tests are necessary in order to achieve sufficient accuracy. It is common to find variations in consecutive runs under the same conditions of the order of 10%.

Roadwheel or Dynamometer—The torque input to maintain a constant speed on a dynamometer wheel is one measure of rolling resistance. However, if rolling resistance is used to decelerate a moving wheel then the time to slow the wheel down is an indirect measure of the rolling loss as well. This method has

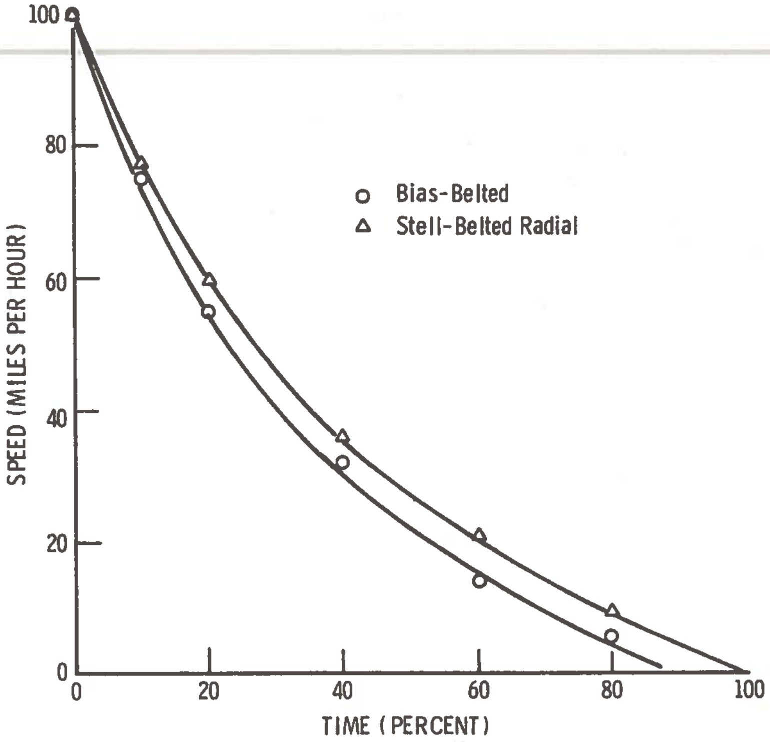


FIGURE 47a. TYPICAL SPEED-TIME PLOT

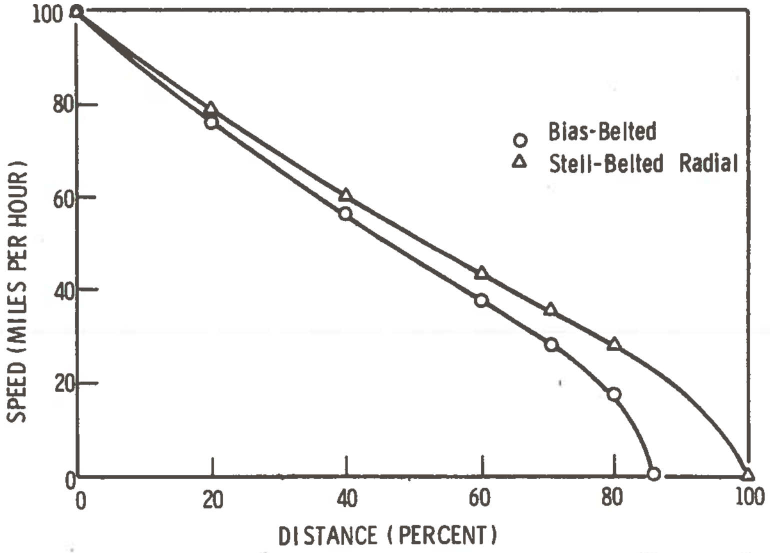


FIGURE 47b. TYPICAL SPEED-DISTANCE PLOT

been exploited rather thoroughly by the tire manufacturing industry and analyses are available for determination of the rolling resistance as a function of coastdown times. A discussion of this method is included in the work of Glemming and Bowers [32].

Although this test is quite common in the tire industry, there is no single recognized test method which is standard for all tire manufacturers. Each experimenter tends to use his own technique for cancelling out losses other than direct rolling loss of the tire, and furthermore each uses his own tire warm-up and data acquisition procedures [6,36,47,64,68,90]. In addition there are definite effects associated with the curvature of the dynamometer wheel so that the data obtained from one test may not be directly comparable to data obtained from another. About the best that may be said for this method is that on a single dynamometer wheel, under carefully controlled conditions, it is possible to measure small differences of rolling resistance between tires of various constructions and designs. There has been, however, a statistical correlation between roadwheel coastdown data and rolling resistance of tires measured on the highway by Goodyear.

4.3 Vehicle Fuel Consumption Measurement of Tire Rolling Resistance

Many studies have been done comparing the effects of radial and bias-ply tires on the fuel economy of standard vehicles. However, in most tests there are so many other uncontrolled variables that this type of experiment cannot provide precise rolling loss data. Various analytical and empirical studies have shown that a 20% reduction in rolling loss of the tires can result in as little as a 3% savings in fuel [27,79]. However, larger variations have also been observed.

Both short-term, highly controlled tests, and long-term, statistically significant tests have been carried out and have produced usable results. However, these data are far more expensive to obtain than laboratory or trailer data if the desired final result is rolling loss information [3]. Typical plots for rolling resistance vs. inflation pressure for a short-term controlled fuel consumption experiment is given in Figure 48, taken from the work of Glemming and Bowers [32].

Vehicle fuel economy test results generally are not repeatable due to the day to day changes in environment, road surface, fuel, drivers, and vehicles, even though the speed, load, tire inflation, rim size, and treadwear state are reasonably controllable.

Many automotive engineers feel that an extremely important factor in rolling loss experiments using highway vehicles is the interaction of the tire size, vehicle weight distribution, and speed, with the power curves of the engine and transmission. Engine efficiency can change dramatically at lower speeds, depending on power output. This effect must be corrected for in any highway test attempting to assess rolling loss figures.

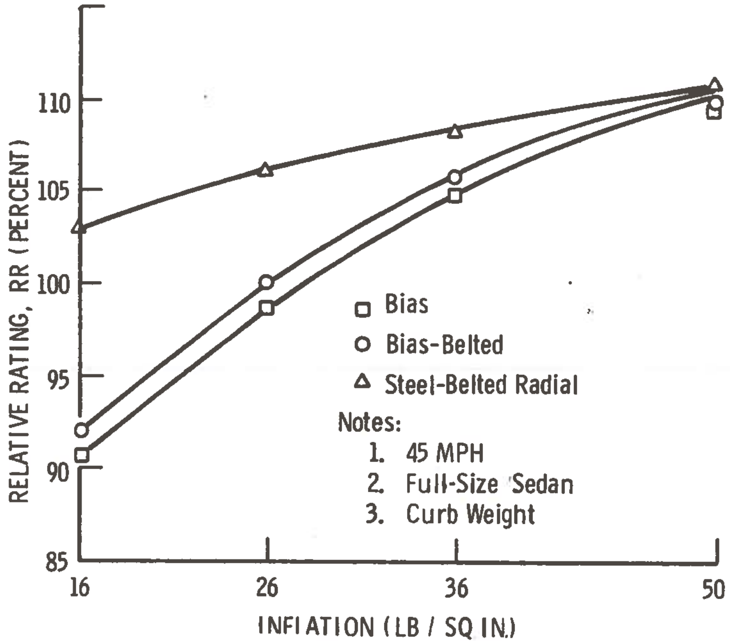


FIGURE 48. RELATIVE ROLLING RESISTANCE VS. INFLATION PRESSURE FROM FUEL CONSUMPTION DATA

The Environmental Protection Agency uses a dynamometer test facility to test fuel economy and emission levels. There has been some question as to the validity of these results, since each drive wheel of the vehicle runs on two small rollers. The curvature of these small rollers can cause significantly different rolling loss characteristics in the tires than are experienced on the roadway. This mode of deformation not only increases rolling loss but may penalize one tire construction more than another. Rather than correct for curvature effects for each type of tire, fuel economy dynamometers could, as an alternative, incorporate the Calspan or General Motors design of a moving belt. The dynamometer could retain the small roller design but use a steel belt with roller bearings support under the tire to provide conditions more nearly those of on-road service.

5. COMMERCIAL CONSIDERATIONS

In this section we attempt to assess the role of some pertinent economic factors in the possible future development of lower rolling loss tires.

As previously pointed out many factors can play a role in decreasing tire rolling resistance. While this is clearly not reflected on a one-to-one basis in fuel economy, approximately 25% of passenger car fuel usage must be charged against tire rolling loss so that improvements in rolling loss are truly important.

The most important variable in controlling tire rolling loss is vehicle weight. This is because it enters as a quadratic term in rolling loss, at least for a solid tire and possibly for a pneumatic tire as well. Since a lighter vehicle also allows a reduction in engine size, which allows yet further weight saving, it appears that from a practical point of view the greatest immediate reduction in tire rolling loss can be accomplished by the trend, already evident in the American automobile market, toward smaller and lighter cars.

Secondly, it has been shown that an increase in tire diameter should reduce tire rolling resistance, all other factors being kept constant. Here we are somewhat at variance with current trends since smaller vehicles generally tend to use smaller wheels, if for no other reason than esthetics. While limited possibilities exist for a more efficient tire by increasing wheel diameter, at least smaller vehicles might continue to use the same diameter wheels as present day large-to-medium vehicles, a design possibility which has not yet been reflected in small production vehicles.

Finally some improvements in rolling resistance are obtainable by reducing the aspect ratio of tires, and this trend is already well established in the tire industry. It will undoubtedly continue further and should be encouraged as being beneficial both in regard to the quantity of material used in making a tire and its inherent power loss.

Turning next to the subject of tire materials, we find that here the tire power loss will almost certainly rank as one, but only one, of several factors upon which material selection is based.

Consider first the subject of tire cord. It has been pointed out previously that cord materials contribute to the overall loss in a tire but are not dominant in the process, so that the cord is usually considered less important than the rubber compounds in determining overall loss. There will undoubtedly be changes in cord materials as new fibers become commercially available and as the economic advantages of one over the other change. That has been the history of the tire manufacturing business for many years, as can be seen from Figure 49 taken from Jakubicek [44].

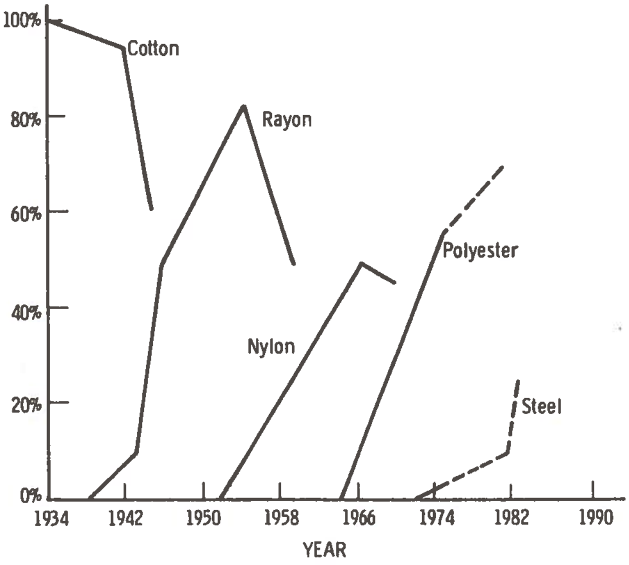


FIGURE 49. FIBERS USED IN TIRE CARCASS REINFORCEMENT

The consensus now seems to be that rayon and nylon have reached or passed their peaks of commercial usefulness in the tire industry. Polyester, glass, and steel are the current major contenders for use in passenger car tires. Fortunately both glass and steel are inherently low-loss materials.

It seems quite probable that with the relatively weak interaction between cord material and rolling loss, the choice of cord materials in future tires will be based on other considerations. Cost, availability, adhesion characteristics and durability are some of these. Others are given in Table 7 taken from Jakubicek [44], where the problems of replacing one tire cord material with another are detailed somewhat more clearly. Whatever choices are finally made will not markedly influence the rolling resistance of tires. Rolling resistance will be determined primarily by other factors.

In regard to the choice of rubber compounds in tires, the influence on rolling loss is somewhat greater than that of cord. Nonetheless that choice must also be tempered by other considerations. Some of these are:

(a) Carcass Rubber Requirements:

Good adhesion to cord
Low hysteresis
Good fatigue resistance

TABLE 7.-COMPARISON OF AMOUNTS OF BELT MATERIAL NEEDED IN A TIRE

	Equal Strength		Equal Modulus	
	Relative Weight	Relative Belt Thickness	Relative Weight	Relative Belt Thickness
Wire	1.0	1.0	1.0	1.0
Fiber "B"	0.2	0.85	0.7	3.2
Fiberglass	0.4	1.46	1.12	4.0
Rayon	0.65	3.07	5.1	21.0

The average strength for steel was used and it is assumed that the cord to rubber compound area ratio is the same for all cords.

(b) Tread Rubber Requirements:

Abrasion resistance
Good wet traction
Good adhesion to carcass compounds

These characteristics are presently obtained primarily through using synthetic rubber compounds in passenger car tires, partly synthetic and partly natural rubber in truck tires, and mostly natural rubber in aircraft and high-speed tires. The world production of natural and synthetic rubber compounds is illustrated in Table 8.

TABLE 8.-WORLD PRODUCTION OF NATURAL AND SYNTHETIC RUBBER

Year	Natural (millions tons)	Synthetic (millions tons)	Total
1962	2.2	2.2	4.4
1964	2.2	2.7	4.9
1970	2.5	3.5	6.0
1975 (est.)	3.0	7.0	10.0

Natural rubber, which exhibits the lowest loss characteristics of any of the widely used rubbers, shows a slow growth in production, while the use of synthetic rubber shows more rapid increases, reflecting both cost factors and the fact that synthetic production can be expanded more rapidly than natural rubber production.

From this table it is clear that very large volumes of rubber products are used, a large share of them in tire production. It is not reasonable to expect rapid shifts from synthetic to natural rubber usage for purposes of conserving energy, nor is it even possible. The quantities needed are not even being produced. One must therefore turn to synthetic rubber compounds for lower loss rubber materials. Barring unforeseen breakthroughs, this means a process of development or evolution from present rubber compounds, selected mostly for a 70 mph speed limit, to somewhat lower loss compounds. We can expect some evolutionary improvements but not radical ones.

Insofar as design of the tire itself is concerned, the radial tire now has so much momentum in penetrating the American market that we can expect some form of radial tire to be with us for many years. That does not mean that there will not be improvements from the design standpoint. These will come, and it is in this area that perhaps the greatest improvements in rolling resistance are possible. Rubber gages between plies can be optimized, and there exist many, many possible design variables that can be readjusted now that reduced speed limits are with us and now that greater emphasis is being placed on fuel economy.

Finally some interesting conclusions concerning the relative importance of material costs and fuel costs may be gained from a brief analysis of the life of a typical pneumatic tire. The modern passenger car tire begins as petrochemical feed stock, i.e., petroleum. Hall [38] has computed that it requires about 7 gallons of oil to manufacture a passenger car tire, out of which 5 gallons are used to make up the raw materials, including processing energy, while 2 gallons are used for the power to fabricate and assemble the tire components and the final tire itself.

Assume that the tire spends its life on a vehicle whose average gasoline mileage is 16 miles per gallon, that 25% of the vehicle losses are chargeable to tire drag, and that the tire life is 30,000 miles. Then the gasoline chargeable to wearing out that single tire may be readily computed as

$$30{,}000 \times \frac{1}{16} \times \frac{1}{4} \times 0.25 = 117 \text{ gallons.}$$

The 7 gallons of petroleum needed to manufacture the tire are negligible compared with this.

From these simple calculations we conclude that such factors as tire retreading or replaceable tread tires, while possibly economically attractive, really have little bearing on energy conservation. Similarly unimportant are manufacturing efficiencies and design changes implemented to save material. The single most important factor here is tire rolling resistance, and even small improvements in it can result in energy savings far overshadowing the energy consumed in making the tire. Thus, rolling resistance is worthy of a serious research effort.

6. CONCLUSIONS

It has been shown in the preceding sections that the rolling resistance of present day pneumatic tires is dependent upon many factors. Each factor and its effect on rolling resistance have already been presented. Thus, rather than attempting to list these in total again, we make recommendations believed to be important to the reduction of rolling resistance. These are listed below in the approximate order of the time scale necessary to deal with them.

Reduction of Tire Rolling Loss Immediately

(a) Increased use of radials

(b) Increased inflation pressures.

Reduction of Tire Rolling Loss Within a Five-Year Period

(a) Reduced aspect ratio of tires.

(b) Continued emphasis on radial tire designs.

(c) Optimization of tire and wheel designs to minimize rollong loss characteristics, including use of lower loss rubber compounds where possible.

(d) Use of thinner tread designs on tires.

Reduction of Tire Rolling Loss on a Longer Time Scale

(a) Development of low loss rubber compounds capable of serving in passenger car design.

(b) Complete optimization of radial tire designs for minimum loss characteristics.

(c) Higher pressure tire designs with greater emphasis on suspension systems for shock cushioning.

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APPENDIX

REPORT OF INVENTIONS

After a diligent review of the work performed under this contract, no new innovation, discovery, improvement, or invention was made.