these tests shows that the rolling resistance of all four tires is approximately 67 pounds, i e , 21 6 pounds per ton for the 3 1 tons of gross weight of the Road Test Truck

AIR RESISTANCE OF AUTOMOBILES

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Wind resistance and air resistance are terms in common use for the force which air exerts on a moving vehicle Air resistance is more properly used when the air is at rest and the vehicle in motion, and this assumption will be made throughout this discussion unless otherwise noted

1 The force which air exerts on a moving vehicle can be measured in two ways First, by holding the vehicle, or a reduced model, in a current of moving air, with appliances for measuring the force produced Second, by causing the vehicle to travel in still air at a known velocity, and measuring the resisting force Examples of both methods will be given in a later article

2 Air resistance of a vehicle will depend on a number of different factors, such as,

a Speed of the vehicle
b Density of the air
c Projected frontal area of the vehicle
d Contour of body, rounding of corners, etc
e Roughness of the road, and trees, bushes, walls, etc along the roadside

The first three factors are of chief importance, and their influence on air resistance can be treated by mathematical analysis The last two items are of minor importance and for the present will be dealt with by experimental coefficients

3 The mathematical theory of resistance of a flat plate to a current of moving air is based on the assumption that the surface causes the stream of air to turn 90 degrees, moving off at right angles to its initial direction The pressure on the plate will be equal to that of a column of air of height $\frac{V^2}{2g}$ feet The pressure in pounds per square foot will be equal to density times $\frac{V^2}{2g}$, where V is feet per second The density of air at 70°F. and atmospheric pressure will be 0 075 pounds per cubic foot

If the car speed be expressed in s = miles per hour instead of V = feet per second, the pressure of the air in pounds per square foot will be, after reduction

$$\text{Pressure} = 0\,0025\ S^2 \tag{1}$$

It might be inferred from (1) that, if the resistance of a car body resembled that of a flat plate as used in this analysis, its resistance might be computed by a formula such as,

$$\text{Resistance} = 0\,0025\ A\ S^2 \tag{2}$$

It is an interesting fact that formula (2) has been confirmed by experiments of several observers It will be better to put the formula in a more general form,

$$\text{Resistance} = k\ A\ S^2 \tag{3}$$

where k is a coefficient to be determined for different types of car bodies, and possibly for quality of road surfaces Values of k used in the past have ranged from 0 0032 to 0 0020 A is the projected area in square feet, and S is the car speed in miles per hour

4 Reference will now be made to four series of air resistance measurements carried out during the past eight years, each conducted by different observers and employing different experimental methods, and each arriving at an independent value of the coefficient k in formula (3)

a Experiments with reduced scale models in a wind tunnel, reported by Jaray[1] in 1922

b Experiments with a full size automobile in a special wind tunnel built for this purpose at Kansas State Agricultural College, Manhattan, Kansas By L E Conrad,[2] 1925

c Experiments with a railway flat car pushed by a locomotive, carrying an automobile facing the direction of motion, with appliances for measuring the resisting force of the air Reported by T R Agg[3] and N Wolfard, 1927

d Experiments by coasting down a hill of uniform grade conducted at Yale University during 1928, and reported in this paper for the first time

5 The coasting method for determining air resistance was suggested

[1] Die Leistungs Berechnungs des Motorwagens, P Jaray, Der Motorwagen, Vol 25, No 29, pp 551–559, 1922

[2] Wind resistance of Automobiles, L E Conrad, Public Roads, Vol 6, pp 203–206, 1925

[3] Investigation of Air Resistance on Automobiles, T R Agg and N Wolfard, Proceedings Sixth Annual Meeting, Highway Research Board, Washington, D C, 1927

by Mr L C. Ryce of Boston, Mass., during the early spring of 1927, with the added suggestion of a hill where the method might be given a trial Preliminary tests indicated that the new method permitted accurate measurement of air resistance under actual road conditions Further tests were made during 1928 with a variety of vehicles, using precautions suggested by the earlier experiments to avoid errors

The coasting method requires special equipment and experimentation as follows:

First A smooth road of uniform grade, not exceeding about 6 per cent

Second To coast down the hill in neutral gear, using an accurate tachometer for measuring the coasting speed. The coasting speed may be defined as the maximum speed that can be had when coasting in neutral gear

Third: To measure the rolling resistance of the vehicle by a chassis dynamometer, at same speed, load, etc , as during the coasting test

Fourth To determine the vehicle weight including observers, and to measure its projected area for air resistance

The air resistance can be computed from the relation,

$$P = R + F. \qquad (4)$$

where P = weight in pounds times grade in per cent divided by 100

R = rolling resistance by chassis dynamometer

F = air resistance, computed from P and R

Having found the air resistance by (4), and knowing the vehicle speed and frontal area, the coefficient in formula (3) can be computed.

6 From the foregoing description of the coasting method it will be seen that most of the factors such as speed, weight, body area and grade can be determined quite easily

Rolling resistance presents greater difficulties, not only in requiring a sensitive chassis dynamometer, but in requiring the duplication of road conditions in the laboratory The resistance of bearings and transmission varies with the speed and temperature, also erratic variations may arise from accidental presence of water or dust on the brake band linings

For perfect agreement it is necessary to make the coasting and laboratory conditions identical Three factors that can be duplicated in the laboratory with ample accuracy are the car speed, the axle loads, and the tire inflation Temperature can be allowed for by running the car for one-half hour at speed at 40 miles per hour before coasting tests are begun, with a similar warming up before laboratory resistance measurements are made. There is a marked decrease in rolling resistance as the tires and transmission warm up, reaching a minimum value in about the time stated, after which there will be little or no further change Variations due to presence of water or dust in the brake bands can be avoided by travelling only on hard surfaced roads before and after the coasting tests, and by keeping the brakes dry

Laboratory conditions differ from those on the road in two minor respects The drum surfaces are smoother than the average road,

TABLE I

Car Weight, Tires, etc

	Chrysler	La Salle	Packard
Weight, front	1,610	2,155	1,930
Weight, rear	1,740	2,210	2,300
Weight total	3,350	4,365	4,230
Tires, size	30 × 5 77	32 × 6 50	32 × 6
Tires, inflation	40	40	40

TABLE II

Rolling Resistance

Measured on chassis dynamometer, pounds at rear tire circumference

Name	Speed	Front	Rear	Total
Chrysler	10	16	26	42
	20	16	26 5	41 5
	30	19	30	49
	40	20	31 5	51 5
	50	21	33	54
	60	21	35	56
La Salle	10	21	33	54
	20	24 5	36	60 5
	30	27	37	64
	40	27	39	66
	50	27 5	41	68 5
	60	29	44	73
Packard	10	18	24 5	42 5
	20	19	27 5	46 5
	30	20	30 5	50 5
	40	20 7	32 5	53 2
	50	22	35 2	57 2
	60	24	37 2	61 2

tending to decrease slightly the laboratory rolling resistance The drum surfaces are curved cylinders, flexing the tire into an arc instead of into a plane surface, and tending to increase slightly the laboratory rolling resistance These differences are small and act in opposite directions, hence, they tend to neutralize each other and may be disregarded

7 Few examples have been published of rolling resistance of automobiles over a wide range of speeds It may be of interest to give a few samples of such measurements from the chassis dynamometer as closely related to the air resistance problem, although it is not necessary in any particular case to measure the rolling resistance except at the coasting speed

Measurements will be reported for three cars whose particulars are given in Table I Rolling resistance figures are given in Table II, speeds 10 to 60 miles per hour, with separate columns for front, rear, and total resistance

TABLE III

ROLLING RESISTANCE, PER 1000 POUND WEIGHT

Measured on chassis dynamometer, pound at rear tire circumference

Name	Speed	Front	Rear	Total
Chrysler	10	10	15	12 5
	20	10	14 6	12 4
	30	11 8	17 7	14 6
	40	12 4	18 1	15 4
	50	13	19	16 1
	60	13	20	16 7
La Salle	10	9 7	15	12 4
	20	11 4	16 3	13 9
	30	12 5	16 7	14 7
	40	12 5	17 6	15 1
	50	12 8	18 6	15 7
	60	13 4	19 9	16 7
Packard	10	9 3	10 6	10 0
	20	9 8	12	11 0
	30	10 4	13 2	11 9
	40	10 7	14 1	12 6
	50	11 4	15 4	13 5
	60	12 4	16 2	14 5

The figures in Table II are recorded as read from the dynamometer scale, and illustrate unavoidable errors incident to the apparatus For example, the front wheel resistance of the Chrysler is recorded as 16 pounds at speeds 10 and 20, and 21 pounds at speeds 50 and 60, whereas there is probably a regular increase of rolling resistance over the whole speed range Such readings should be plotted on cross-section paper, where irregularities can be smoothed out by a curve

All cars show a regular increase of rolling resistance with speed, in both front and rear wheels, a total of over 30 per cent increase for speed change from 10 to 60 m p h. Rolling resistance often has been assumed constant at all speeds, but this is far from true for these cars

The rear wheel resistance is greater than the front, which was to be expected since the gears and propeller shaft turn with the rear wheels

The rolling resistance of the three cars differs considerably, being largest for the LaSalle and smallest for the Chrysler When the resistances are to basis of equal car weight as in Table III, where the unit is pounds per 1000 pound weight, the differences are largely removed On the basis of equal weight the Chrysler and LaSalle are nearly identical at all speeds, while the Packard resistance is a little less

Rolling resistance figures from German practice, in pounds per 1000 pound weight, were quoted by Jaray[4] in 1922, limits 10–30, average 20 and constant at all speeds

Recent experiments with a test car on concrete and asphalt roads, reported by Prof H B Shaw[5] of North Carolina State College, gave rolling resistance of 11 5 pounds per 1000 pound weight, at speeds of 15 to 25 miles per hour

The figures in Tables II and III are supplemented by further tests at 5 miles per hour, and at walking speed The low speed tests gave little further information except to prove that the rolling resistance decreased very little below speed of 10 miles per hour It will be proper to repeat that the figures given in Tables II and III were obtained when tires and transmission were well warmed up by running under load When not thus warmed up the rolling resistance will be considerably greater

8 Two different hills have been employed for making coasting tests

First, a 6 0 per cent grade, one mile long, at start of the Mohawk Trail, near Greenfield, Mass This road was cut in the side of Shelburne Mountain, practically uniform in grade and quite straight The pavement is concrete, several years old and with cracks filled with tar Most of the road is lined with trees on one side and earth or stone wall on the other.

Second, a 4 78 per cent grade, 1000 feet long, on the Boston post road near Branford, Conn This pavement is of concrete, four lanes wide, and in perfect condition, and without any obstructions along side of the road

9 The various steps of conducting a coasting test for air resistance may be described as follows

First, examine wheels for evidence of freeness from brake drag, etc , then warm car up by driving fast for about 20 miles

Coasting tests are best made in the early dawn, at which time the air is most likely to be at rest, and the road clear of traffic Summer temperature is desirable

The car is driven to the top of the hill at approximate coasting speed, then allowed to roll in neutral gear, observing change of speed by the

[4] Die Leistungs Berechnungs des Motorwagens, P Jaray, Der Motorwagen, Vol 25, No 29, pp 551-559, 1922

[5] Proc Sixth Annual Meeting, Highway Research Board, p 75 1927

fifth wheel tachometer. When the speed has become constant for one or two hundred feet, it may be assumed as the true coasting speed. Runs should be repeated several times, starting a little above and a little below the estimated coasting speed Wind observations are to be made during the progress of the coasting, to determine its velocity and direction, as evidence that the air is at rest, or nearly so

TABLE IV

AIR RESISTANCE OF SEDANS BY COASTING METHOD, BOSTON POST ROAD, NEAR BRANFORD, CONN , 4 78 PER CENT GRADE

	1	2	3	4	5	6	7	8	9
	Date of test 1928	Name of car	Body type	Weight of car lb	Projected area sq ft	Coasting speed m p h	Rolling resistance lb	Air resistance lb	Coefficient in $k A S^2$
1	6–7	Chrysler 72	Sedan	3,782	26 2	51 0	60	121	0 00178
2	6–7	Chrysler 80	Sedan	4,597	29 6	55 5	79	141	0 00155
3	6–7	Chrysler 70	Sedan	3,689	27 0	51 0	60	116	0 00166
4	6–8	Packard 8	Sedan	5,222	30 6	57 5	88	162	0 00160
5	6–8	Chrysler 70 (check)	Sedan	3,665	27 0	51 0	61	114 2	0 00163
6	6–9	Buick 1926	Sedan	3,812	28 3	50 0	57	125 2	0 00176
7	6–11	Overland 6	Sedan	2,957	26 6	43 2	58	83 3	0 00168
8	6–12	P-A 1928	Sedan	4,187	28 0	47 5	88	112 2	0 00178
9	6–14	Franklin 1928	Sedan	3,957	28 5	49 0	77	112	0 00164
10	6–15	Chevrolet 1928	Sedan	2,827	25 2	41 0	68	67	0 00158
11	6–18	Dodge 1928	Sedan	3,277	25 3	48 1	64 5	92	0 00158
12	6–21	Graham-Paige 1928	Sedan	3,722	27 1	47 3	80	98	0 00162
13	6–21	Graham-Paige Model 610	Sedan	3,242	24 7	46 7		90	0 00167

At conclusion of the coasting test, the car should be driven to the laboratory for measurement of rolling resistance on the chassis dynamometer, where load, speed and temperature conditions are duplicated as nearly as possible

Knowing the rolling resistance, per cent grade, weight of car with observers, the air resistance can be computed as already explained

TABLE V

AIR RESISTANCE OF COUPES, ROADSTERS, TOURING CARS, COASTING METHOD, BOSTON POST ROAD, 4 78 PER CENT GRADE

	1	2	3	4	5	6	7	8	9
	Date of test 1928	Name of car	Body type	Weight of car lb	Projected area sq ft	Coasting speed m p h	Rolling resistance lb	Air resistance lb	Coefficient in $k\ A\ S^2$
1	5-23	Oakland	Roadster	3,187	22 4 top down	45	51	101 5	0 00223
2	5-23	Oakland	Roadster	3,187	22 4, top up	45	51	101 5	0 00207
3	6-8	Buick	Touring	4,297	23 3 top down	52 5	71	135	0 00210
4	6-8	Buick	Touring	4,297	27 5 top up	51 5	71	135	0 00185
5	6-9	Chrysler 62	Roadster	3,167	21 7 top down	47 5	49	102 5	0 00209
6	6-9	Chrysler 62	Roadster	3,167	23 5 top up	46 0	49	102 5	0 00206
7	6-11	Overland Whippet 4	Roadster	2,532	20 5 top down	40 3	56	65	0 00195
8	6-11	Overland Whippet 4	Roadster	2,532	22 0 top up	40 8	56	65	0 00178
9	6-12	Studebaker A-830	Coupe	3,697	27 3	50 0	65	112	0 00164
10	6-14	Ford 1928	Coupe	2,752	24 6	41 8	47	85	0 00197
11	6-15	Chevrolet 1928	Coupe	2,607	24 6	40 5	49	76	0 00188
12	6-18	Dodge	Coupe	2,947	23 6	41 2	56	85	0 00212

The projected area of the car is measured, after which all terms in the air resistance formula (3) are known except the coefficient k, whose value is thus determined.

10 Projected area of car may be measured in three parts, thus:

(1) Body rectangle: $a \times b$

where a = height, bottom of running board to mean level of curved top of car

b = width of body at rear doors

(2) Projecting fenders: $2c \times d$

where c = height, bottom of running board, to top of rear fenders

d = projecting width of fender from car body

(3) Tire area below running board $2e \times f$

where e = bottom of running board to ground

f = tire width

Projected area = sum of (1), (2), and (3) in square feet

11 Table IV affords data of air resistance measurements of different cars of sedan type, made on the Branford hill during June, 1927 The items, weight, projected area, rolling resistance, and coasting speed are given in appropriate columns Nine different manufacturers are represented, with car weights including observers ranging from 2,800 to 5,200 pounds Particular interest attaches to the last column, which gives the experimental value of the coefficient k in the air resistance formula (3), maximum value 0 00178, minimum value 0 00155 average value 0 00166

12 Table V gives similar data of air resistance of coupe, roadster and touring types, with a limited number of examples of each kind Examination of the values of the coefficient k, given in last column of the table, shows that the air resistance of these bodies is greater than for the sedans of Table IV Taking all cars listed in Table V, except those with top folded down, the average value of k is 0 00192, or 15 per cent greater than the average of all sedans in Table IV

Another interesting comparison can be made of three light sedans from Table IV and three light roadsters, top up, and some roadsters with top down, from Table V The comparative figures for these groups are

	Projected area square feet	Air resistance (50 m p h)
3 light sedans	25 5	104
3 light roadsters (top up)	23 2	114
3 light roadsters (top down)	21 5	112

Comparing the first two groups the sedans have 10 per cent more body area and 10 per cent less air resistance

A similar conclusion is drawn from the two sets of roadster figures When the top is lowered, reducing the body area by nearly 2 square feet, the air resistance remains practically constant

It would be unwise to draw sweeping conclusions from a limited number of experiments, but these seem to be evidence that the sedan type of body offers considerably less air resistance than any of the other types mentioned

13 A comparison has been made in Table VI of the coasting speed and air resistance of two identical cars on different test hills It shows that the average air resistance of the Branford hill, as measured by the coefficient k, was different for the two cars, and the same proportionate

difference was also observed on the Greenfield hill, except that the latter values were slightly higher

The observed difference in k was 8 per cent, which indicates that differences of this order may be caused by the presence of trees or similar obstructions along the road It follows that air resistance is affected chiefly by the size and shape of the vehicle, and to a lesser extent by the obstructions along the road

14 An interesting comparison can be made of the four methods of experimentation referred to by examining the formulas which were deduced to express the results

TABLE VI

AIR RESISTANCE ON DIFFERENT GRADES

6 0 per cent, 5,000 feet on Mohawk Trail, near Greenfield, Mass
4 78 per cent, 1,000 feet on Boston Post Road, near Branford, Conn
Greenfield, road slightly rough, lined with trees
Branford, road very smooth, four lanes wide, no trees

	1 Date of test 1928	2 Name of car	3 Body type	4 Weight of car lb	5 Projected area sq ft	6 Coasting speed m p h	7 Rolling resistance lb	8 Air resistance lb	9 Coefficient in $k A S^2$
1	4–22(B)	Chrysler 70	Sedan	3,812	27 0	51 0	60	122	0 00174
2	4–26(G)	Chrysler 70	Sedan	3,787	27 0	58 5	60	167	0 00181
3	4–22(B)	Packard 6	Sedan	4,645	29 0	56 5	76	146	0 00158
4	4–26(G)	Packard 6	Sedan	4,680	29 0	64 5	76	205	0 00170

Summary

Chrysler, Branford, 9 tests, average, k = 0 00166
Chrysler, Greenfield, average, k = 0 00181 (9 per cent more)
Packard, Branford, average, k = 0 00157
Packard, Greenfield, average, k = 0 00170 (8 per cent more)

Jaray, reduced scale models in wind tunnel, 1922,

$$R = (0\ 0017\text{–}18)\ A\ S^2 \text{ for closed cars}$$

$$R = (0\ 0023\text{–}26)\ A\ S^2 \text{ for open cars}$$

Conrad, full-size automobiles in wind tunnel, 1925

$$R = 0\ 00145\ A\ S^{2\ 14} \text{ (average, closed and open cars)}$$

Agg and Wolford, automobiles carried on railway flat car, 1926

$$R = 0\ 00167\ A\ S^{2\ 10} \text{ (average, closed and open cars)}$$

Coasting on uniform grade, 1928

$R = 0\,0017\text{–}18\ A\ S^2$ (sedans)

$R = 0\,0019\ A\ S^2$ (average coupe, roadster, touring)

$R = 0\,0021\ A\ S^2$ (average touring and roadster, top down)

As the above formulas are not strictly comparable on account of fractional exponents, a further comparison will be made by computing the air resistance at 50 miles per hour, for a projected area of 26 square feet in each case

	Air resistance lb
Jaray, for closed cars	114
Jaray, for open cars	160
Conrad, average of all cars	167
Agg and Wolfard, all cars	161
Coasting method for sedans	114
Coasting method for coupes, roadsters, touring	124
Coasting method for roadsters, touring, top down	136

15 Air resistance formulas in recent handbooks usually have contained coefficients of 0 0025 or larger The coefficients quoted by Jaray are practically identical with those obtained by the new coasting method, both giving values of 0 0017 to 0 0018 Probably the agreement is accidental, especially since the wind tunnel experiments referred to by Jaray were made on models of German cars built as early as 1921, while the coasting tests were made with 1928 American sedans in most cases Jaray's coefficients for open cars are about 15 per cent larger than those obtained by the coasting method

In appraising the value of the different methods of measuring air resistance, it must be admitted that the coasting method has the advantage of a full size vehicle actually travelling on a smooth road at considerable speed, in still air Under these conditions, the true air resistance acts on the vehicle, but its accurate measurement is dependent on the chassis dynamometer where the rolling resistance is determined

The coasting tests reported in this paper seem to indicate that each type of car body has its own characteristic coefficient in the air resistance formula, and that each road may have its influence in modifying the air resistance

Indirect confirmation of the smaller values of the coefficients, 0 0017 to 0 0020, has been found in chassis dynamometer tests where the power of the engine has been measured A prediction can be made of maximum speed of the car on level, or on grade, using a computed air resistance When this computation is made with the lower coefficients, the speeds have been found to agree with road tests made under the assigned conditions, whereas with a larger coefficient, 0025, satisfactory agreement of computed and actual speeds have not been obtained.

DISCUSSION

ON

AIR RESISTANCE OF AUTOMOBILES

PROFESSOR W E LAY, *University of Michigan*· The increased speed at which our cars are operating on the highways, the fact that certain states have taken off the high speed limit, and that some states are even considering a low speed limit on federal highways, has brought a whole new series of problems to the designer and builder of automotive vehicles These new problems are many and various Among them are the stability of vehicles on the road at highway speeds, with regard both to wind and regularity of pavement surface, the question of brakes of the greatly increased capacity required by high speeds and also the greatly increased power required for high speeds There is an alternative to the problem of increased power requirement and that is stream lining the motor vehicle itself so that less power is required This has been done to a certain extent for passenger vehicles but we still see great big rectangular bodies for trucks whose builders have made no attempt to reduce the air resistance in the least We find that several truck makers are advertising top speed for their trucks of 55 miles per hour

Several busses that make an average speed of forty miles an hour or better are manufactured by these makers That means that they must, or at least they should, consider the effects of the stream lining on the power requirements We just have the announcement of the new Dusenburg car which, in order to get 112 miles per hour speed required 256 horsepower It is quite certain that more attention will be paid to stream lining of motor vehicles