REPORT OF COMMITTEE ON HIGHWAY TRANSPORTATION COSTS

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THE AIR RESISTANCE OF MOTOR VEHICLES

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SYNOPSIS

Tests of the air resistance of motor vehicle bodies, including a study of test methods and aerodynamic characteristics of some simple body forms Wind tunnel tests of highway vehicles are complicated by the fact that a road surface must be provided Tests were made by four methods (1) Model Free, no road surface provided, (2) Using a flat plate as the road surface, (3) Using the flat plate with boundary layer partially removed, and (4) Reflection method, using duplicate models placed bottom to bottom The data showing the percentage of improvement due to streamlining are fairly consistent when measured by all four methods

This is a progress report of an investigation of the aerodynamic characteristics of simple automobile body forms and a comparative study of wind tunnel test methods as applied to tests of small scale models of automobile bodies It is based on the work of three graduate students, Messrs Smellie, Fries, and Lowry, in the wind tunnel of the Department of Aeronautical Engineering, at the University of Michigan, during the year 1930-1931

The operating speed of automotive vehicles is increasing. Ten years ago cars with fifty horsepower engines had speeds of about sixty miles per hour With the coming of good roads the public demanded more speed, which was met mainly by increasing the power of the engine To obtain a speed increase of fifteen to twenty miles per hour required an engine of nearly double the power. The use of such an engine reduced the distance travelled per gallon of fuel by nearly one-fourth There was, however, another factor influencing the manufacturer to increase his engine power The increase in speed and density of traffic made it mandatory that the vehicle stop and accelerate at rates never before attained The development of four wheel brakes met the first requirement and increased engine power met the second. In the meantime, however, we have learned how to build a silent second gear which will give us still greater acceleration at low and medium speeds, without further increase in engine power The use of a higher gear ratio for direct drive will then greatly increase the fuel mileage, while reducing the air resistance of the vehicle will not only increase the fuel mileage but will also increase the top speed of the car and the acceleration at high speed, without further increase of engine power Under such circumstances, streamlining the car to reduce the air resistance seems obvious as the next step in improving vehicle performance both as to top speed and fuel mileage

To understand what must be done we must remember that the motor vehicle operates at the bottom of an ocean of air under a pressure of nearly fifteen pounds on every square inch of surface exposed This fluid has both weight and inertia At our altitude the air contained in a twenty-eight inch cube weighs about one pound Its weight enables it to float the airship Akron much as the Leviathan is sustained by the Atlantic Ocean Because of the air's inertia, the airplane is able to fly To move an object slowly through the air requires little effort while to move it at high velocity requires the application of considerable power

The total resistance against which a car must be driven is made up of two factors, the air resistance and the rolling resistance The rolling resistance is nearly constant, increasing only slightly at the higher speeds The air resistance starting at zero increases as the square of the velocity and at speeds above forty miles per hour becomes the major absorber of horsepower The air resistance is usually expressed mathematically by the equation

$$R = KAV^2$$

where

R = the air resistance force in pounds
V = the car speed in miles per hour
A = the cross sectional area in square feet
K = an experimental coefficient depending on the form of the car

This air resistance may also be considered in two divisions—skin friction and form resistance The skin friction is due to the viscosity of the air and the frictional resistance between it and the surface of the car. This kind of resistance is always present in moving bodies and can be reduced but little It constitutes only 10 to 15 per cent of the total air resistance of the present car The remaining 85 to 90 per cent of form resistance is due to turbulent whirls and eddies set up as the car passes through the air Theoretically this may be entirely eliminated

Perhaps you have seen a car driven rapidly down a leaf strewn road and have observed the eddies and whirls of leaves and air which continue long after the car has passed It may be plainly seen that the car has greatly disturbed the air through which it moved The area of disturbance extends outward and upward far beyond the space through which the car actually passed Should the car move at a high speed the air will whirl and eddy with tremendous energy The energy left in the wake of the speeding car has only one origin, the potential energy in our fuel tank A body so shaped that it will open up a passage and replace the air without eddies or turbulence has no form resistance and is said to be streamlined

The most active fish and the swiftest flying birds are streamlined by nature so that they move through their native element with the least possible resistance The contours of the airship and the airplane have been developed most carefully, but the automobile, bus, and even trucks, which now are driven at speeds comparable to the early airplane, have been sadly neglected

In a passenger car the body, which forms the greater bulk of the vehicle, is essentially a rectangular box or compartment in which may be carried a certain number of passengers Its shape and size must be about the same whether the car cost $500 or $5000 and whether it be streamlined or not As the car moves through the air it must open up a passageway, bore a hole if you please, large enough for this compartment to pass through In this manner is determined the size, shape, and cross-sectional area of the passageway It then remains for us to lay out a front section to open up this passageway through which our compartment may move and a rear section to close it with the least possible disturbance of the surrounding air

With this idea in view Model No 1 was a rectangular box of such dimensions that it would just enclose a one-eighth scale model of a typical sedan Model No 2 was just like it except that all sharp corners and edges were rounded to a ¾ inch (six inches full scale) radius These two may be seen in the lower part of Figure 1 Models 2, 3, 4, and 5 shown in Figure 2 had different arrangements of wheel housings No 2 had only stub wheels representing that part of the wheel extending below the body Nos 3, 4 and 5 had the wheels entirely external to the body, in closed, and in open pockets respectively

A center section, the passenger carrying compartment, was then made up with the same shape and area of greatest cross section but with the top curved slightly from front to rear Front sections were made with a flat windshield in a vertical position, at a slant of 22½ and 45 degrees with the vertical and finally an elliptical front section In like manner four rear sections were made, a stub, medium, 45 degree and finally a greatly elongated section entirely impractical but completing the series By various combinations of the midsection with different front and rear sections as shown in Figures 3, 4, 5, and 6, and the composite drawing, Figure 7, models number 7 to 22 were

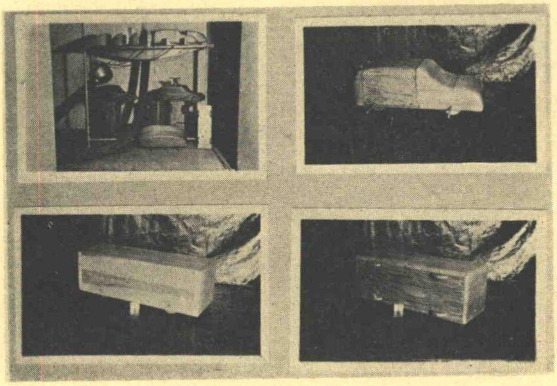

Figure 1

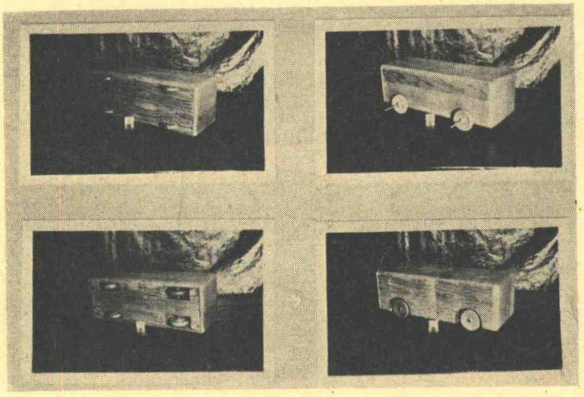

Figure 2

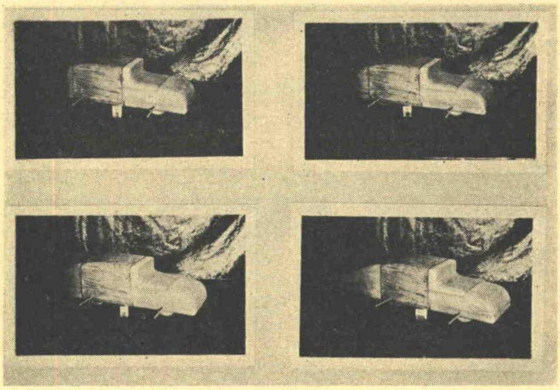

Figure 3

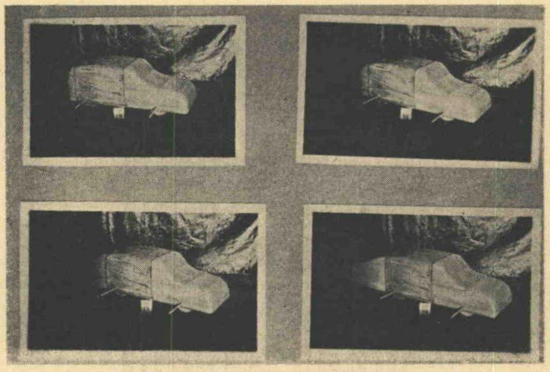

Figure 4

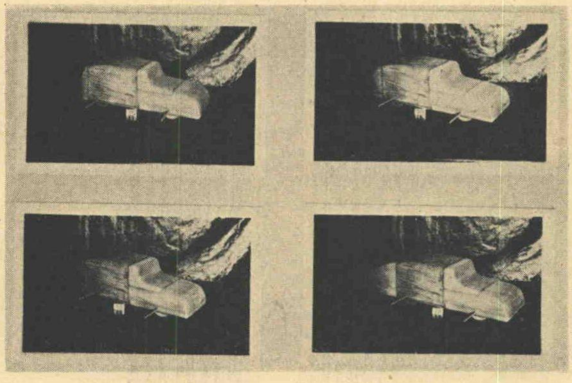

Figure 5

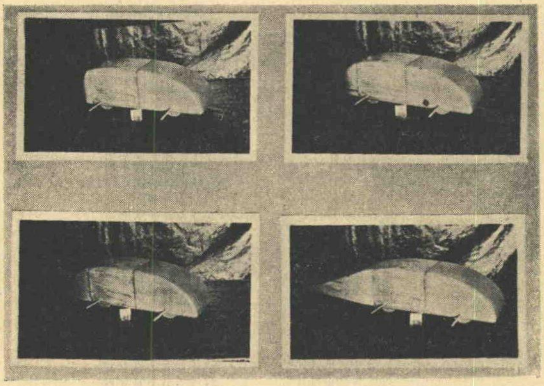

Figure 6

obtained Thus far the model contours have been simple, being made up of straight lines, circular arcs, ellipses, or parabolas Using the

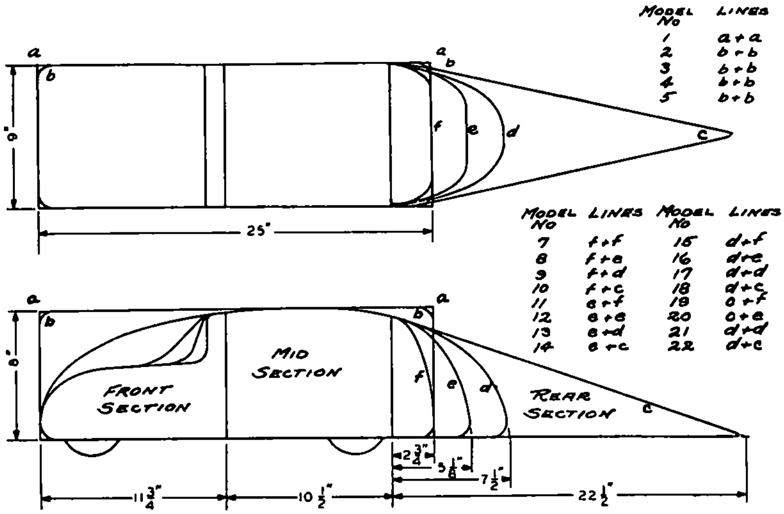

Figure 7 Models for Wind-Tunnel Tests, Scale 1″ = 5″

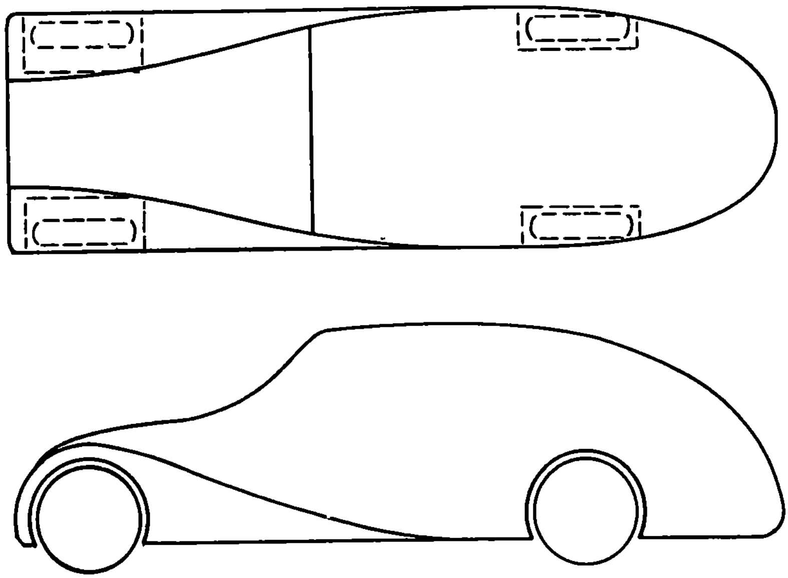

Figure 8 Model No 23

results obtained so far as a basis, model 23 shown in Figure 8 was laid out along more conventional lines with front fenders and a narrowed hood for the engine This model was set up with radiators of round, vertical flat, and slanting vee shape for model numbers 23-25, as shown in Figure 9. On this model was also formed a vee shaped vertical windshield with a 105 degree included angle and also a similar vee windshield set at a slant of 45 degrees. These last two arrangements are called models numbers 26 and 27. A final model, number 28, was then laid out which seemed to make a possible combination of streamlining, utility and good appearance as shown in the lower right hand corner of Figure 9. This was then compared with a quarter scale model of a 1929 automobile which was termed model number 29.

This has been not only a study of models but of test methods. To determine the drag of an airfoil or balloon model is comparatively simple, while the test of an automobile model is complicated by the necessity of providing a road surface. We find that twenty-one years

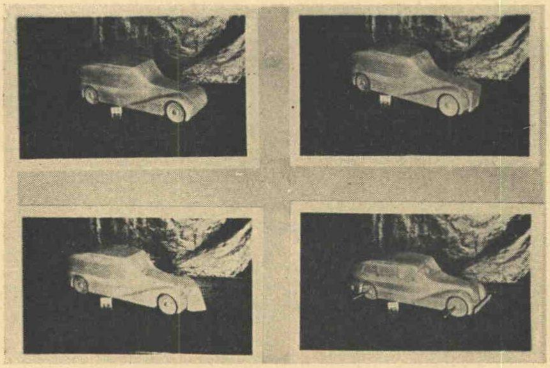

Figure 9

ago Eifel tried to use a running belt and found it impracticable because of an uncontrollable flapping. An apparatus capable of driving a moving belt at ninety miles an hour would be so large that unless it is built integral with the tunnel it would produce greater disturbances in the air stream than the model itself. Nine years ago Jaray used a flat plate as a road surface, but we know that such an arrangement will not duplicate the conditions under which a car actually operates. It can be built and placed in the air stream in such a manner that it will create little or no disturbance of the air flow in the region about the model excepting that it has a boundary layer extending up toward the model. A layer of air is attached to the plate surface and does not move at all. Succeeding layers above the plate flow at increasing speeds until at .60 inches above the plate the velocity is only 2 or 3 per cent less than that of the main air stream. This type of flow is termed viscous flow and the layer in which it occurs is called the boundary layer. There is however a similar boundary layer on the under surface of the model itself and between the two there is a much reduced velocity of the air moving underneath the body.

It would seem reasonable that if the boundary layer could be removed from the plate surface so that the air flow along the plate surface was not retarded, the model would be surrounded by the same conditions as the actual car. This suggestion was made by Professor Stalker and such a plate was made with some two thousand holes drilled in its upper surface, through which the air of the boundary

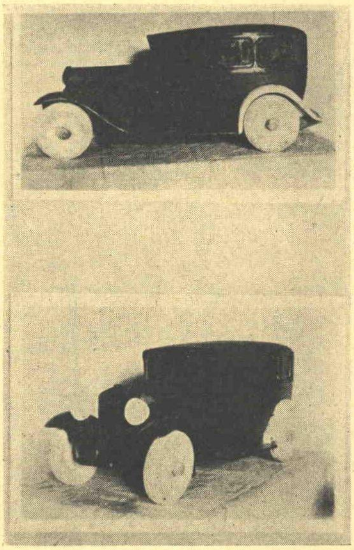

Figure 10

layer was removed by suction. With our apparatus it was possible to remove only about one-third of the boundary layer. Results obtained by extrapolation indicate that if the boundary layer had been completely removed the results would agree with those obtained by the reflection method.

The remaining method, called the aerodynamic reflection method, used by Rumpler, Pawlowski and others, consists of placing two identical models bottom to bottom. This will produce a neutral plane of air flow between them whose maximum velocity is practically that of the main air stream while the pressure effects on the under surface of the model tested should approach those of the car operating on the road. The lower model is supported entirely by guy wires and only the upper model is tested.

The tests were conducted in a wind tunnel with an Eifel chamber and double return ducts as shown in Figure 11. The octagonal throat was reduced to six foot diameter to obtain speeds up to 90 miles per hour. Test runs were made by 50, 60, 70, 80 and 90 miles per hour. The method of supporting the models in the air stream as seen in

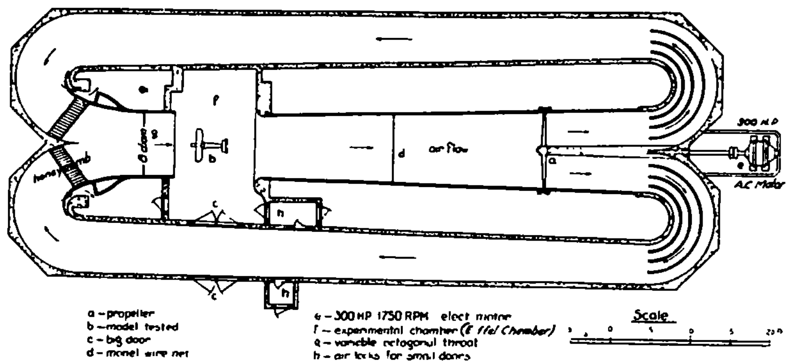

Figure 11 University of Michigan 8-Foot Octagonal Wind Tunnel

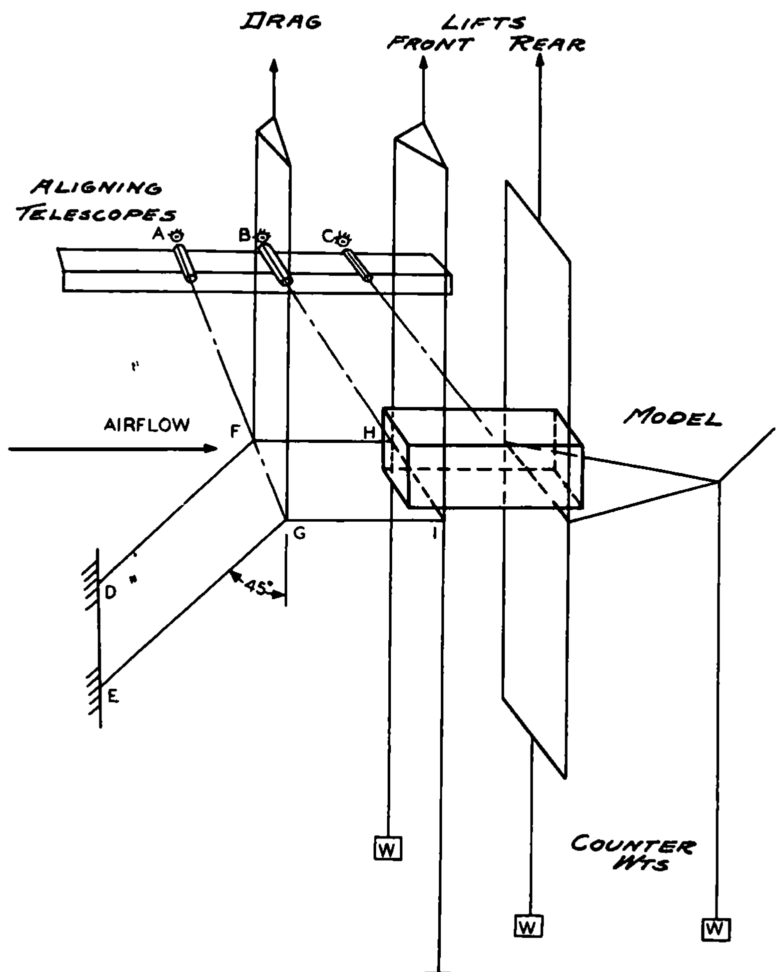

Figure 12 Wind-Tunnel Set-Up

Figure 12 made it possible not only to measure the drag but also the front and rear lift and the pitching moment. Tests were made with

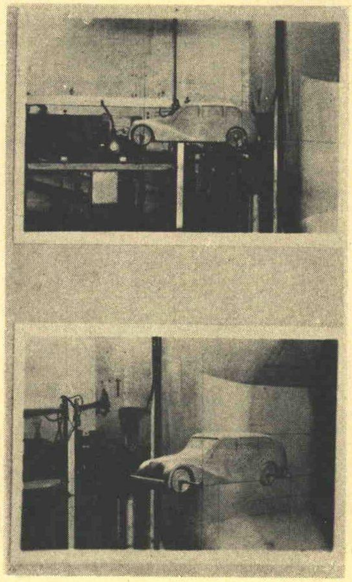

Figure 13

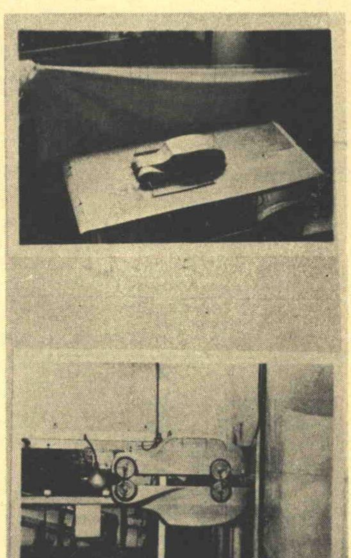

Figure 14

the models hanging free without provision for the road surface as shown in Figure 13.

In Figure 14 is shown the plate which was used without removal of the boundary layer according to Eifel's method. It was also used when the boundary layer was partially removed according to Stalker's suggestion. In the lower part is shown the set up of models by the reflection method, the lower model being supported by guy wires and in no way connected to the upper model or to the weighing scales

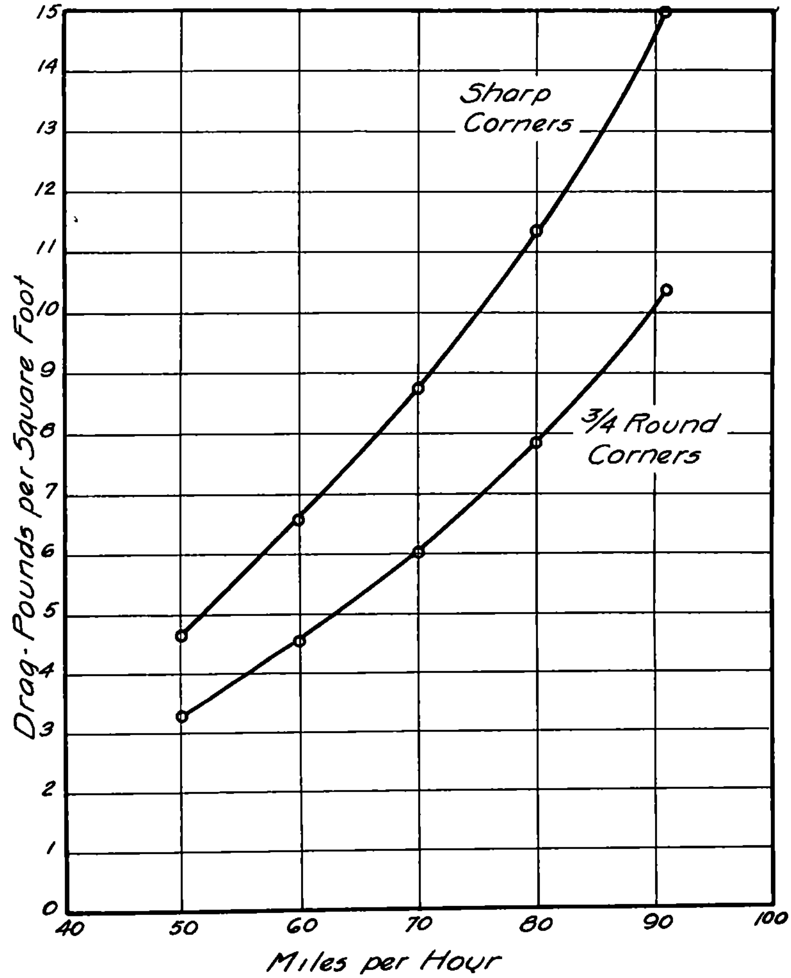

Figure 15. Drag Curves, Rectangular Model

All of the wind tunnel tests results are given in terms of "K" the drag coefficient, expressed in pounds per square foot of area. Although it was not exactly correct it was convenient to work out the results assuming the drag to vary as the square of the velocity. All data were plotted on logarithmic graph paper and a straight line faired through the experimental points The error involved in this method was within the limits of experimental error over the velocity range covered. These results were also plotted against speed Figure 15 shows such drag curves for the rectangular models with sharp and with rounded corners and edges Figure 16 is a typical curve sheet showing the effect of front section form variation

To briefly summarize the results, the values of "K" are represented by the lengths of the black bars on Figures 17, 18 and 19 At the top of Figure 17 is shown the "K" for model No 1, the rectangular model with sharp edges and corners, while No 2 shows the 30 per cent improvement made by rounding the corners and edges Comparison of models No 21 and 6 shows that a slight convex curvature of the sides of the center section will effect a reduction of over 20 per cent.

The next sixteen bars represent the variation which may be obtained by the use of different front sections grouped according to the rear section used with them The maximum reduction obtained by changing the front varies from 14 4 per cent with a poor rear section to nearly 50 per cent with the best rear section Figure 18 shows the same data grouped according to the front section used The maximum reduction obtained by changing the rear contours varied from 30 per cent with the poorest front section to nearly 60 per cent when tested with the best front section. This shows that the rear contour is most important It also shows that a poor front or rear contour may spoil the effectiveness of an excellent design of the other end of the body.

On Figure 19, models 24, 25, and 23 show that the round radiator shape is better than an inclined vee shape and has a drag 21 per cent less than that of a vertical plane shape The next three, Numbers 9, 13 and 17, show the superiority of the 45 degree inclination of the flat windshield over a vertical or a 22½ degree slant Numbers 23, 26 and 27 show that vee windshields do not improve air flow conditions for this model, possibly because it is streamlined principally in profile as seemed necessary from the practical standpoint Numbers 17 and 23 show the 21 per cent loss attending the use of a more conventional hood and front fenders The rather small effect of several wheel housing arrangements is shown by Numbers 2, 3, 4 and 5 The results obtained by testing the same model, No 28, by five different methods is also shown.

Method A—using the flat plate without removal of boundary layer.

Method B—using the plate with partial removal of the layer by applying one-half the maximum suction.

Method C—using the plate and applying full suction to remove about one-third of the boundary layer

Method D—hanging the model free in the air stream without making provision for the road surface

Method E—using the reflection method with two identical models.

The air flow about the models may be studied qualitatively by use of a light steel wand and a short length of silk thread By placing the

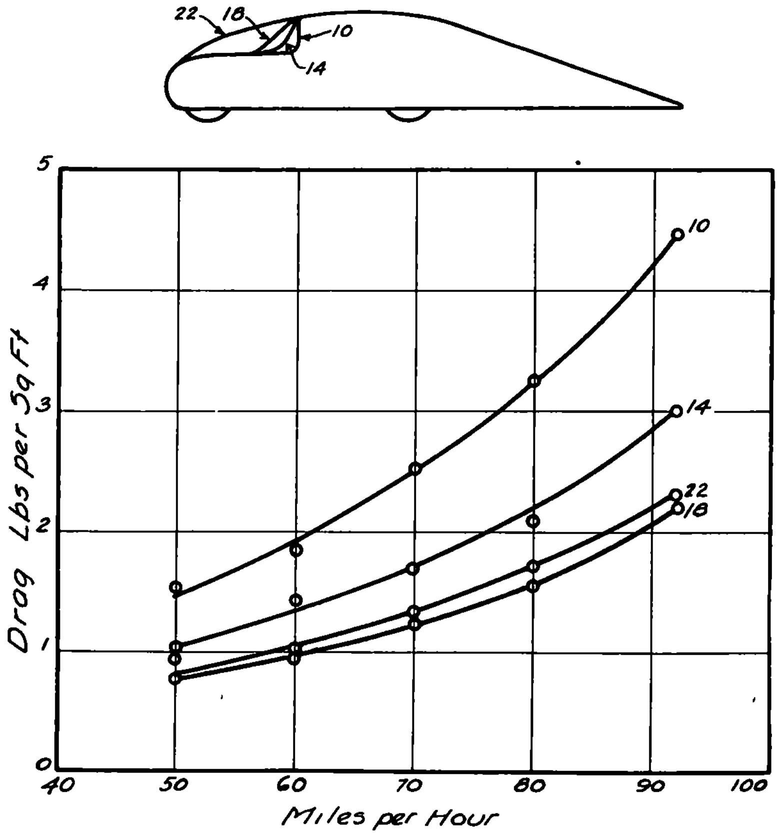

Figure 16. Drag Curves, Streamlined Rear, Various Front Sections

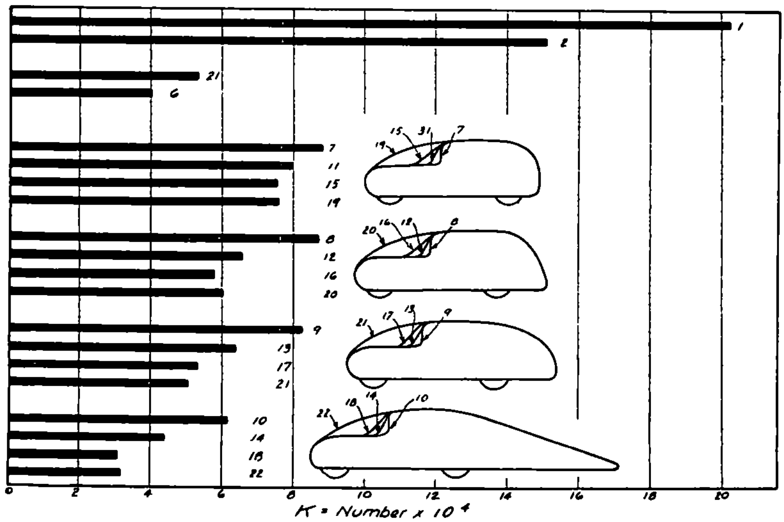

Figure 17. Values of K in the Equation $R = KAV^2$

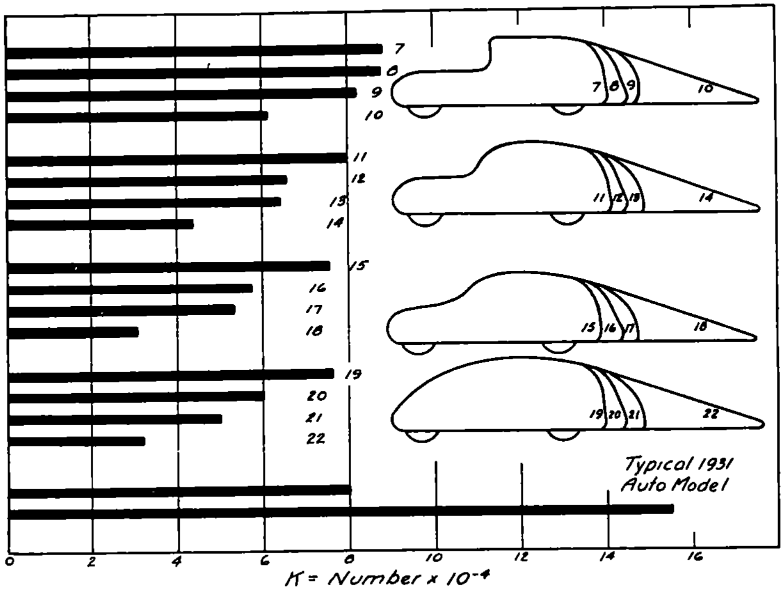

Figure 18. Values of K in the Formula $R = KAV^2$

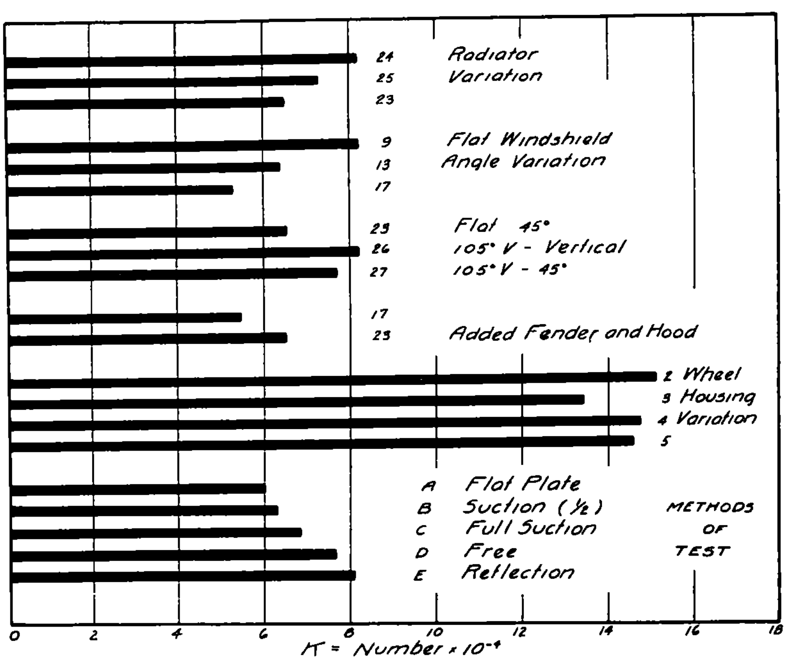

Figure 19 Values of K in the Formula $R = KAV^2$

tip of the wand with its thread in front of the car its position and direction may be noted and plotted on cross section paper Then moving the tip of the wand to where the free end of the thread had been the line may be continued step by step on the cross section paper as shown in Figures 20 and 21 for the model number 28 These lines indicate very clearly how a model may be improved from the aerodynamic standpoint

This is a progress report and full scale bodies are now being built to be tested on the road to find the relation between the wind tunnel data and the actual operation of the vehicle. The wind tunnel method is much cheaper, more rapid and furnishes much more information

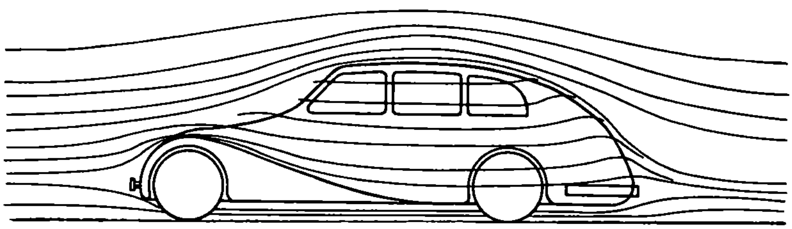

Figure 20. Air-Flow Diagram No 1 Model No. 28

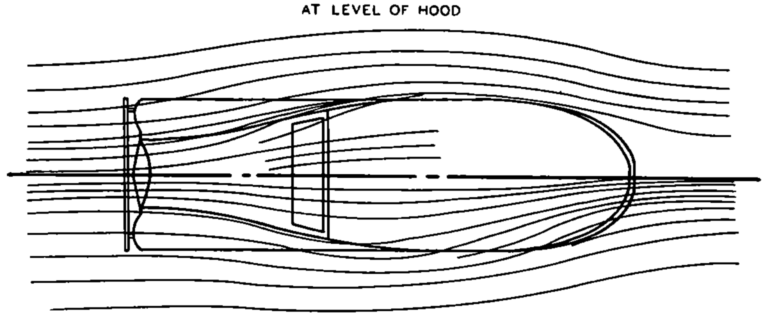

Figure 21. Air-Flow Diagram No. 2 Model No. 28

than is gained by the road test At high speeds it is important to know if the vehicle has a pitching moment or any tendency to lift off the ground These data are easily obtained in the wind tunnel.

We believe that the results obtained in our initial effort in the study of motor vehicle shapes indicate great possibilities of improvement The body makers' difficulty in applying the knowledge of streamlining now available is fully appreciated The public will spend more money for their conception of beauty in a car even though it has a lower speed and fuel mileage than a streamlined vehicle that looks like a monster. But the beautiful car of a decade ago looks uncouth today By judicious compromise between beauty and utility and by continual improvement of the aerodynamic characteristics we may finally accustom the public to a streamlined vehicle

TABLE I

FRONT SECTION VARIATIONS

	Model Number	K		Reduction Per Cent
		By Plate	By Reflection	
A Stub Rear Section				
(1) Vertical Windshield	7	0 000756	0 000886	0 0
(2) 22½° Windshield	11	0 000682	0 000799	9 7
(3) 45° Windshield	15	0 000647	0 000758	14 4
(4) Elliptical Front	19	0 000651	0 000763	13 9
B Medium (22½°) Rear				
(1) Vertical Windshield	8	0 000751	0 000880	0 0
(2) 22½° Windshield	12	0 000564	0 000661	24 8
(3) 45° Windshield	16	0 000494	0 000579	34 2
(4) Elliptical Front	20	0 000517	0 000606	31 1
C 45° Rear Section				
(1) Vertical Windshield	9	0 00704	0 000825	0 0
(2) 22½° Windshield	13	0 000548	0 000642	22 2
(3) 45° Windshield	17	0 000458	0 000537	34 9
(4) Elliptical Front	21	0 000430	0 000504	38 9
D Streamline Rear				
(1) Vertical Windshield	10	0 000526	0 000617	0 0
(2) 22½° Windshield	14	0 000377	0 000442	28 3
(3) 45° Windshield	18	0 000264	0 000309	49 8
(4) Elliptical Front	22	0 000273	0 000320	48 1

TABLE II

REAR SECTION VARIATIONS

	Model Number	K By Plate	K By Reflection	Reduction Per Cent
A Vertical Windshield				
(1) Stub Rear	7	0 000756	0 000886	0 0
(2) Medium Rear	8	0 000751	0 000880	0 7
(3) 45° Rear	9	0 000704	0 000825	6 9
(4) Streamline Rear	10	0 000526	0 000617	30 4
B 22½° Windshield				
(1) Stub Rear	11	0 000682	0 000799	0 0
(2) Medium Rear	12	0 000564	0 000661	17 3
(3) 45° Rear	13	0 000548	0 000642	19 7
(4) Streamline Rear	14	0 000377	0 000442	44 8
C 45° Windshield				
(1) Stub Rear	15	0 000647	0 000758	0 0
(2) Medium Rear	16	0 000494	0 000579	23 6
(3) 45° Rear	17	0 000458	0 000537	29 2
(4) Streamline Rear	18	0 000264	0 000309	59 2
D Elliptical Front				
(1) Stub Rear	19	0 000651	0 000763	0 0
(2) Medium Rear	20	0 000517	0 000606	20 5
(3) 45° Rear	21	0 000430	0 000504	33 9
(4) Streamline Rear	22	0 000273	0 000320	58 1

TABLE III

Plan Form Variations

	Model Number	K		Reduction Per Cent
		By Plate	By Reflection	
A Straight Sides	21	0 000430	0 000504	0 0
B Bulging Sides	6	0 000349	0 000409	18 8

TABLE IV

Radiator Variations

	Model Number	K		Reduction Per Cent
		By Plate	By Reflection	
A Flat-Vertical	24	0 000704	0 000825	0 0
B V-45°	25	0 000625	0 000733	11 2
C Curved	23	0 000556	0 000652	21 1

TABLE V

Wind Shield Variations

	Model Number	K		Reduction Per Cent
		By Plate	By Reflection	
A F at Windshields				
(1) Vertical	9	0 000704	0 000825	0 0
(2) 22½°	13	0 000548	0 000642	22 0
(3) 45°	17	0 000458	0 000537	39 4
Note—45° rear straight sides				
B V-Windshields				
(1) Flat—45°	23	0 000556	0 000652	0 0
(2) 105° V-Vertical	26	0 000705	0 000826	—27 7 0 0
(3) 105° V-45°	27	0 000657	0 000770	—18 3 6 7
Note—Plan form variation with front fenders				

TABLE VI

RECTANGULAR FORM

		Model Number	K		Reduction Per Cent
			By Plate	By Reflection	
A	Sharp Edges	1	0 00184	0 00215	0 0
B	Rounded Edges	2	0 00129	0 00151	29 9
A	45° Front and 45° Rear Sections	17	0 000458	0 000537	0 0
B	Same with Fender and Hood	23	0 000556	0 000652	—21 4

TABLE VII

WHEEL VARIATIONS

		Model Number	K		Reduction Per Cent
			By Plate	By Reflection	
A	Stub Wheels	2	0 00129	0 00151	0 0
B	Wheels Outside	3	0 00115	0 00135	10 8*
C	Wheel Pockets Open	5	0 00125	0 00147	3 1
D	Wheel Pockets Closed	4	0 00126	0 00148	2 3

*Disregarding the additional area due to the wheels, the variation is —1 16%

TABLE VIII

FINAL MODELS

		Model Number	K		A	B	E
			By Plate	By Reflection			
A	Flat Plate		0 00327	0 00327	0 0		15 57
B	1930 Sedan Model	29	0 00132	0 001547	59 7	0 0	6 28
C	Streamline Car Model	28	0 000685	0 000802	80 6	48 2	3 26
D	Streamline Form Model	23	0 000556	0 000651	83 0	57 9	2 65
E	Perfect Streamline Body		0 000210	0 000320	93 6	84 1	1 00

TABLE IX

Methods of Testing

		Model Number	K	Variation—Per Cent			
				100% Method C		100% Method E	
A	Flat Plate	28	0 000594	86 8	−13 2	74 0	−26 0
B	Suction (½)	28	0 000621	90 6	− 9 4	77 3	−22 7
C	Full Suction	28	0 000685	100 0	0 0	85 2	−14 8
D	Free	28	0 000761	111 0	11 0	94 5	− 5 5
E	Reflection	28	0 000803	117 2	17 2	100 0	− 0 0

TABLE X

Summary

	Model Number	K		Reduction Per Cent	Factor
		By Plate	By Reflection		
Flat Plate			0 00327		15 57
Box—Sharp Corners	1	0 00184	0 00216		8 76
Box—Rounded Corners	2	0 00129	0 00151		6 14
Box—R. C —Wheels Outside	3	0 00115	0 00135		5 48
Box—R C —Wheel Pockets Closed	4	0 00126	0 00148		6 00
Box—R C —Wheel Pockets Open	5	0 00125	0 00146		5 95
Bulging Model—45° x 45°	6	0 000349	0 000409		1 66
Vertical Windshield—Stub Rear	7	0 000756	0 000886	0 0	3 60
Vertical Windshield—Medium Rear	8	0 000751	0 000880	0 7	3 51
Vertical Windshield—45° Rear	9	0 000704	0 000825	6 9	3 35
Vertical Windshield—Streamline Rear	10	0 000526	0 000616	30 4	2 50
22½° Windshield—Stub Rear	11	0 000682	0 000799	9 8	3 25
22½° Windshield—Medium Rear	12	0 000564	0 000661	25 3	2 69
22½° Windshield—45° Rear	13	0 000548	0 000642	27 5	2 61
22½° Windshield—Streamline Rear	14	0 000377	0 000442	50 1	1 80
45° Windshield—Stub Rear	15	0 000647	0 000758	14 4	3 08
45° Windshield—Medium Rear	16	0 000494	0 000579	34 6	2 35
45° Windshield—45° Rear	17	0 000458	0 000536	39 4	2 18
45° Windshield—Streamline Rear	18	0 000264	0 000309	65 1	1 29
Elliptical Front—Stub Rear	19	0 000651	0 000763	13 9	3 10
Elliptical Front—Medium Rear	20	0 000517	0 000606	31 6	2 46
Elliptical Front—45° Rear	21	0 000430	0 000504	43 1	2 15
Elliptical Front—Streamline Rear	22	0 000273	0 000320	63 9	1 30
Streamline Form Model	23	0 000556	0 000651	26 4	2 65
Streamline Form Flat Radiator	24	0 000704	0 000825	6 9	3 35
Streamline Form V-45° Radiator	25	0 000625	0 000732	17 3	2 98
Streamline Form 105°V-Vertical Windshield	26	0 000704	0 000825	6 9	3 35
Streamline Form 105°V-45° Windshield	27	0 000657	0 000770	13 0	3 13
Streamline Car Model (Final)	28	0 000685	0 000802	9 4	3 26
1930 Sedan Model	29	0 001320	0 001547		6 28
Perfect Streamline Body		0 000210	0 000246	72 2	1 00