EFFECT OF TIRE RESISTANCE ON FUEL CONSUMPTION

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ABSTRACT

In this paper an analysis is made of the factors which go to make up the total fuel required by an automobile in order to determine how the consumption of fuel can be influenced by the tires.

The range of values for the rolling resistance of tires, including balloon tires, is shown and comparisons made with average values for the other factors in such a way that the possible influence of tires is easily seen.

The case of balloon tires is taken up in detail and it is shown that the gain in cushioning resulting from the use of balloon tires is obtained with a small increase in rolling resistance.

General figures are given which afford a basis by which the probable effect on fuel consumption due to a change in tire equipment can be predicted.

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I. INTRODUCTION

In this paper an answer is given to the question "What effect have tires on the fuel consumption of an automobile?" Considerable information has been published on the power loss and the rolling resistance of tires from which it is a simple matter to determine the amount of fuel which, under a particular set of conditions, should be charged against the tires. Such figures, however, mean little to the car owner or fleet operator unless a correlation is made with the total amount of fuel used by the car under various conditions and the avoidable and unavoidable tire losses separated.

In this paper average values have been calculated for the items which make up the total rolling resistance of an automobile and comparisons made with the maximum and minimum values for the rolling resistance of tires. In this way the possible influence of tires is easily seen, and a basis is afforded by which their effect on the fuel consumption can be determined for individual cases.

II. FACTORS WHICH COMPRISE THE ROLLING RESISTANCE OF AN AUTOMOBILE

In order that the proper evaluation be given to the effect of tires on fuel consumption it is necessary to consider the various resistances which the energy contained in the fuel is required to overcome. These are (1) the resistance due to friction in the engine; (2) that due to friction in transmitting power to the rear wheels, which has been designated chassis resistance; (3) wind resistance; (4) that due to the tires; and (5) that due to accelerating a car or driving it uphill. Average values which could be compared with tire resistance have been calculated for the first three items using as a basis the results published by Prof. E. H. Lockwood, of Yale University.[1] These data are based on tests of a great many different cars and are believed to represent what may be expected in average performance. It was realized that with the many uncertainties of car operation average or general values only are desired and that unnecessary complications would be introduced by a consideration of unessential details. Accordingly, several assumptions have been made in the interest of simplicity which are not absolutely correct, but which are sufficiently so for the purpose. A study of the diagrams which follow will bear out the futility of attempting too great accuracy.

III. CALCULATION OF VALUES

1. RESISTANCE DUE TO FRICTION IN THE ENGINE

The results of engine tests have demonstrated that the resistance due to engine friction is very nearly constant. There is usually a tendency for it to increase slightly with speed and load, but for the purpose of this paper this has been disregarded and a constant value used, based on car weight since, in general, the heavier the car the larger the engine and the greater the friction. The reader should not confuse the resistance due to friction, which in this paper is expressed as pounds of tractive resistance, with the friction horsepower, as, of course, the latter increases almost directly with the speed.

The value of engine friction expressed in pounds of tractive resistance is based on an assumed mechanical efficiency of 85 per cent for an engine when running at a good efficient speed and developing its maximum power. For this purpose the maximum power corresponding to a car speed of 30 miles per hour has been taken as a fair figure.

Using the results of tests on 17 different cars it is found that the resistance per 1,000 pounds of car weight due to engine friction varies from 17.5 to 26 pounds and averages 21.7 pounds. Using the data of one car only, the method of computing these values is as follows:

[1] Automotive Industries, Apr. 20, 1922.

Weight of car	pounds	3, 390
Maximum brake horsepower, 30 m. p. h	horsepower	27. 5
Indicated horsepower based on 85 per cent efficiency 27.5÷0.85	do	32. 4
Friction horsepower 32.4−27. 5	do	4. 9
Resistance due to engine friction, $\frac{4.9\times60\times33,000}{5,280\times30}$	pounds	61. 2
Resistance due to engine friction per 1,000 pounds car weight, $\frac{61.2}{3.390}$	do	18. 1
Range of values for above based on 17 cars:		
Minimum	do	17. 5
Maximum	do	26. 0
Average	do	21. 7

2. RESISTANCE DUE TO CHASSIS FRICTION

This resistance is due principally to friction in the transmission, the differential, and the rear axle bearings, together with the resistance due to churning of the lubricant. Its value is small compared with the other resistances referred to and is subject to large variations. This has been brought out by rear axle tests where even in the same axle large differences are found, due to the temperature of the lubricant. The dragging of brake bands, which is not uncommon, would appear as chassis friction. In tests of 9 out of 17 cars the effect of 100 per cent increase in speed on the chassis resistance was not apparent, and in the remainder of the cars it was very small, so that the influence of speed has been disregarded. From the general knowledge of gears and bearings it is probable that the chassis friction would increase somewhat with an increase in the power transmitted. However, since this item is small compared with the other more or less unknown variables, it is seen that any error due to overlooking it will not be great. The range of values due to chassis resistance varies from 3 to 33 pounds apparently bearing no direct relation to the car weight. Accordingly, the average value, which is 14.7 pounds, has been used for all cars. The method of calculation is illustrated by the following, using the data of one car only:

	Pounds
Weight of car, front	1, 575
Weight of car, rear	1, 815
Rolling resistance of rear wheels (including chassis friction)	34
Rolling resistance of front tires (neglecting front wheel bearings)	17
Rolling resistance [2] of rear tires $17\times\frac{1,815}{1,575}$	19. 6
Resistance due to chassis friction 34−19.6	14. 4
Range of values for above based on 15 cars:	
Minimum	3. 0
Maximum	33. 4
Average	14. 7

[2] See section 4, p. 216.

3. WIND RESISTANCE

This resistance is that which still air offers to the movement of the car. It has been calculated from the formula

$$R = A \times V^2 \times 0.003$$

where

R = the wind resistance in pounds,
A = the frontal area of the car in square feet,
V = the speed of the car in M. P. H.,
0.003 = a constant.[3]

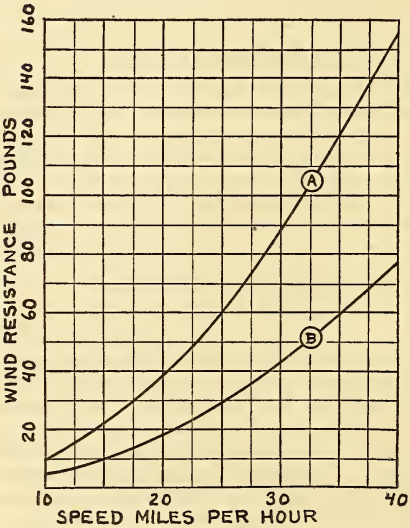

FIG. 1.—*Wind resistance offered by an automobile*

A, Maximum frontal area. *B*, Minimum frontal area.

Values for A were taken from 16 square feet minimum to 32.6 square feet maximum.

This resistance increases as the square of the speed and is an important factor in total car resistance particularly at high speeds. Minimum and maximum values have been used in making comparisons which may be taken to include not only differences due to frontal area but also those due to car shape. The range of values which are shown in Figure 1 is based on still air. If a wind is blowing, the values will be increased or decreased by amounts depending upon its direction and velocity.

4. RESISTANCE DUE TO TIRES.

The resistance of tires is based on the data contained in Technologic Paper No. 240, together with similar tests on 15 balloon tires. It is taken to be constant for different speeds, and proportional to the axle load. The increase in resistance of the rear tires due to the transmission of power has been disregarded, since tests have shown this increase to be small.

[3] This is a common value used for this constant, although there is some experimental data indicating that it may be a little high.

In order to determine if the same differences in rolling resistance which are brought out by laboratory tests would also show up in service, road tests of rolling resistance were made on 3½-inch fabric, 3½-inch cord, and 4.40-inch balloon tires, and the results compared with results of dynamometer tests on the same tires. In making the road tests a car was successively equipped with tires of each kind under different air pressures, and the rolling resistance determined by towing it on a level road and measuring directly the tractive force required. These tests checked very closely with the laboratory tests and showed that the range of values obtained in the laboratory could be safely employed to represent what could be expected on paved roads, such as those on which the average car runs a large part of the time.

These values for different kinds of tires are shown in Figure 2. For the purpose of this paper the largest rolling resistance is taken to be 22 pounds and the smallest 8 pounds per 1,000 pounds axle load, which values it will be seen from Figure 2 represent the approximate upper and lower extremes.

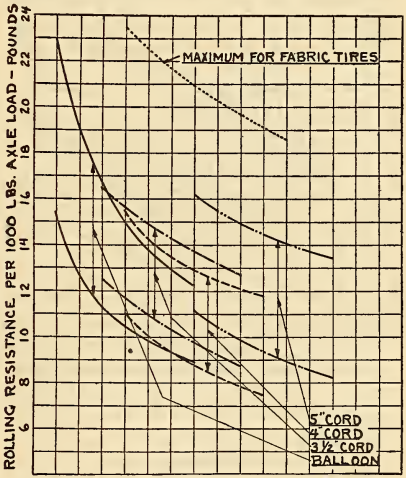

Fig. 2.—*The rolling resistance of pneumatic tires*

IV. EFFECT OF TIRES ON FUEL CONSUMPTION

In Figures 3, 4, and 5 the values which constitute the car resistance have been combined to show total car resistance based on a 3,000-pound car operating at speeds of from 10 to 40 miles per hour. Similar results were tabulated for a 2,000-pound car and a 4,000-pound car, but it was found that the relation between the different items did not differ materially from those given, and that the conclusions drawn from Figures 3, 4, and 5 may be considered of general application.

In Figure 3 level road conditions are shown for a car having a minimum of wind resistance; in Figure 4 level road conditions and a

maximum of wind resistance; and in Figure 5 a maximum wind resistance with the engine doing work equivalent to driving a car up a 5 per cent grade. The last represents quite an extreme condition and one under which the average car does not often operate.

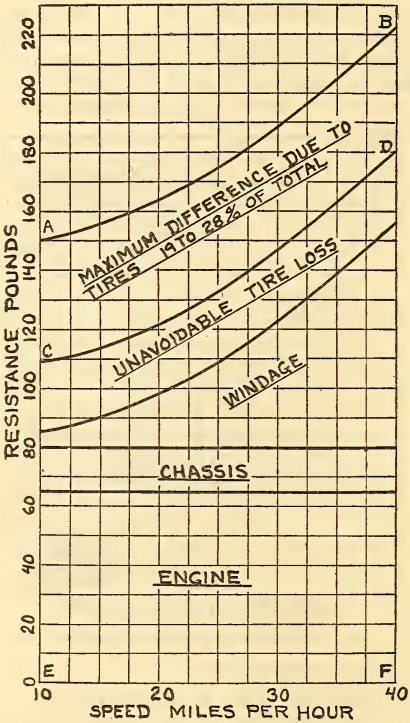

Fig. 3.—*Summary of resistances*

Weight of car, 3,000 pounds; wind resistance, minimum; level road conditions.

In all three figures the vertical height under line *CD* represents the total resistance which energy from the fuel is required to overcome if the car is equipped with tires having a minimum rolling resistance (8 pounds per 1,000). The vertical height under line *AB* represents the total resistance if the car is equipped with tires having a maximum rolling resistance (22 pounds per 1,000). Since the vertical heights represent total resistance, including friction of the engine, they are proportional to the indicated horsepower of the engine and, hence, also proportional to the fuel consumption. Accordingly, the relation which each resistance bears to the total resistance represents the proportion of total fuel consumption chargeable to each individual resistance and may be seen directly from the figures. By comparing the vertical height between lines *AB* and *CD* with the total height under *AB*, the maximum percentage difference in fuel consumption due to tires is easily found. It will be noted that possible differences due to tires vary from 9 per cent under the high-speed conditions of Figure 5 to 28 per cent under the low-speed conditions of Figure 3.

These represent quite extreme conditions, both with respect to car operation and to the range of tire resistance. By referring to Figure 2, if fabric tires are elimnated, the rolling resistance of most tires is found to lie between 9 and 15 pounds per 1,000 pounds axle load, a variation of 6 pounds. If this value is taken in place of 14 pounds as used in the foregoing and a speed of 20 miles per hour assumed as average, the maximum *probable* differences in fuel consumption due to any change in tire equipment vary from 6 per cent under the conditions of Figure 5 to 12 per cent under the conditions of Figure 3. Expressing this difference in more general terms, it may be stated that a difference in tire resistance of 1 pound per 1,000 pounds axle load will result in a 1 to 2 per cent difference in fuel consumption, or in a 1 to 2 per cent difference in miles per gallon of fuel.

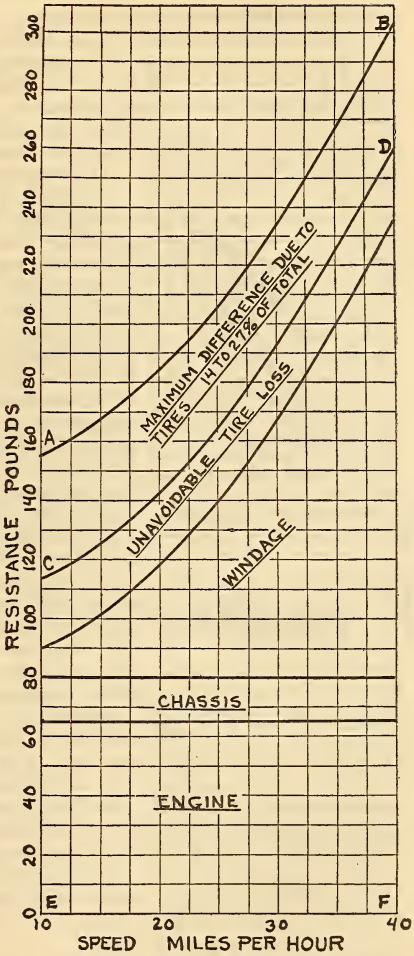

FIG. 4.—*Summary of resistances*
Weight of car, 3,000 pounds; wind resistance, maximum; level road conditions.

On first thought it may appear that thermal efficiency of the engine will influence these conclusions. This efficiency, however, if taken into consideration, simply amounts to an "overhead charge" on all items of resistance, and, hence, does not alter the proportion of the fuel chargeable to each resistance.

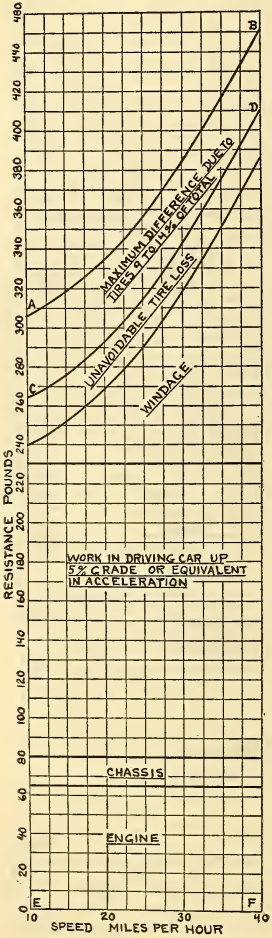

FIG. 5.—*Summary of resistances*
Weight of car, 3,000 pounds; wind resistance, maximum; up-grade conditions.

The following data were obtained by driving a car over a level course about 3 miles long and accurately measuring the fuel consumption. No attempt was made to determine all the factors which make up the total resistance, but simply to determine whether a standard car would show differences in fuel consumption in accordance with conclusions reached in this paper as a result of dynamometer tests. The car was first equipped with a set of fabric tires and then with a set of cord tires, the rolling resistances of which had previously been determined in the laboratory.

This should not be considered as a general comparison of cord and fabric tires, as the dynamometer tests showed that with respect to efficiency they might be classed as "good fabrics" and "poor cords." There was, however, a decided difference in the rolling resistances, so that a logical comparison can be made by simply considering this relation. Comparisons were made with the following six tire conditions:

A. Fabric tires (45 pounds inflation) *v.* cord tires (40 pounds inflation) with the car accelerated and decelerated.

B. Fabric tires (55 pounds inflation) *v.* cord tires (50 pounds inflation) with car accelerated and decelerated.

C. Fabric tires (65 pounds inflation) *v.* cord tires (60 pounds inflation) with car accelerated and decelerated.

D. Fabric tires (65 pounds inflation) *v.* cord tires (60 pounds inflation) with car run at a constant speed of 15 miles per hour.

E. Same as D, except with car run at a constant speed of 20 miles per hour.

F. Fabric tires (45 pounds inflation) *v.* cord tires (60 pounds inflation) with car accelerated and decelerated.

	A	B	C	D	E	F
Difference in rolling resistance per 1,000 pounds load as determined in the laboratory.....pounds..	3.3	3.5	3.8	3.8	3.8	5.8
Actual miles per gallon of fuel on road with different tires:						
Fabric	22.60	22.90	23.28	22.01	25.20	22.60
Cord	23.66	23.72	24.95	23.62	26.57	24.95
Difference in miles per gallon	1.06	.82	1.67	1.61	1.37	2.35
Per cent loss due to tires with higher rolling resistance	4.5	3.5	6.7	6.8	5.2	9.4
Per cent loss per 1 pound difference in rolling resistance	1.37	1.06	1.76	1.79	1.37	1.62

It will be noted that under the conditions of test F, where there is the greatest difference in tire resistance, the highest per cent loss in "miles per gallon" is found. In tests A and B, where the differences in rolling resistance are the least, there are the smallest losses in "miles per gallon." In C, D, and E, where the differences in tire resistance are intermediate, the losses in "miles per gallon" are also intermediate. There is some inconsistency between tests A and B which can only be explained as due to unknown conditions during the tests, such as wind, tire temperatures, unavoidable irregularities due to traffic, etc., but as a whole the results are what would be expected.

By reducing the per cent losses to per cent losses per 1 pound difference in tire resistance it will be seen that they all lie between 1 and 2 per cent and confirm the conclusions reached as the result of dynamometer tests.

A discussion of this subject would not be complete without showing in a more definite manner than in Figure 2 the status of the balloon tire. A blanket statement can not be made that a change from high pressure to balloon tires will result in an increase in rolling resistance, as the difference between the two types is comparatively small, and individual balloon tires may show either a higher or lower rolling resistance than individual high-pressure tires. However, it appears from Figure 2 that as a class balloon tires have a greater rolling resistance than high-pressure cord tires, the amount depending on the inflation pressures considered. In the absence of a recognized standard for inflation pressures, comparisons are made on a basis of 30 pounds per square inch for balloon tires and 45, 50, and 60 pounds for 3½, 4, and 5 inch cord tires, respectively. These latter are somewhat less than the generally recommended pressures, but are believed to represent more nearly actual operating conditions.

On this basis the average rolling resistance for high-pressure cord tires is 11.8 pounds per 1,000 pounds axle load, for balloon tires 13.5 pounds, and for the now almost obsolete fabric tires (except the 3½-inch size) 17.1 pounds. Thus, it is seen that the gain in cushioning which is known to result from the use of balloon tires is obtained at an increase of 1.7 pounds in rolling resistance. This estimate may be rather conservative in that balloon tires in many cases are run at lower inflation pressures than 30 pounds, which would result in a greater increase in rolling resistance over high-pressure tires. However, it will be seen from Figure 2 that a considerably lower pressure could be used and still keep the rolling resistance below that of the fabric tire. Accordingly, it may be stated that from the standpoint of rolling resistance balloon tires as a class lie between the fabric tire and the high-pressure cord.

It is a matter of common observation that a car is subject to less vibration when the tires are soft than when they are well inflated, and dynamometer tests (see T240) show that the rolling resistance of a tire increases as the inflation pressure is reduced. Thus, it is found that the increased cushioning which is characteristic of balloon tires is secured at the expense of rolling resistance. Accordingly, in considering the relative merits of high and low pressure tires the disadvantage of increase in the rolling resistance of balloon tires should be compared with the advantages of greater riding comfort and greater protection which they give to the various parts of the car against shock. This protection would obviously result in less wear, so that the various bearings would remain tight for a longer period with a consequent decrease in repair expense.

Conflicting statements have been made as to whether the fuel consumption of an automobile will be increased by the use of balloon tires. The reason for such differences may be explained by considering the following points: (*a*) As has been pointed out previously, a change from high pressure to balloon tires does not necessarily result in a greater rolling resistance. This is dependent upon the specific tires under consideration and the conditions under which they are operated. (*b*) While as an *average* it appears that a higher rolling resistance will result from the use of balloon tires the difference between the two types of tires is small, so that any difference in fuel consumption will be correspondingly small. Accordingly, unless very accurate determinations are made, any difference in fuel consumption will not be apparent. (*c*) In all the data shown smooth road conditions are assumed. If the road is rough, another factor is added to the resistances which the fuel must overcome due to energy absorbed by the springs, snubbers, etc., caused by a vertical movement of the car body. This is an indeterminate factor dependent on the degree of road roughness, stiffness of springs, etc.

The use of balloon tires favors a reduction in any losses of energy due to this cause and thus tends, from the standpoint of fuel consumption, to counteract any increase due to a greater rolling resistance. The same reasoning might also be applied to high-pressure tires run at low-inflation pressures, but in this case the cushioning is not as great as would result from the use of balloon tires on account of the smaller air volume and, in addition, their design does not permit of the use of the lower pressures without a considerable sacrifice in tire life.

V. CONCLUSIONS

In the analysis made of the various items which are responsible for the fuel consumption of an automobile the object is to point out the *possible* and *probable* effects of different tires and not to recommend from this standpoint the use of any particular type. Pneumatic tires are used in order to cushion the car, and while higher pressures result in a saving of fuel it is done at the expense of cushioning and accordingly a compromise must be made. Abnormally low pressures should, of course, be avoided as they not only shorten the tire's life, but also materially increase the fuel consumption. It will be noted, however, that for tires of the same type, which have about equal cushioning properties, some have a much lower rolling resistance than others. The use of those having the lower rolling resistance would obviously result in a direct saving—other things being equal. It will also be seen that there is as much difference in rolling resistance with the same tire properly and improperly inflated as there is in different tires, and accordingly, from the standpoint of the influence on fuel consumption, this feature should be given as much consideration as the selection of the tire itself.

Statements are often heard that one make of tire has a rolling resistance 25 or 30 per cent less than another and the impression is conveyed, perhaps unintentionally, that the fuel consumption will vary in the same proportion. The fallacy of such a conclusion is clearly shown from the figures in Section IV. These show what possible influence tires can have and afford a basis by which it is possible to predict how a tire change will effect the fuel consumption, provided, of course, that the relative resistance of the tires are known.

WASHINGTON, December 25, 1924.