MOTOR VEHICLE OPERATING COSTS, ROAD ROUGHNESS AND SLIPPERINESS OF VARIOUS BITUMINOUS AND PORTLAND CEMENT CONCRETE SURFACES *

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SYNOPSIS

During 1941-42, tests were run in Kansas, Missouri, and Wyoming on five types of bituminous surfaces and on two types of concrete surfaces, each with widely different surface characteristics These tests were a continuation of the study conducted along the same lines on untreated gravel and concrete roads in Iowa in 1938-39 The magnitude of these tests is indicated by the fact that they involved detailed observations and measurements of gasoline mileage, oil mileage, tire wear, vehicle repairs and maintenance, road roughness, and road slipperiness on nine major road surface types for a total of 450,000 vehicle miles with eight test cars, a tow-truck, and two trailers By spreading this program over four States and over four years including all four seasons of the year, the results may be considered to be fairly representative of vehicle operation on a large proportion of the mileage of the highways of the United States

The tests on the concrete and bituminous surfaces covered indicated that differences in vehicle operating costs on these two major road surface types are negligible if they are maintained with a moderately smooth riding surface

In view of the critical rubber shortage today, the results of the measurements of tire wear and of road slipperiness were two of the most important features of this investigation The wear at 60 m p h average speed on the most abrasive surface was found to be 11 times greater than the wear at 35 m p h on the least abrasive surface The effect of speed in tests on the same surface indicated wear rates two to four times greater at 60 m p h than at 35 m p h The effects of type of surface were even greater with wear rates for the same speed being five times greater on the abrasive chat rock chip bituminous and broomed concrete surfaces than on the glazed sandy and the limestone chip bituminous surfaces In the present war emergency, the use of a seal coat which provides a slight excess of asphalt, without causing bleeding and a slippery road condition when wet, is recommended as an effective and justifiable method to reduce tire wear This should strictly be an emergency measure for the duration only while the national speed limit of 35 m p h remains in effect, since the skidding hazard at speeds above 35 m p h on surfaces of this type when wet is a continual cause of accidents

Reports on research in the field of highway economics have been given a prominent place at the annual meetings of the Highway Research Board ever since the Board was established in 1920. Committee No. 1 of the Board was the Committee on Economic Theory of Highway Improvement with T. R. Agg as chairman It was recognized at that early date that vehicle operating costs varied greatly with the type and condition of roads and that despite the increased costs for road construction and maintenance, tremendous savings in vehicle operating costs could be realized by road improvements for which these savings were properly evaluated. At the time when Committee

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* A report of the data obtained during 1941-42 on Project 219 of the Engineering Experiment Station with the Public Roads Administration of the U S Public Works Agency, Washington, D C, cooperating

No. 1 was organized Dean Agg started the extensive experimental studies at the Iowa Engineering Experiment Station involving thousands of road tests of many types with cars and trucks on all kinds of roads, a program which has been carried forward at this station for more than 20 years For the past 10 years, the writer has been in charge of this work and has presented reports from time to time at the annual meetings of the Highway Research Board on various phases of this testing program All of the important items of vehicle operation which are influenced by the type and condition of the road surface have been investigated although the greatest emphasis has been on the determination of the cost differentials in vehicle operation due to the roadway type and condition The results of these tests have clearly demonstrated that it pays to build improved highways, that transportation is cheaper, faster, more comfortable, and in practically all respects more satisfactory on roads and streets improved to high standards of construction and maintenance based on the traffic requirements than on cheaply built roads or on roads built to low standards of construction and maintenance with little or no regard for the traffic requirements

In this report results are presented of tests made during 1941-42 to determine the vehicle operating costs, road roughness, and road slipperiness of various bituminous and portland cement concrete road surfaces The tests were a continuation of the study on untreated gravel and portland cement concrete described in 1939[1] The investigation has been conducted by the Iowa Engineering Experiment Station with the U. S. Public Roads Administration cooperating. The State highway departments of Iowa, Kansas, Missouri, and Wyoming also cooperated

OBJECTIVES AND NEED FOR INVESTIGATION

Portland cement concrete surfaces and the various bituminous types provide more than 300,000 miles of roads in the State highway systems of the United States In addition there are more than 800,000 miles of untreated roads for which a dustless bituminous or concrete type of surface appears to be economically justified. In view of the importance of the various types of these road surfaces, there is need for knowing accurately the cost differentials in motor vehicle operation which are due to variations in roadway type and condition in connection with the planning of programs of construction, maintenance, and relocation of main routes to save distance, to relieve congestion, and to increase the safety of driving

The present war emergency has placed a premium upon information leading to the conservation of rubber, motor fuel, oil, vehicles, and related highway and highway transport materials The results of this investigation should provide useful information along these lines.

DIFFERENCES IN SURFACE TYPES AND SCOPE OF INVESTIGATION

In planning these tests, it was recognized that there are certain fundamental differences in the various types of concrete and bituminous road surfaces However, as far as their effect on vehicle operation is concerned, the most important differences are in their surface characteristics Today there are two types of surface finish commonly used in the construction of concrete pavements and three types in the construction of bituminous roads. For the concrete pavements, they are. (1) the belted finish and (2) the broomed finish. For the bituminous surfaces they are (1) the plain seal coat finish or the use of a seal coat which causes asphalt to bleed to the surface and produce a glazing effect over the surface.

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[1] *Proceedings*, Highway Research Board, Vol 19, p 68 (1939)

(2) the sandy or sandy-gravel seal coat finish, and (3) the crushed rock or gravel chip finish developed by the use of an asphalt seal coat with crushed stone or gravel chips as cover material There are many variations in the degree of fineness or coarseness of the surface textures, especially of the bituminous surfaces There are also variations due to the hardness and sharpness of the aggregate To determine the differences in results in vehicle operation caused by these variations, tests were run over two different types of concrete pavement and five different types of bituminous surfaces.

The surfaces selected as most suitable for this investigation included 370 miles of bituminous surfaces in Kansas, 40 miles of bituminous surfaces in Wyoming, 150 miles of belted concrete in Kansas and 18 miles of broomed concrete in Missouri In the previous study of concrete and gravel roads, tests were run on 233 miles of belted concrete and 237 miles of untreated gravel in Iowa during a two year period from 1938 to 1940 The magnitude and comprehensive nature of all of these tests is indicated by the fact that they involved detailed observations and measurements of the important vehicle operation items such as gasoline mileage, oil mileage, tire wear, vehicle repairs and maintenance, road roughness, and road slipperiness on nine major road surface types for a total of 450,000 vehicle miles with eight test cars, a tow-truck, and two trailers. By spreading this testing program over four large states and over four years, including all four seasons of the year, the results may be considered to be representative of vehicle operation on a large proportion of the mileage of the highways of the United States

THE TESTING PROGRAM

Test Cars

The vehicle operating cost studies on the concrete and bituminous surfaces in 1941 and 1942 were made with three standard 1941 Plymouth two-door sedans which were identical in every respect (Fig 1) The 1938-40 tests on Iowa concrete and gravel roads were made with five Chevrolet test cars described in the 1939 report. The average loaded weight of each Plymouth test car was 3,420 lb and for each Chevrolet test car 3,430 lb The tires used on the Plymouth cars were the standard 6.00 by 16-in four-ply 100-level[2] type and were of the same type and brand used on the Chevrolet test cars in 1938-40 As in the previous study, the tires were special only to the extent that they were furnished by the manufacturer from the same run of tread stock to assure uniformity in the manufacturing process and uniformity in the wear properties as far as the type of rubber was concerned. The similarity in the loaded weights of the Plymouth and Chevrolet test cars and the uniformity in the tires used for the 1938-40 and the 1941-42 tests, were important advantages in making the test results, particularly the tire wear, comparable for these two different makes of cars and for the surfaces in both the 1938-40 and the 1941-42 tests

Figure 1. One of the Three Identical Test Cars Used in the 1941-42 Tests

[2] 100-level tires are the tires regularly used as original equipment on new cars and their price is the 100 per cent price level or base price upon which tires of lower or higher price levels are rated

Test Routes

In the major study with the Plymouth test cars, routine driving tests were run on a year-round basis on a bituminous route and on a portland cement concrete route in east central Kansas. One of the cars, Plymouth No. 2, was driven exclusively on a bituminous circle type route 312 miles long, and another test car, Plymouth No. 1, was driven exclusively on a belted portland cement concrete route 160.5 miles long which cut diagonally across the bituminous route. A round trip on the concrete route was 321 miles. The third test car, Plymouth No. 3, was driven on short sections (18 to 20 miles long) of various types of concrete and bituminous surfaces for a sufficient mileage (4,000 to 5,000 miles on each surface) to determine the effect of these surface types and textures on the major items of vehicle operation, which were correlated with the measurements of road roughness and road slipperiness of these surfaces made at the same time.

The tests with Plymouth No. 3 included the following surfaces, (1) a glazed sandy bituminous (excess asphalt bleeding type, very slippery when wet), (2) a sandy bituminous (a non-bleeding sandy texture), and (3) a coarse-textured chat rock chip bituminous surface. These surfaces were located in central Kansas and the tests were run during the fall of 1941. During the spring of 1942 tests were run, with the same car and under about the same weather conditions as prevailed during the previous fall, on (1) broomed concrete in Missouri, (2) a limestone chip bituminous surface in Wyoming, and (3) a crushed gravel chip bituminous surface also in Wyoming.

The mileage of various surface types on the two long test routes in Kansas on which the major study was made in 1941-42 is given in Table 1.

It will be noted that the concrete route included old and new concrete with surface textures ranging from a coarse sandy belted texture to a smooth belted texture. The coarse sandy texture, as shown in the close-up photographs in Figure 2, has surface characteristics somewhat similar to broomed concrete and is the type of belted surface finish widely used on concrete pavements in recent years to provide a non-skid type surface. The belt finish construction used on the older concrete pavements provided a finer sandy texture with belt markings less distinct than on the newer concrete pavements. The wear due to traffic also caused the older concrete surfaces to have a smoother and less abrasive surface texture than that observed on the newer pavements.

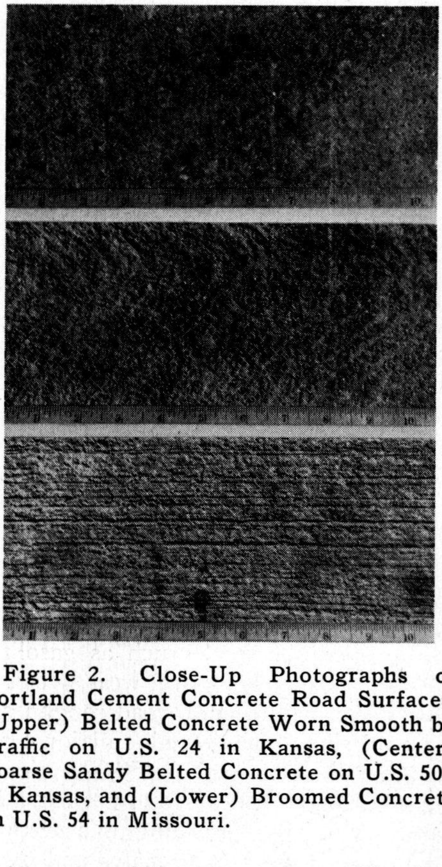

Figure 2. Close-Up Photographs of Portland Cement Concrete Road Surfaces. (Upper) Belted Concrete Worn Smooth by Traffic on U.S. 24 in Kansas, (Center) Coarse Sandy Belted Concrete on U.S. 50S in Kansas, and (Lower) Broomed Concrete on U.S. 54 in Missouri.

The bituminous route was predominantly of the sandy bituminous type but other important types of surfaces were also included, such as, the hard abrasive chat rock chip, the softer limestone chip, and the mosaic gravel type which consisted of pebbles with rounded edges either placed in such a way or worn and oriented by traffic in such a way as to provide a smooth mosaic pattern A survey of the bituminous route was made during the hottest part of the summer (on July 17, 1942) to determine the extent to which bleeding of asphalt was evident on each of these surface types The results of this survey, shown in Table 1, indicated that the largest amount of bleeding was developed on the sandy bituminous, that equal mileages of bleeding and non-bleeding sections were found on the chat rock chip sections and the least amount of bleeding was observed on the limestone chip and the mosaic gravel sections.

A large part of the bituminous route was built with a good stabilized base but more than half of the mileage was built with a cheaper, less stable base and with a surface which was subject to a certain amount of spring break-up and raveling

TABLE 1

CLASSIFICATION OF ROAD SURFACES ON THE PORTLAND CEMENT CONCRETE AND BITUMINOUS ROUTES IN KANSAS ON THE BASIS OF AGE AND SURFACE TEXTURE TYPES

PORTLAND CEMENT CONCRETE ROUTE

Type of surface	Year built	Total miles[a]	Percentage of total miles
Coarse sandy belted texture ..	1931–40	147.70	46.0
Medium sandy belted texture	1927–32	89 40	27 9
Smooth belted texture	1921–27	42.03	13 1
Sandy bituminous	1931–39	15 86	4 9
Brick, concrete and asphalt in cities and towns		26 08	8 1
		321 07	100 0

[a] The values given are for a round trip The actual length of each section or surface type is one half of the length given in table

BITUMINOUS ROUTE

Type of surface	Year built	Mileage observed July 17, 1942		Total miles	Percentage of total miles
		Bleeding	Non-bleeding		
Sandy texture	1932–39	90.47	71 24	161.71	51.8
Chat rock chip	1931–40	22 53	22.92	45 45	14 6
Limestone chip	1933–40	5 83	11 62	17 45	5.6
Mosaic gravel	1935–39	7 23	17 77	25 00	8 0
Untreated gravel (road under repair)		.	.	5 76	1.9
Smooth belted portland cement concrete	1923–27			43 44	13.9
Brick, concrete and asphalt in cities and towns				13 21	4.2
				312 02	100 0

especially along the edges. Except during the winter season, certain short sections of the bituminous route were always torn up and under repair. This mileage is shown in Table 1 as less than 2 per cent of the total mileage for July 17, 1942, and may be considered as typical of the mileage of road under repair for the entire year.

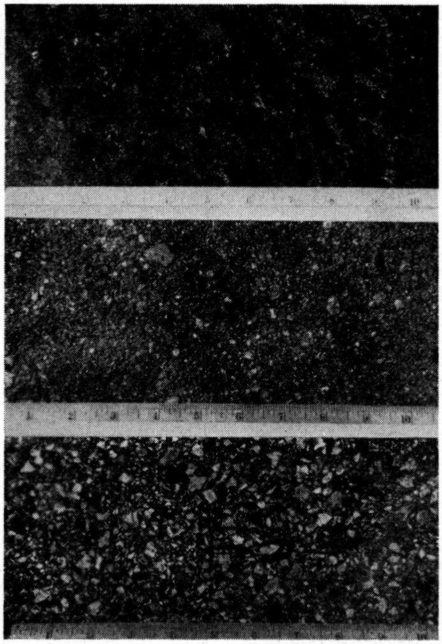

Figure 3. Close-Up Photographs of Bituminous Surfaces in Kansas. (Upper) Glazed Sandy Bituminous on Kansas Route 96, (Center) Sandy Bituminous on U.S. 77, and (Lower) Chat Rock Chip Bituminous on Kansas Route 99.

The close-up photographs in Figs. 2, 3, and 4 clearly indicate the major differences in surface texture of all of the types of surfaces on which tests were run.

PRELIMINARY DEVELOPMENT WORK WITH THE CARS

The three new Plymouth test cars were checked thoroughly and brought up to the manufacturer's specifications for all adjustments by an expert mechanic, assigned to do all the servicing and mechanical work on the cars. They were then broken in according to a definite schedule in which speeds were raised from 30 to 70 m.p.h. in 5 m.p.h. increments every 300 miles. Car 1 was broken in on the concrete test route in Iowa used in the 1938-40 study. Car 2 was broken in on a bituminous route near Ames. Car 3 was alternated on the concrete and the bituminous route in the break-in runs.

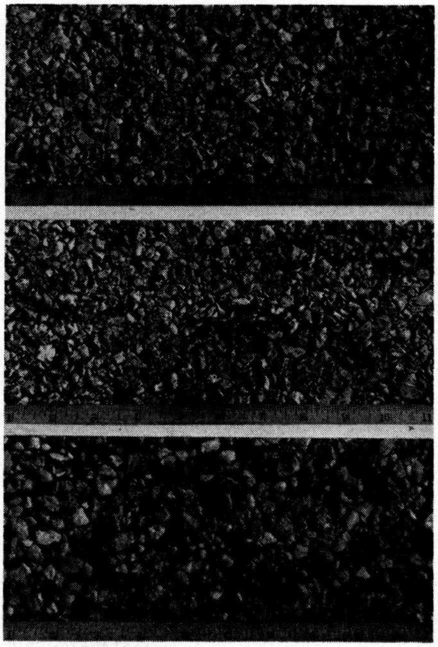

Figure 4. Close-Up Photographs of Bituminous Surfaces in Wyoming on U.S. 30. (Upper) Limestone Chip Bituminous, (Center) Same Surface with Slight Excess Amount of Asphalt, and (Lower) Crushed Gravel Chip Bituminous.

Before the break-in runs were started each car was equipped with an instrument box with stop watches, clocks, thermocouple switch, gauges, and electric counters used in the routine tests and in the special tests to obtain records of important items of vehicle operation such as, gasoline consumption, the actual running time, the number of clutch and brake applications, the braking time, the temperature of gasoline, oil, air, etc., the manifold vacuum, and the time over a measured mile or two mile course for checking the accuracy of the speedometers. Driver control instruments consisting of a Tapley decelerometer and a ball bank indicator were mounted on the dash of the car (Fig. 5). The decelerometer was used to aid the driver to conform to a standard stopping rate of 8 ft. per sec. at which all regular stops were to be made. The ball bank indicator was used to aid the driver in holding the speed on curves at or slightly below the safe and comfortable maximum speed as indicated by a ball bank angle of 10 deg.

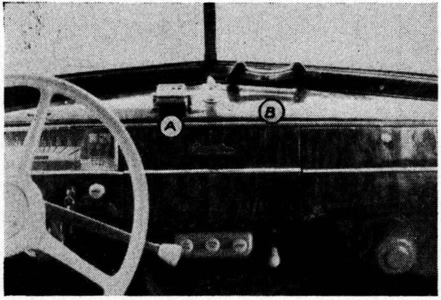

Figure 5. Driver Control Instruments. (A) Tapley Decelerometer to Control Rate of Stopping, (B) Ball Bank Indicator to Control Maximum Speed on Curves.

After a final checkup following the break-in runs, the cars were calibrated by means of standard performance tests to determine the relative performance characteristics of each car under like operating conditions. The tests were run on a straight level concrete test course north of Ames and consisted of maximum acceleration in all gears, deceleration or coasting in high gear and in neutral, and gasoline consumption over a 5-mile course at each 10-mile speed from 10 to 70 m.p.h. In these tests a fifth wheel was used for accurate speed determinations. A printing chronograph (Fig. 6) was used to measure time to the nearest 0.01 sec. and thereby assure the desired accuracy in a comparison of the performance characteristics of the cars

GENERAL PLAN OF OPERATION

Tests with Cars 1 and 2 on the Two Major Routes in Kansas

The general plan of operation on the two major routes in Kansas with the two Plymouth test cars differed from the plan followed in the Iowa tests described in the 1939 report with respect to two items, (1) only one car was used on each surface instead of two operated in tandem with a spacing of about 300 yards as in the Iowa tests, and (2) the Kansas tests were run by driving on both surfaces on the same day instead of driving on one surface one day and on the other surface the next day which was the plan followed in the Iowa tests. The results in operating costs obtained when two cars were run on the same surface at the same time were so nearly identical for the two years of operation in Iowa, that it seemed unwise to go to the expense of running the two additional cars required to do

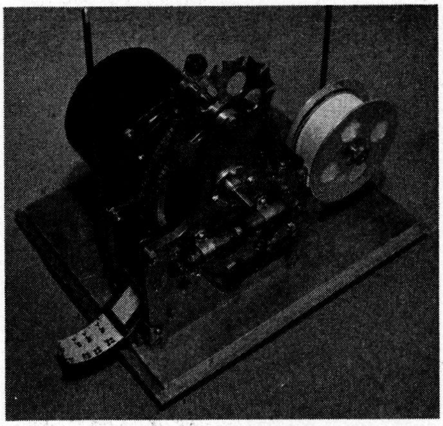

Figure 6. Printing Chronograph Records Time Measurements in 0.01-Sec. Units

this in the Kansas tests. By running the two cars on the same day on two test routes as close together as the concrete and bituminous routes in Kansas, the variations due to weather effects, such as wind velocity and air temperature, were considered to be of no practical significance.

In the routine tests four driver-observers (two to each car) were sent out each day. The men alternated driving every 50 miles and were rotated from one car to the other on successive days. At the 50-mile stops, wind velocity determinations were made using a four cup anemometer (Fig. 7), tire pressures were checked using an accurately calibrated Bourdon tube type pressure gauge with suitable fittings (Fig. 8), and humidity readings were taken with a hand-aspirated psychrometer (Fig. 9). Tests were run at four nominal speeds, 35, 45, 55, and 65 m.p.h. on each route. Four runs at each

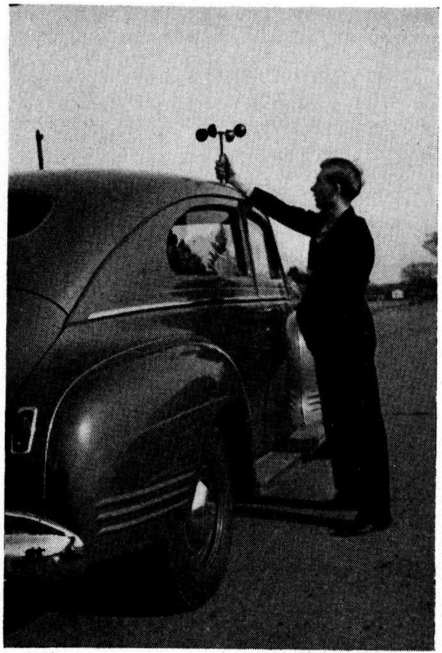

Figure 7. Four-Cup Anemometer Used to Measure Wind Velocity

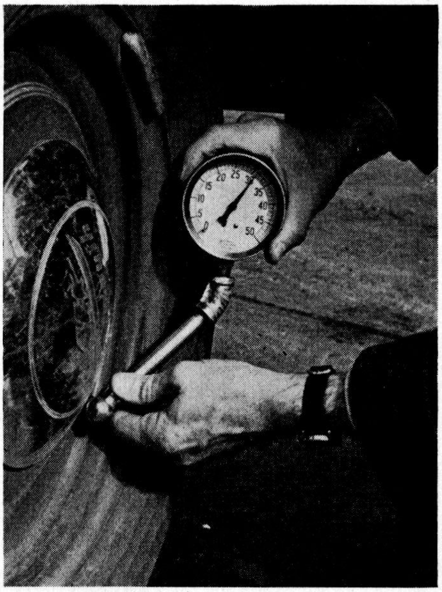

Figure 8. Bourdon Type Pressure Gauge Used to Provide an Accurate Measure of Tire Pressure.

Figure 9. Hand Aspirated Psychrometer Used to Measure Air Temperatures and Humidity.

speed (about 1,300 miles) were completed before tire and overall gasoline and oil measurements were taken for the given speed. On each route, test sections were laid out 4 to 10 miles long. On these sections special measurements were made to determine variations in gasoline mileage due to differences in surface texture, grades, curves, and road roughness. Accurate gasoline and oil readings were taken at the beginning and end of each run. Readings were also taken from the gasoline meter electric counters at the beginning and end of each specially marked section together with the readings of stop watches, brake and clutch counters, and the various temperatures using thermocouples for gasoline, water, oil, and air for each car.

A check on the amount of gasoline used during each speed series was obtained by draining the gas tank and measuring the volume of gasoline This amount subtracted from that added during the test provided an accurate measure of the gasoline used. The crankcase oil was also drained at the end of each speed series, and carefully measured by weighing. Oil changes were based on the results of tests of the used oil by the Kansas Highway Commission testing laboratory. During the summer months changes were made on an average of about every 3,000 miles, while during the rest of the year, changes every 4,000 miles were adequate, to keep the oil clear and clean with only a trace of carbon, sludge, gummy residues, and abrasives which if present in large amounts would have caused ring sticking, high oil consumption, and excessive wear on engine parts The cartridges of the oil filters were changed after they had been used 5,000 to 7,500 miles. The garage mechanic inspected and lubricated each car at the end of each speed series.

TABLE 2

VEHICLE OPERATION DATA FOR ONE YEAR'S TEST DRIVING ON PORTLAND CEMENT CONCRETE AND BITUMINOUS ROADS IN KANSAS
1941–1942

Item	Car No	Type of surface	Fall, 1941	Winter, 1942	Spring, 1942	Summer, 1942
Miles traveled	1	Concrete	7,547 1	7,901 3	7,934.5	7,928 0
	2	Bituminous	7,548 2	7,838.0	7,986 9	7,688 7
Average speed, m p h	1	Concrete	43 78	43 62	42 94	44 54
	2	Bituminous	44 51	45 10	44 98	44 92
Gasoline, miles per gallon	1	Concrete	19.02	18 71	19 94	19 96[a]
	2	Bituminous	18 56	18 32	19 14	18 96[a]
Oil, quarts per thousand miles[b]	1	Concrete	2 25	2 28	2.02	2 40
	2	Bituminous	2 52	2 55	2 50	2 73
Tires, rate of wear, 0 001 in per thousand miles[c]	1	Concrete	7 51	7 66	6 81	6 77
	2	Bituminous	8 19	8 24	8 14	7 97

[a] Note difference in calibration curve of 2 cars for this season (In calibration tests average gasoline mileage on car 1 averaged 2 0 miles per gallon higher than on car 2 at end of season under identical operating conditions)

[b] Includes oil added and also refills after draining oil

[c] Average wear per tire for each of five tires.

The general vehicle operation data for the cars on the two major routes in Kansas are given in Table 2 It will be noted that the total distance traveled per car during each season ranged from 7,550 miles to 8,000 miles At the end of each season's runs the standard performance tests were conducted on a level three mile concrete test course on U S 24 twenty miles west of Topeka. This test course was similar to the test course near Ames

The results of all tests were summarized as soon after the test runs were made as practicable and complete summary tables and charts were prepared from the daily records for each speed series and for the runs for each season Every effort was made to keep a continual check on the performance of the cars and on the accuracy of the daily records. While the lubrication and the engine and car inspection service was better than for the average car, it was similar in many respects to that provided today in large fleet operation. On the basis of these measurements and the general plan of operation just described, the vehicle operating costs so obtained are conservative and are minimum rather than average values for the given road conditions.

An important principle which governed all our operations was that both cars were to be operated and serviced in like manner in every respect so that the resulting costs would reflect as nearly as possible the true costs on these important surface types

TESTS WITH CAR 3 ON THE SPECIAL TYPES OF BITUMINOUS AND CONCRETE ROAD SURFACES

The tests with car 3 on the six different surface types followed the same general plan as the tests with cars 1 and 2 but they were run independently of cars 1 and 2 and they were confined to three speeds: 35, 55, and 65 m p.h. Since the test courses selected for car 3 were only 18 to 20 miles long, thereby making it possible to confine the tests to one surface type and texture, it was necessary to run back and forth over each section of a given type each day at the scheduled speed until 1,000 to 1,200 miles, required for accurate tire measurements, was accumulated at that speed Gasoline and oil measurements were made in the same way as with cars 1 and 2. The lubrication and car inspection service also followed the standard procedure, although since this car was operated in widely separated locations and the work was done at six different garages by different mechanics it could hardly be expected that the engine performance on this car, especially in the item of gasoline mileage, would be identical with the performance of cars 1 and 2 For this reason greater weight should be given to the gasoline mileage results for the various surface textures with cars 1 and 2 than with car 3 The greatest value of the tests with car 3 was that accurate data on tire wear were provided for each of six different types of road surfaces and since the tires on all the test cars during the past four years were identical, these results could be correlated with the results of tire wear for cars 1 and 2 and also with the results for the Chevrolet test cars on the concrete and gravel roads in Iowa.

SPECIAL TESTS FOR MEASURING SURFACE TEXTURE, ROAD ROUGHNESS, AND COEFFICIENTS OF FRICTION

During the period when routine driving tests were under way on the various road surfaces, many special tests were run on all the surfaces to determine road surface characteristics which had a variable effect on such items in vehicle operation as gasoline and oil mileage, tire wear, riding comfort, braking distance, and resistance to skidding The special tests included measurements of surface texture by means of close-up photographs and by the use of a road profilometer (Fig 10) which provided a record of the surface profile or texture on a magnified scale. Road roughness measurements were taken over every mile of road surface on which tests were run by using the standardizable Public Roads Administration Road Roughness Indicator (Fig. 11) which was built specially for this project. Stopping distance tests were run on all of the surfaces in the wet and dry condition using one of the Chevrolet test cars equipped with a stopping distance gun and all the other test equipment to obtain an accurate measure of stopping distances (Fig. 12). Coefficients of friction were computed from the results in the stopping distance tests and were also measured by towing-braking tests using a high speed Four Wheel Drive tow truck and a special trailer equipped with air brakes and an integrating dynamometer to measure the braking forces (Fig. 13). The tow truck

Figure 10. Road Profilometer Used to Measure Surface Texture

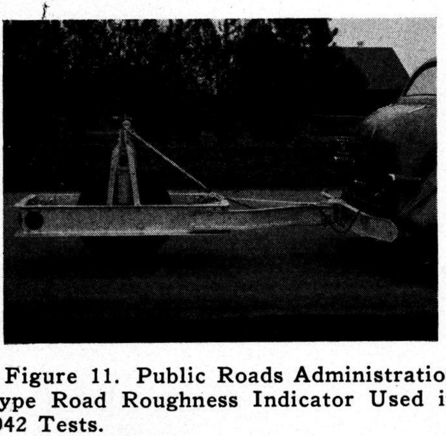

Figure 11. Public Roads Administration Type Road Roughness Indicator Used in 1942 Tests.

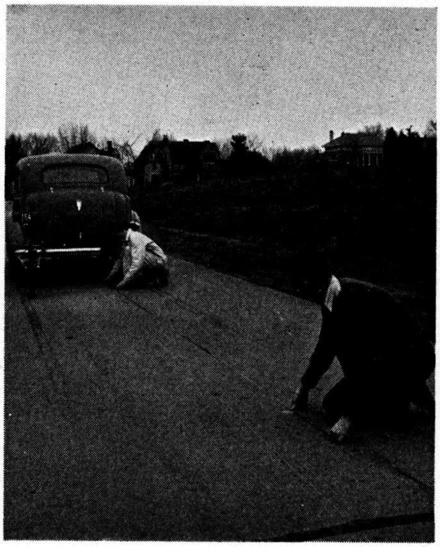

Figure 12. Measuring Coefficient of Friction by Means of Stopping Distance Test.

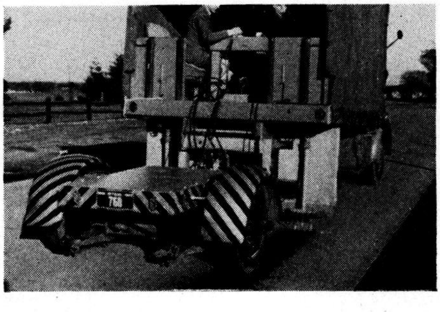

Figure 13. Showing Method of Sprinkling Surface in Towing-Braking Tests

carried a 250-gal water tank and was equipped with a high pressure pump and sprinkler system to apply water on the road surface for the braking tests with the surface in the wet condition (Fig. 13).

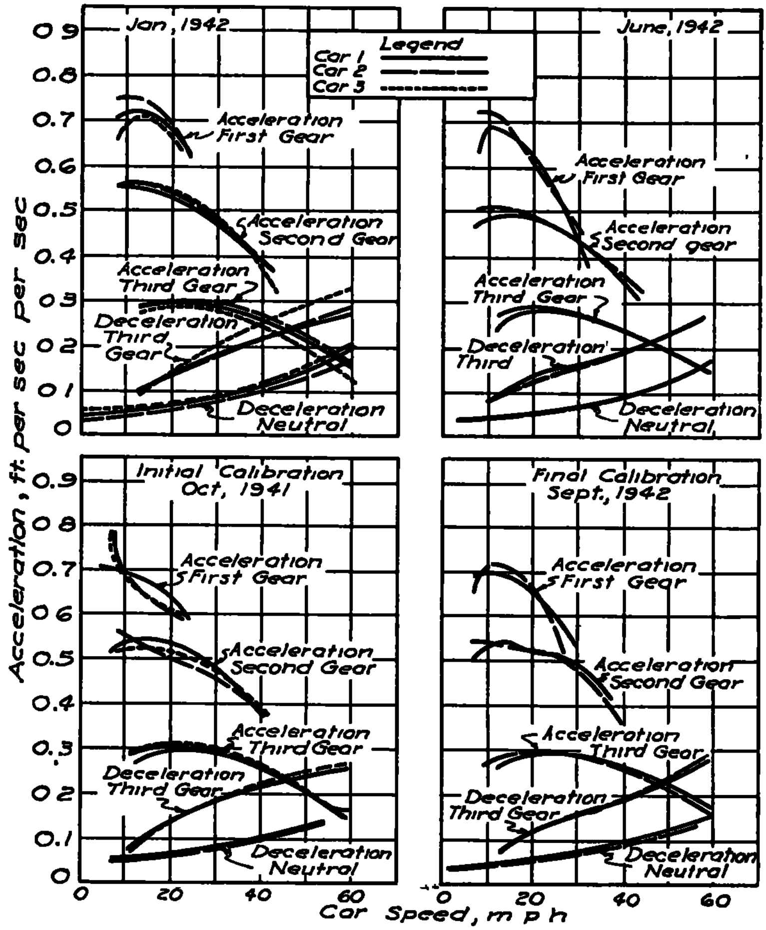

Figure 14. Acceleration and Deceleration Characteristics During 1941 and 1942 Tests on Kansas Road Surfaces

RESULTS

The results of the most important phases of the tests on the various portland cement concrete and bituminous surfaces have been summarized in Tables 1 to 5 and in Figures 14 to 27 The items covered are. the general vehicle operation data and operating costs on the various surfaces which included such items as miles driven, average speed, gasoline mileage, acceleration in the various gears, rolling, air, and engine resistance under standard conditions to determine the uniformity in the performance of the test cars; the analysis of gasoline mileage at various speeds on each surface; the analysis of tire wear including the effect of speed variations and wheel position; the measurement of road roughness and of surface textures by the use of a road profilometer and close-up photographs;

and the measurement of road slipperiness in terms of coefficients of friction and the stopping distances in braking tests.

Standard Performance Tests

Typical results of the acceleration and deceleration tests for the Plymouth test cars are given in Figure 14 for tests conducted at various times during 1941 and 1942 in Kansas. The differences in the general car performance characteristics as revealed by these tests were remarkably small. This indicates that for all practical purposes the cars were identical and were kept in good adjustment. The gasoline mileage results in the calibration tests made at the beginning of the study and at the end of each season are given in Figure 15 In the original calibrations, car 1 gave about 1 mile per gallon less mileage at all speeds than car 2 However, by the end of the same season, the mileage was identical for both cars and remained so for the rest of the year up to the last calibration when the gasoline mileage for car 1 was about 1½ miles per gallon more than for car 2. The composite calibration values for both cars for the entire year were practically identical and therefore correction factors were not necessary to adjust for differences in their gasoline mileage characteristics.

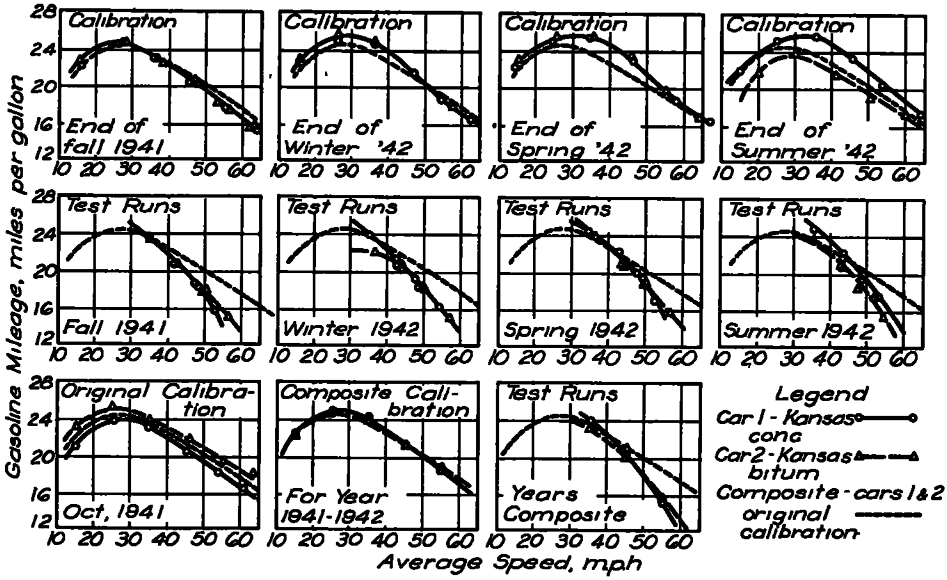

Figure 15. Gasoline Mileage Results for One Year's Test Driving on P.C. Concrete and Various Bituminous Surfaces in the State of Kansas

Comparison of the results obtained in the standard performance tests with the 1938 Chevrolet test cars and the 1941 Plymouths is of interest because they were made under very nearly identical conditions and reflect the improvement in the performance of the later cars. The gasoline mileage for the 1941 Plymouth cars was 2 miles per gallon greater than for the 1938 Chevrolets over the entire speed range from 20 to 65 m p h. This improved mileage was due largely to the use of a lower gear ratio, 3 90 to 1, on the Plymouths as compared to 4 222 to 1 on the Chevrolets, which resulted in lower rates of acceleration in high gear This reduction was not so noticeable in second and low gear as in high gear when compared with the values obtained for the Chevrolets Although the 1941 Plymouths appeared to have an improved streamlined design as compared to the 1938 Chevrolets, the results of the coasting tests in neutral on a level concrete surface for a zero wind velocity condition indicated slightly higher rates of deceleration for the Plymouths than for the Chevrolets. This difference was not due to a change in the streamlining but largely to the fact that the frontal area of the Plymouths was 1 92 sq ft. larger than that of the Chevrolets

Gasoline Consumption

The measurement of gasoline consumption on all of the surfaces was one of the most critical tests made in this investigation Special precautions were taken to assure accurate measurements Three independent methods of measurement were used (1) the service station pump, (2) the calibrated gasoline gauge on the dash of the car, and (3) the fuel meter The service station pump which was calibrated twice a month with a standard 5-gal. measure provided accuracy of approximately 0 01 gal. for each 10 to 15 gallons added to the tank. The gauge on the dash provided accurate readings only to the nearest 0.5 gal but since the gasoline was drained out of the tank at the end of each speed series, the amount used could be measured with an accuracy of better than 0 1 gal for each 60 to 80 gallons added to the tank during the given speed series. The fuel meter consisted of a copper Sylphon bellows, a special valve mechanism, and an electric counter which automatically provided a record of the gasoline used in 0 01-gal. units This meter was the one used in the 1938-40 tests Improvements were made in the valve mechanism to make it more dependable and to improve its accuracy. The calibrations of the meter made at the end of each speed series (approximately every week when regular runs were under way) indicated an accuracy of about one half of one per cent during the 1,300 miles in each speed series. When stated in terms of miles per gallon in the usual range of 16 to 24 miles per gallon, the largest difference which the meter calibrations indicated should be considered as due to the meter was 0.1 mile per gallon. Calibrations of the cars for fuel mileage in road tests under the most favorable conditions using large glass burette tubes (too hazardous and inconvenient for regular use), with which the gasoline used could be measured in 0 001-gal units, indicated a variation in gasoline mileage of 0.2 to 0 4 mile per gallon or two to four times greater than the variations within the limits of meter accuracy From this it is evident that the accuracy of the meters was more than ample to measure the variations in gasoline mileage due to the differences in engine performance and type of road surface

The gasoline used in these tests was a regular grade leaded gasoline Samples tested by the Kansas and the Iowa Highway Commission testing laboratories indicated A P I. gravity values of 58 9 for the summer gasoline and with a gradual increase to 64.9 for the winter gasoline The highest initial boiling point was 112 deg during the summer and 81 deg during the winter, with average maximum end points of 392 deg. for both summer and winter The Reid vapor pressure varied from a low value of 6.6 lb. for the summer gasoline to a high value of 12 1 for the winter gasoline The octane rating showed a progressive decrease during the year with a maximum octane number of 73 3 in October, 1941, when the tests started to a low value of 69 4 in August, 1942, near the close of the tests This change in octane number was due to the increased demands for tetraethyl lead created by our defense and war efforts during this period The change in octane number was not large enough to be reflected in the results of the tests although a slightly objectionable pinging of the motor was observed when accelerating with wide open throttle during the spring and summer of 1942.

The average gasoline mileage for each season in the regular driving tests on the concrete and bituminous routes in Kansas are given in Table 2. Another factor which should be considered in comparing fuel requirements on these surfaces was the change in gasoline mileage for the various car speeds It will be noted in Table 2 and in Figure 16 that the average speeds on the bituminous route were from 0.4 to 2.0 miles per hour higher than on the concrete route This was due to the effect of reduced speeds on the streets of the larger cities on the concrete route. The total miles of travel on city streets on the concrete route amounted to 26.08 miles and on the bituminous route to 13.21 miles The higher average speeds on the bituminous route are therefore quite reasonable.

The average gasoline mileage for each season as given in Table 2 varied from 18.71 to 19.96 miles per gallon on the concrete route and from 18.32 to 19.14 miles per gallon on the bituminous route These differences may be considered only slightly greater than the experimental error in this type of measurement. In fact, a large part of the differences were due to the differences in car speed on each surface as is evident in an analysis of the curves for gasoline mileage for the regular test runs in Figure 15. The results on both surfaces were almost identical for the fall, winter, and spring seasons, and only in the summer season was the gasoline mileage lower on the bituminous route than on the concrete route. The lower mileage on the bituminous route during the summer season was not due to a marked difference in the surfaces but rather to the differences in the performance of the two test cars. The calibrations at the end of the spring season (Fig. 15) indicated that the gasoline mileage for the two cars was identical and that there was a progressive increase in gasoline mileage in the tests for each successive season The calibrations with car 1 at the end of the summer season indicated satisfactory performance and was in line with the trend in gasoline mileage previously noted However, the calibrations with car 2 made under identical conditions as car 1 indicated a drop of 1½ to 2 miles per gallon below the expected values When the mechanic checked the motor of this car to determine the reasons for the difference, he found that the timing had slipped about five degrees off the standard setting and the carburetor float was out of adjustment. Since the average difference in gasoline mileage on the regular test runs for the two cars in the summer season was only 1 mile per gallon as compared to 2 miles per gallon in the calibration tests at the end of the season, it seems reasonable to conclude that the gasoline mileage on the concrete and bituminous surfaces during the summer season would have been the same as in the previous seasons if the motor adjustments had been maintained satisfactorily throughout the entire season

It is not surprising that the gasoline mileages on the bituminous and concrete surfaces were the same at corresponding speeds because both surfaces were relatively firm and smooth and free of loose sand and other types of aggregate The mileage of bituminous surface under repair averaged less than 2 per cent of the total and the loose material in these sections had little effect on the average gasoline mileage for the entire route Further evidence of the reasonableness of these results, is provided by the results of tests on the Iowa untreated gravel and the Iowa portland cement concrete over a period of two years, 1938-1940, where the average difference in gasoline mileage at corresponding speeds was only two miles per gallon despite the presence of considerable loose gravel over the entire route, their rough washboarded condition when dry, and their soft and muddy condition when wet.

The Effect of Speed on Gasoline Mileage

The results of the gasoline mileage tests at speeds ranging from 15 to 65 m p h. have special significance during the present period of gasoline rationing and a 35 m p h speed limit In the calibration tests on the three mile test course, the nominal speeds were maintained throughout the tests and gasoline mileages of 24 to 26 miles per gallon were obtained at 35 m p h. as compared to 16 and 17 miles per gallon at 65 m p h In the regular driving tests over the 312 and 321-mile test routes, the gasoline mileage remained in the range of 24 to 26 miles per gallon at 35 m.p h., but for a nominal or scheduled speed of 65 m p.h , the gasoline mileage was reduced to 15 and 16 miles per gallon and the actual average speed was only 53 m p h. on the concrete route and 56 m p h on the bituminous route Thus, the tests proved that for a top cruising speed of 65 m p h as compared to 35 m p h , the gasoline consumption was more than 60 per cent higher. Yet the average gain in speed was less than 20 m p h. because at the faster speeds the drivers had to slow down more frequently and to a greater extent due to traffic interference, road hazards, sharp curves, and the restrictions in speed in cities and towns The number of brake applications and the braking time were increased 60 per cent at 65 m p h. as compared to 35 m p h If there had been more cities and towns and heavier traffic on these test routes, the difference in gasoline consumption and the reduction in the average speed would have been even greater

The average speeds obtained for various nominal speeds on the concrete and bituminous test routes in Kansas are shown in Figure 16 It is significant that for speeds up to 35 m.p.h. there was very little reduction in the average speed below the scheduled or nominal speed. The similarity in the driving conditions on the concrete route in Iowa as compared to the concrete route in Kansas is indicated in Figure 16 by the fact that the average speeds for corresponding nominal speeds were very nearly identical.

The test data in this study have indicated that the decrease in gasoline mileage with increase in speed was due largely to increased air and engine resistance which vary approximately as the square of the speed, and also to increased rolling resistance and the braking and accelerating forces which build up at a high rate as the speed is increased A conservative estimate of the effect of the 35 m.p.h speed limit where it is observed is that the average gasoline mileages for rural traffic should be increased 30 to 40 per cent.

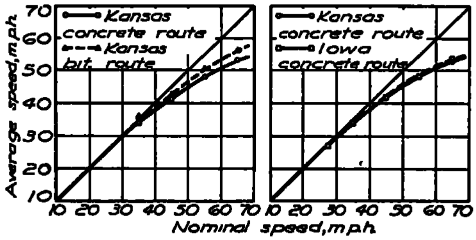

Figure 16. Average Speeds Obtained for Various Nominal Speeds on the Concrete and Bituminous Test Routes in Kansas and on the Concrete Test Route in Iowa and in Kansas.

Oil Consumption

Oil consumptions in terms of the oil added to maintain the oil level in the crankcase at the full mark are shown in Figure 17 for the test during each season with car 1 on the concrete route and car 2 on the bituminous route. The composite results for the entire year's driving in Kansas and for two years of driving in Iowa are also shown. The oil used per

1,000 miles including the new oil added when oil changes were made is given in Table 2 for each season. These results indicated that more oil was used on the bituminous route than on the concrete route during each season. The average increase in terms of oil added amounted to about 20 per cent and in terms of total oil used, it was about 12 per cent This difference was due to the fact that the oil was added in quart units and in no case was oil added unless a full quart was needed to bring it up to or slightly below the full mark with the car on a level surface. For average speed conditions only one to two quarts of oil were added

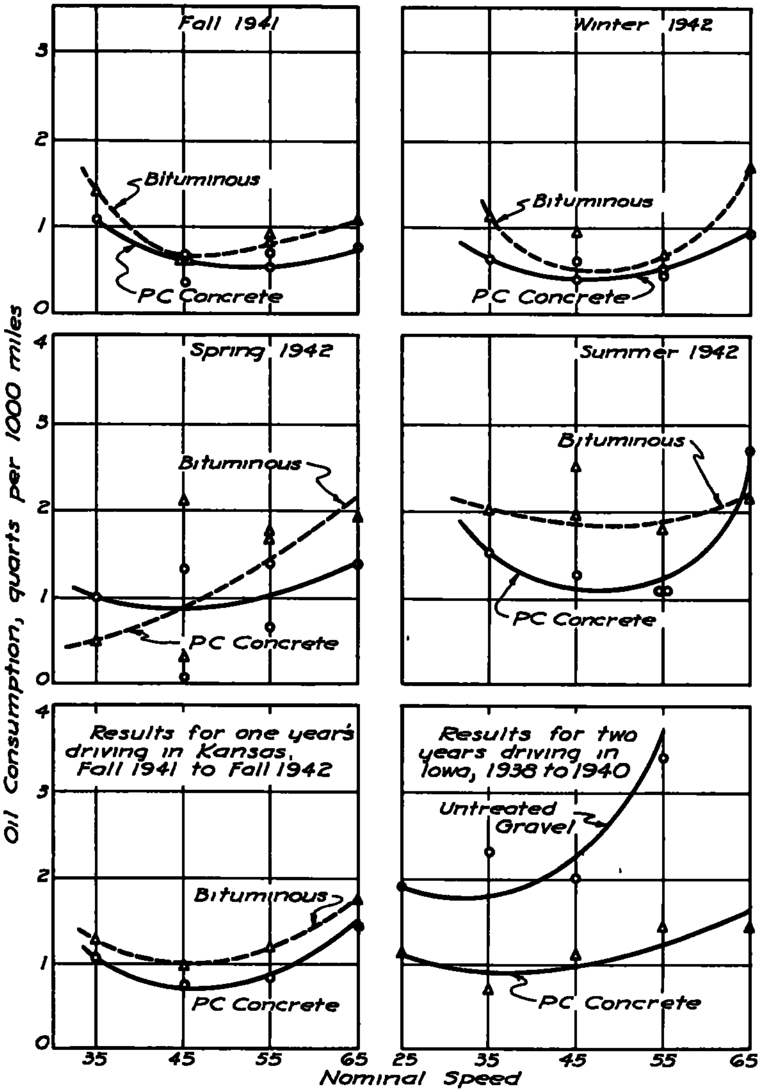

Figure 17. Oil Consumption on Concrete and Bituminous Surfaces in Kansas Based on One Year of Driving

before an oil change was necessary every 3,000 to 4,000 miles as explained on page 21.

The differences in oil used were fairly consistent and only in the case of two speed series was the oil used on the concrete route higher than on the bituminous route. There are two explanations for the greater amount of oil used on the bituminous route; one of them relates to differences in the engines of the cars and the other to differences in the road surfaces. There are many factors which influence the oil consumption characteristics of gasoline engines and it was not within the scope of this investigation to determine these factors. However, it should be pointed out that the calibration tests proved that the cars were identical and that in the regular driving tests and in all special tests both cars were operated, inspected and serviced in the same way. A factor related to the type of road surface which may have contributed to increased oil consumption on the bituminous route was the greater road roughness on this route. The average road roughness as measured with the P.R.A. roughness indicator amounted to 172 in. per mile for the bituminous route as compared to 129 in. per mile for the concrete route. It is possible that since the rougher bituminous surfaces caused more churning, splashing, and fogging of the oil in the crankcase than on the concrete route, a slightly larger amount of oil was lost in this way through the breather pipe from the crankcase or was forced past the rings.

It is interesting to note that the oil consumption of the 1938 Chevrolets on the Iowa concrete route compared favorably with that of the 1941 Plymouths on the Kansas concrete route. The evidence in the Iowa tests clearly showed that the type of road surface can be a factor in the amount of oil used because twice as much oil was used on the rough dusty gravel roads as was used on the concrete roads for which the roughness index was one half to one third as high as for the gravel roads.

Actually the differences in oil consumption in the Kansas tests are relatively unimportant when expressed in terms of unit costs because they did not exceed 0.01 per cent per mile out of a total cost of 1.50 cents per mile for the fuel, oil, tire, and maintenance costs for these cars. Nevertheless, the evidence is definite enough that it may be used as one of the reasons for the much needed improvement in the smoothness of road surfaces.

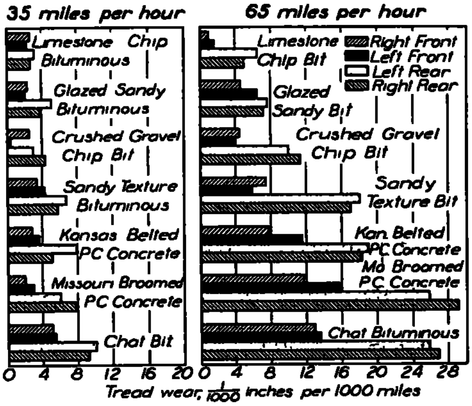

Figure 18. Tire Tread Wear at Each Wheel Position on Various Concrete and Bituminous Surfaces for Nominal Driving Speeds of 35 and 65 Miles Per Hour.

Tire Wear

In view of the present critical shortage of rubber, the results of the tire wear measurements provided the most timely and in many respects the most important information obtained in this investigation. The tests were planned to provide an accurate measure of the variations in tire tread wear caused by variations in car speed and in the abrasiveness of the many different types of road surfaces which were specially selected for this purpose. The results of the tire wear tests on the various portland cement concrete and bituminous surfaces in Kansas, Missouri, and Wyoming are given in Figs 18 to 20 For comparative purposes the results of the 1938-40 tire wear data on the Iowa concrete and untreated gravel surfaces are also shown in Figs 21 and 22. The rate of wear during each season in the Kansas tests for the tires on car 1 operated on the concrete route and on car 2 on the bituminous route are given in Table 2

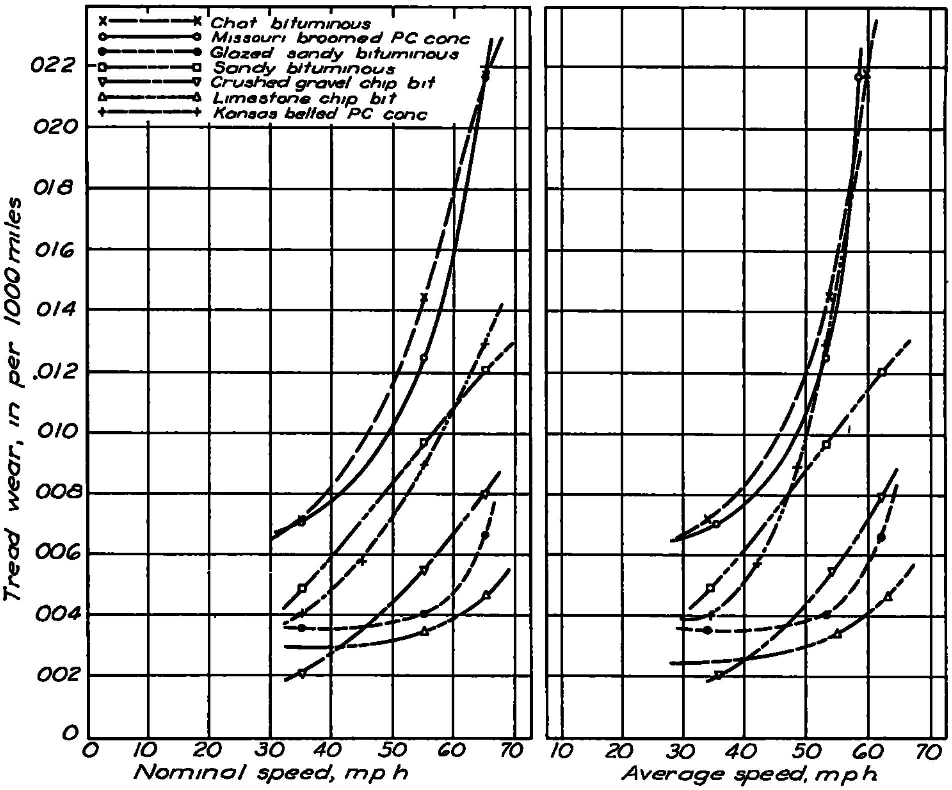

Figure 19. The Effect of Car Speed on Tire Tread Wear on Various Types of P.C. Concrete and Bituminous Road Surfaces

All measurements of tire wear were made on the basis of tread depth using a depth gauge graduated in 0.001-in. units. Readings of the tread depth were taken at 20 points equally spaced along the inside and outside grooves of each tire with the tires inflated to 28 lb per sq in, which was the standard pressure to which all tires were inflated before starting the regular or special driving tests.

The effect of the type of road surface and of an increase in speed from 35 m p h. to 65 m p h. on the rate of tire tread wear is shown most effectively in the bar charts of Figure 18 These charts also show the wear at each wheel position The lowest wear was observed on the limestone chip bituminous surface although the wear on the glazed sandy and the crushed gravel chip bituminous surfaces was only slightly higher

On all of the surfaces with a low rate of tire wear there was evidence of excess asphalt and a tendency for bleeding to develop in hot weather In a survey of the surfaces to determine the extent of bleeding, it was found that 65 per cent of the limestone chip surface and more than 90 per cent of the glazed sandy bituminous showed evidence of bleeding Although the crushed gravel chip surface showed little evidence of bleeding, there was an indication of a slight excess in the amount of asphalt used in the seal coat on this surface which can be observed in the close-up photograph in Fig. 4. Another factor which contributed to the low wear observed on the limestone chip surface was that the limestone chips were fairly soft and the edges of the chips were worn smooth and slightly rounded by traffic (see Fig 4)

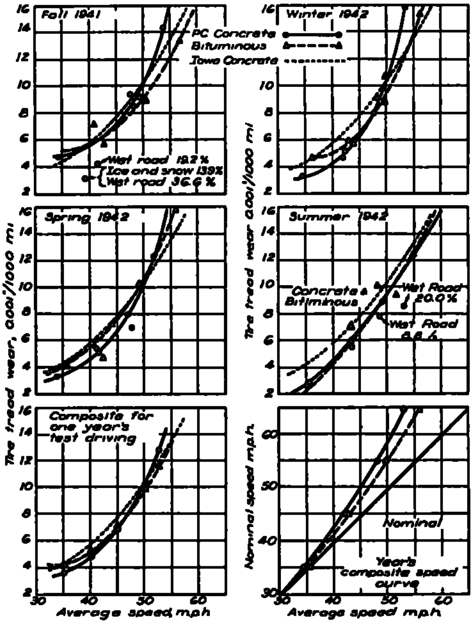

Figure 20. Tire Wear for One Year's Driving on the Portland Cement Concrete Test Route and a Test Route Made Up of Various Bituminous Surfaces in Kansas as Compared with Wear on Iowa P.C. Concrete. (All Data as Measured, with No Corrections for Wet Surfaces or Temperature Variation.)

The highest rate of tire wear was observed on the chat rock chip bituminous

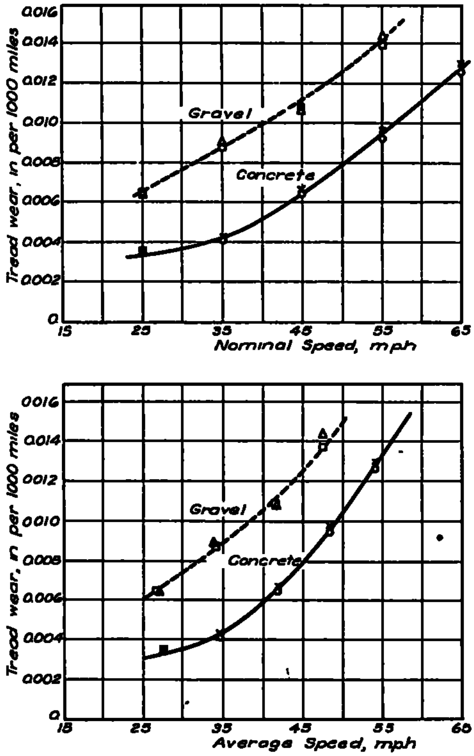

Figure 21. The effect of car speed on Tire Wear on Gravel and Concrete Roads in Iowa—Above Curves Corrected to Standard Conditions.

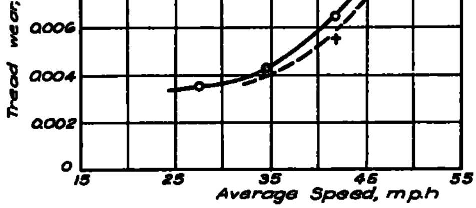

Figure 22. Tire Tread Wear on Belted Portland Cement Concrete Pavements in Iowa and in Kansas.

and the broomed concrete surfaces. The chat rock chips were hard sharp flint-like particles to which the asphalt did not adhere readily and thus provided a highly abrasive surface The sand in the broomed concrete surface was also hard and sharp which together with the sharp edges and ridges caused by the broomed finish, as shown in the close-up photograph in Fig 2, was responsible for the high rate of tire wear.

In comparing the widely varying tire wear rates at speeds above 35 m p h , a distinction should be made between the nominal speed wear and the average speed wear The data in Fig 19 indicate that average speed is the better basis for comparison because it is the more definite speed value of the two The nominal speed is indefinite because there is no way of telling the extent to which this speed was maintained during the entire trip In the following comparisons reference will generally be made to the wear at average speeds.

All of the data on tire wear in this report clearly show that variations in car speed and in the type of road surface are the two most important factors which influence the rate of tire tread wear According to Figure 19 the lowest rate in these tests was 0.002 in. per 1,000 miles on a crushed gravel chip bituminous surface at 35 m.p h and the highest rate observed was 0 022 in per 1,000 miles on the chat rock chip bituminous surface at 60 m p.h. The highest rate was 11 times greater than the lowest rate

In regard to the speed effects it was observed that the highest increase in the rate of tread wear was obtained on the most abrasive surfaces and the smallest increase on the least abrasive surfaces. Thus the unit wear on the chat surface was 7.4 thousandths of an inch per 1,000 miles at 35 m p.h , and 22 at 60 m p h On the Kansas belted concrete the unit wear at corresponding speeds was 4.2 and 20.6 thousandths of an inch per 1,000 miles On the limestone chip surface the wear increased from 2 5 to 4 2 thousandths of an inch per 1,000 miles over this same speed range It is evident that the wear at 60 m p.h average speed was 2 to 4 times greater than the wear at 35 m p.h. This means that tire life mileages can be increased in these same proportions if cars are operated at speeds of 35 m p h which was established as the national speed limit on November 1, 1942

The differences in the wear rates due to the type of road surface were found to be even greater than the differences due to the speed effects The greatest change in the wear rate due to the type of surface was observed at the highest speed and the least change at the lowest speed At 60 m.p h. average speed, the lowest wear was observed on the limestone chip bituminous surface with a value of 4 2 thousandths of an inch per 1,000 miles and the highest wear was on the chat surface with a rate of 22 which was 5 4 times greater than the wear on the limestone chip surface. At 35 m p h the tire wear rates varied from 2 1 on the crushed gravel bituminous to 7 4 on the chat bituminous, 7 1 on the broomed concrete, and 9 0 on the Iowa untreated gravel. This indicates a maximum ratio of 4.3 in the wear rates due to the type of surface at the lowest speed in these tests as compared to a ratio of 5 4 at the highest speed

Despite the large differences in tread wear which may be attributed to the type of road surface, it is interesting to note that the differences in wear in the year-round tests on the 312-mile bituminous route and the 321 miles of concrete route in Kansas were relatively small. In Figure 20 the tire wear on both routes is shown for each season as compared to the average wear for two years of driving on Iowa concrete According to these curves, the wear on the concrete route was less than on the bituminous route for speeds up to 50 m.p.h. and for speeds above 50 m.p.h. the reverse was true. The data in Table 2 show that the average unit wear was approximately 10 per cent higher on the bituminous route than on the concrete route. A large part of this difference was due to the fact that the average speed on the bituminous route was from one half to two m.p.h. higher than on the concrete route. The remarkable uniformity in the tire wear on belted concrete proved to be an interesting feature of the tire wear tests. This property of belted concrete is clearly indicated in Fig. 22 which shows that the average tire wear on Iowa belted concrete was almost identical with the wear on Kansas belted concrete.

An important result obtained in the tire wear tests which has special significance during the present rubber shortage was the large tire mileage obtained on all of the test cars despite the fact that approximately 16 per cent of the total mileage was run at 65 m.p.h., 32 per cent at 55 m.p.h., 36 per cent at 45 m.p.h. and 16 per cent at 35 m.p.h. When the tests were brought to a close at the end of the year cars 1 and 2 had been driven 38,000 miles with an average tire mileage of 30,400 miles on each of the five tires. The last tire measurements made at 38,000 miles indicated that 0.089 in. of tread was left on car 1 and 0.068 in. on car 2. These tread depths were equivalent to 28 and 22 per cent, respectively, of the 0.32 in. of original tread depth. By assuming that the same wear rate would be in effect until the tires were worn smooth as the rate that had been in effect for the last 8,000 miles, the computed life mileage of the tires on car 1 was found to be 43,000 miles as compared to 39,000 miles for car 2. In a special study of tire replacements and tire mileage based on the best statistics available on tire production and the total motor vehicle travel in the United States, the writer arrived at an average tire life mileage for all tires in the United States of 23,000 miles for the year 1940. While the true tire life mileage probably differed from this figure by as much as 10 per cent, the present mileages and the expected mileages of the tires on the test cars were so far above the prewar national average that it was considered worthy of special mention as an indication of what may be accomplished in conserving tires on civilian cars. The most important factors which contributed to the high tire life mileages obtained in these tests were: (1) tire inflation pressures were maintained at the recommended value of 28 lb. per sq. in. (cold) all of the time and pressures were checked daily, (2) tires were rotated from one wheel position to the next at the end of every speed series or every 1,300 miles, (3) the cars were driven at uniform speeds whenever possible, braking and accelerating were carefully controlled and held to a minimum; (4) wheel alignment and wheel balance were checked, and corrected when necessary, at the end of each season, and (5) speeds on sharp curves were restricted to the safe and comfortable maximum as determined by a ball bank indicator mounted on the dash of each test car.

The tests of tire wear indicated that the lives of tires may be prolonged during the present emergency by giving special attention to reduction of the abrasiveness of road surfaces. The tests clearly showed that the wear on bituminous surfaces could be greatly reduced by the application of a seal coat with a slight excess of asphalt up to the point where bleeding creates a slippery-when-wet condition. The use of a heavy seal coat and the slippery road condition which usually develops after such a seal coat is applied, would be considered as a very dangerous practice for the prewar speeds of 50 and 60 m.p.h., but this hazard, if kept under control, should not be serious if traffic observes the present national speed limit of 35 m.p.h. The use of soft aggregate with rounded edges for cover material is also recommended to reduce tire wear

The limestone chip, crushed gravel chip, and the sandy bituminous surfaces were of this general type. The tire wear on these surfaces was low and they were not slippery when wet. Other aggregate with like properties such as pea gravel or sand with rounded particles should be equally satisfactory.

SUMMARY OF OPERATING COSTS FOR THE TWO TEST CARS ON THE CONCRETE AND BITUMINOUS ROUTES

A summary statement of the operating cost of all items measured for one year's driving on the concrete and bituminous test routes in Kansas is given in Table 3. Also given in this table for comparative purposes are the operating costs for the same items for the Chevrolet test car 4 on the concrete test route in Iowa during a corresponding period of operation All of the costs represent actual expenditures No attempt was made to evaluate wear for parts not replaced or for depreciation The tire costs were based on tread depth wear and repairs.

Since the measurements of gasoline, oil, and the rate of tire wear showed that operating costs increase with an increase in car speed, the higher average speed on the bituminous route should be considered as an important factor contributing to the higher unit operating costs on this route.

The largest single item of cost measured in these tests was that for gasoline which accounted for approximately 65 per cent of the total for gasoline, oil, tires, and car maintenance. The unit cost for gasoline used by car 2 on the bituminous route was 0 998 cent per mile as compared to 0 972 cent per mile for car 1 on the Kansas concrete route and 1.000 cent per mile for car 4 on the Iowa concrete route. The measurements showed that the gasoline requirements increased 2.2 per cent for each mile per hour increase in speed within the range of 40 to 50 m p h. Therefore, only about one-half of the 2 6 per cent difference in gasoline costs on the bituminous and concrete routes should be charged against the road surfaces. It is logical to expect a slight increase in the fuel requirements on the bituminous surfaces as compared to the concrete surfaces because the former provide a flexible and the latter a rigid type of surface Also, approximately two per cent of the total mileage on the bituminous route was torn up and under repair during the year and the roughness index of the bituminous route was 30 per cent higher than that of the concrete route. Actually the effect on the gasoline costs due to the difference in surface condition was not very large and the measured difference of 1 5 per cent higher cost on the bituminous route may be considered as a reasonably accurate average value for the difference in this item of cost on these two major surface types.

The gasoline cost for car 4 on the Iowa concrete route were about 5 per cent higher than for car 1 on the Kansas concrete route at the same speed. This greater cost was due to a higher rear axle ratio on car 4 as previously explained and not to a difference in the road surface

The motor lubrication costs in Table 3 are generally referred to in this report as the oil costs and include the cost of crankcase oil and of the oil filter replacement units The total oil costs amounted to less than 0 1 cent per mile for each of the test cars and while the costs for car 2 on the bituminous route were slightly higher than for car 1 on the concrete route, the difference was less than 0 01 cent per mile which is too small to warrant further consideration.

The tire and tube costs amounted to about 12 per cent of the total operating cost for the four items measured in these tests. For car 2 on the bituminous route the total tire and tube costs amounted to 0 18 cent per mile as compared to 0 175 and 0 174 cent per mile for cars 1 and 4, respectively, on the concrete routes. The tire wear measurements at 35 and 45 m.p h showed that the rate of tire wear increased approximately 8 per cent for each mile per hour increase in the average speed of the test cars. When corrections due to speed were applied to the tire wear on the concrete routes to reduce all tire wear and tire costs to the same speed value, the tire costs on the bituminous route were found to be 3½ per cent higher than on the Kansas belted concrete and 12 per cent lower than on the Iowa belted concrete.

The tire wear costs on the bituminous route and on the Kansas concrete route may be considered as fairly representative of the wear for bituminous ,and concrete pavements in general use today However, tests were run on other bituminous surfaces where tire wear rates were 2 to 3 times the average rate observed on the 312-mile bituminous route and tests were run on still other bituminous surfaces where the rates were one half to one third the average wear rate observed on the bituminous route. While the differences in the wear rates on the concrete surfaces were much smaller than on the bituminous surfaces, the tests on broomed concrete indicated wear rates more than 50 per cent higher than the average rate on the belted concrete. In view of the high tire wear costs on the extremely abrasive types of surfaces, it is not advisable to build surfaces of this type nor is it advisable to build surfaces with a slippery glazed finish. The results of the tire wear tests indicated that it is possible to build road surfaces on which cars can be operated with low rates of tire wear and low tire costs without making these surfaces slippery when wet

The data in Table 3 indicated that the maintenance costs for car 2 operated on the bituminous route were approximately 5 per cent higher than for car 1 on the concrete route. The car washing costs were higher on the bituminous route because road oil was splashed on the car at certain times when road oiling was under way. Also there was more than the normal amount of rain in Kansas in 1941-42 and it was found that car 2 on the bituminous route required more work to keep it clean and properly serviced than car 1 on the concrete route. Actually, the net difference in maintenance costs for cars 1 and 2 was only 0.015 cent per mile out of a total average maintenance cost of 0.25 cent per mile. This is a small but at the same time a logical difference in favor of the concrete surfaces.

The maintenance costs for car 4 driven on the Iowa concrete route were almost double the corresponding costs for cars 1 and 2. Car 4 was greased and the engine and car checked every 1,000 miles as compared to every 1,300 miles for cars 1 and 2 in Kansas but despite the greater care given car 4 the costs for major repairs were greater for it than for the Kansas cars An explanation advanced by the mechanic who serviced the cars is that the reduction in maintenance costs for the 1941 model cars reflected the mechanical improvements in cars of this type over the three year period from 1938 to 1941.

The total running costs for gasoline, oil, tires and maintenance amounted to 1 474 cents per mile for car 1 on the concrete route and 1 536 cents per mile for car 2 on the bituminous route. As mentioned earlier, one reason for the higher cost on the bituminous route was the higher average speed of car 2 on this route. After making corrections for differences in speed, the cost on the bituminous route was found to be 0.04 cent per mile higher than on the concrete route On the basis of an average total cost of 1 474 cents per mile on the concrete route, this represented an increase in operating cost on the bituminous route as compared to the concrete route of approximately 2½ per cent. In the opinion of the writer this is a reasonable difference in operating cost which comes fairly close to the true difference for these two major

TABLE 3

Operating Costs of All Items Measured for One Year's Test Driving on Concrete and Bituminous Road Surfaces in Kansas and Iowa 1941–1942

Car number and surface	Miles driven	Average speed, m p h	Gasoline costs, cents per mile	Motor lubrication cost, ¢ per mile		Tire and tube cost, ¢ per mile		Maintenance cost, cents per mile							Total costs, cents per mile
				Oil cost	Filtering cost	Wear	Repair	Greasing	Washing	Inspection		Seasonal or major repairs		Total maintenance	
										Labor	Parts	Labor	Parts		
Plym No. 1 Concrete (Kansas)	37,059	42.7	0.972	0.064	0.020	0.165	0.010	0.071	0.021	0.075	0.018	0.040	0.018	0.243	1.474
Plym No 2 Bituminous (Kansas)	37,060	43.2	0.998	0.072	0.020	0.181	0.007	0.071	0.033	0.072	0.018	0.040	0.024	0.258	1.536
Chev No 4 Concrete (Iowa)	36,100	40.7	1.000	0.068	0.030	0.174	0.000	0.107	0.038	0.109	0.040	0.094	0.082	0.470	1.742

Unit prices used

Gasoline	18.5¢ per gal	Tires	$15.70 each	Washing	50¢ per hour
Oil	25¢ per qt	Tubes	$3.65 each	Mechanic's labor	$1.00 per hour

All parts at standard retail prices

TABLE 4

Summary of Road Roughness Measurements made During 1941–42 with the Public Roads Administration Roughness Indicator on Various Sections of the Concrete and Bituminous Routes in Kansas, Inches per Mile

Surface type	Fall, 1941			Winter, 1942			Spring, 1942			Summer, 1942		
	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum
Bituminous route												
48 rural sections	171	357	108	170	293	106	176	325	110	171	378	104
10 urban sections	257	460	131	246	402	125	267	625	135	211	355	98[a]
Concrete route												
26 rural sections	133	266	86	125	287	75	128	304	79	128	274	78
6 urban sections	221	474	106	215	484	106	228	426	106	219	432	106

[a] New paving through Burlington, Kansas.

surfaces in Kansas and in the United States as a whole However, it is a small difference when consideration is given to the fact that the bituminous route in Kansas like bituminous roads in all parts of the United States included many miles of low cost surfaces which were continually subject to patching, surface treatments and other repair work.

It seems reasonable to conclude on the basis of the results of the extensive tests conducted in this study that the differences in vehicle operating costs on the various bituminous and concrete surfaces are negligible if they are constructed and maintained with a moderately smooth riding surface free of loose sand and other types of aggregate

ROAD ROUGHNESS

While the main emphasis in this investigation of vehicle operating characteristics was on the cost differentials for the four major vehicle operating cost items, the measurement of three other characteristics was considered to be of very nearly the same importance. These were road roughness, surface texture, and the coefficients of friction for surfaces in the wet and dry condition.

The road roughness was measured with the Public Roads Administration standardizable road roughness indicator described by Catudal[8] Measurements were made on all of the test sections at least once during the year while on the Kansas concrete and bituminous routes measurements were made during each season of the year This involved detailed measurements of the roughness in each traffic lane at 20 m p.h. for more than 950 miles per season During the fall season the tests were made with the Public Roads Administration equipment and with the services of Mr A L Catudal of the Public Roads Administration The tests in the winter, spring, and summer were made with the roughness indicator of the same design built specially for this project (Fig 11). As nearly as could be determined, the roughness values obtained with it were in very close agreement with the values obtained with the Public Roads Administration equipment.

The results of the road roughness measurements are given in Table 4 and in Figs 23 to 26

The summary of the roughness measurements on the concrete and bituminous routes in Kansas given in Table 4 and Fig 23, indicates the wide range in the roughness values obtained on these routes The lowest value measured was 75 in per mile on one of the recently built sections of the concrete route. The maximum value was measured on a crushed stone detour in Burlington, Kansas, with a roughness index of 625 in per mile The next highest value was on a brick pavement in Emporia with a roughness value of 484 in. per mile. On the rural sections of the bituminous route the highest value was 378 in. per mile and the lowest was 104 in per mile as compared to 304 and 75 in. per mile for the corresponding values on the concrete route The average value for the rural sections on the bituminous route for the entire year was 172 in. per mile as compared to 129 in per mile on the concrete route. This clearly indicated that the concrete road surfaces in Kansas were considerably smoother than the bituminous surfaces

In Kansas as in Iowa the roughest pavement sections were encountered in the cities and towns with average values for the entire mileage of city pavements of 211 to 267 in. per mile These surfaces were usually old brick or worn out and badly cracked concrete pavements or bituminous pavements subject to rutting and shoving or, if badly cracked, subject to raveling. The roughness values mea-

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[8] A L Catudal, "Standardizable Equipment for Evaluation Road Surface Roughness," *Proceedings*, Highway Research Board, Vol 20, p 621 (1940)

sured on these sections usually ran from 430 to 486 in per mile. All of these sections were on main U. S and State routes and must have been very unsatisfactory to through traffic although they had the doubtful advantage of serving as automatic speed regulators

No marked change was observed in the roughness values measured in each of the four seasons The greatest change was observed on the bituminous route in the spring season due largely to the spring breakup and the large amount of patching necessary at this time of the year. The best record on the bituminous route was obtained during the winter because the maintenance engineers planned to bring these surfaces to the best possible state of repair for the winter. In Kansas the combination of improved maintenance in the fall, the smoothing effect of traffic, and the lower temperatures in the winter were the principal reasons for the smoother and more stable bituminous surface conditions in the winter than in the summer.

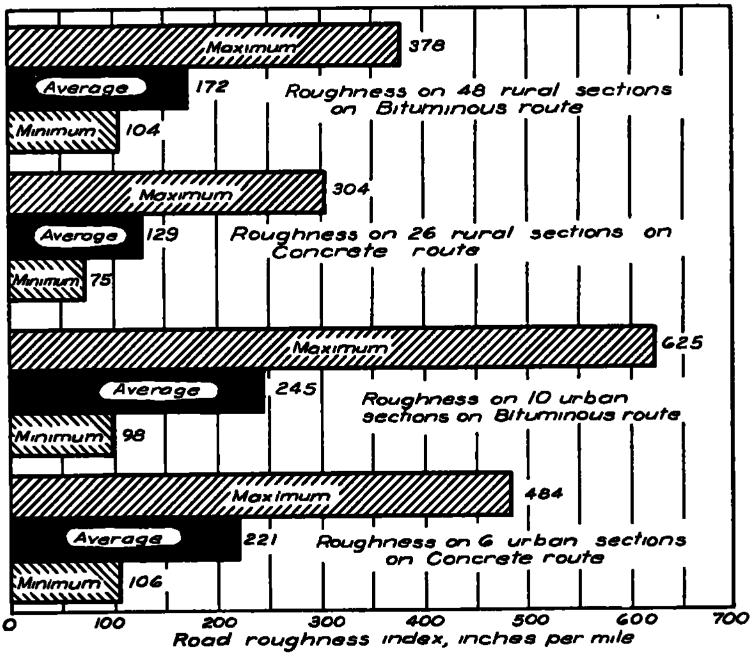

Figure 23. Summary of Road Roughness Measurements Made on Kansas Test Routes During Each Season of Test Driving in 1941 and 1942

In Figures 24 and 25 the road roughness values are given for each half mile of the 12 to 24 mile test sections on the various types of bituminous and concrete surfaces. The roughness indices of the belted concrete in Kansas and on the broomed concrete in Missouri indicated not only that these surfaces were the smoothest of all the surfaces on which tests were run but also their roughness values were the most consistent. The greatest variation on the concrete surfaces amounted to 20 per cent from the average as compared to 40 and 50 per cent on the majority of the bituminous surfaces. The highest average roughness values and the greatest variation in roughness was observed on the glazed sandy bituminous. The excess asphalt which was very evident on this surface caused shoving and creeping of the bituminous mat which not

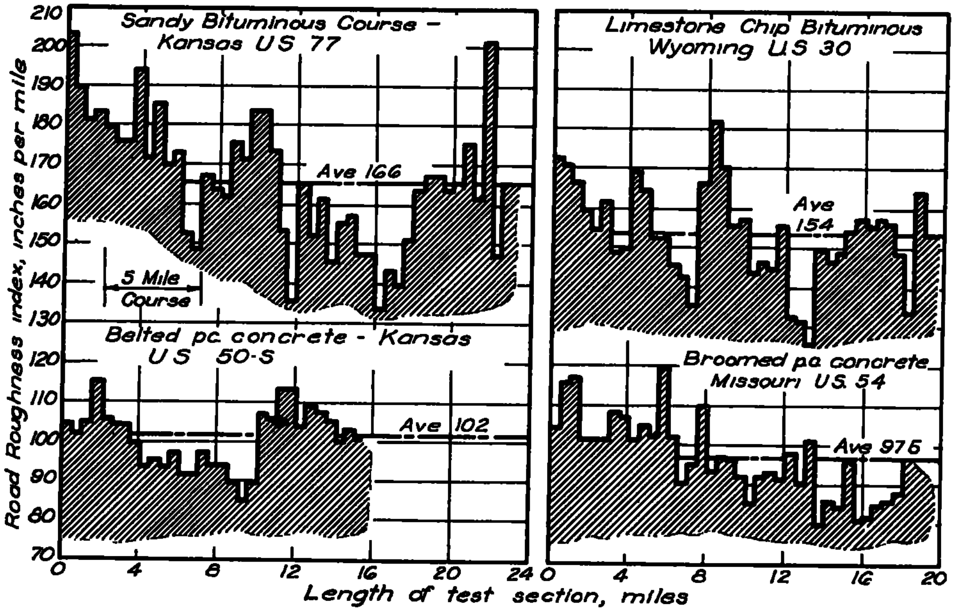

Figure 24. Typical Road Roughness Measurements on Bituminous and P.C. Concrete Road Surfaces at Standard Speed of 20 M.P.H.

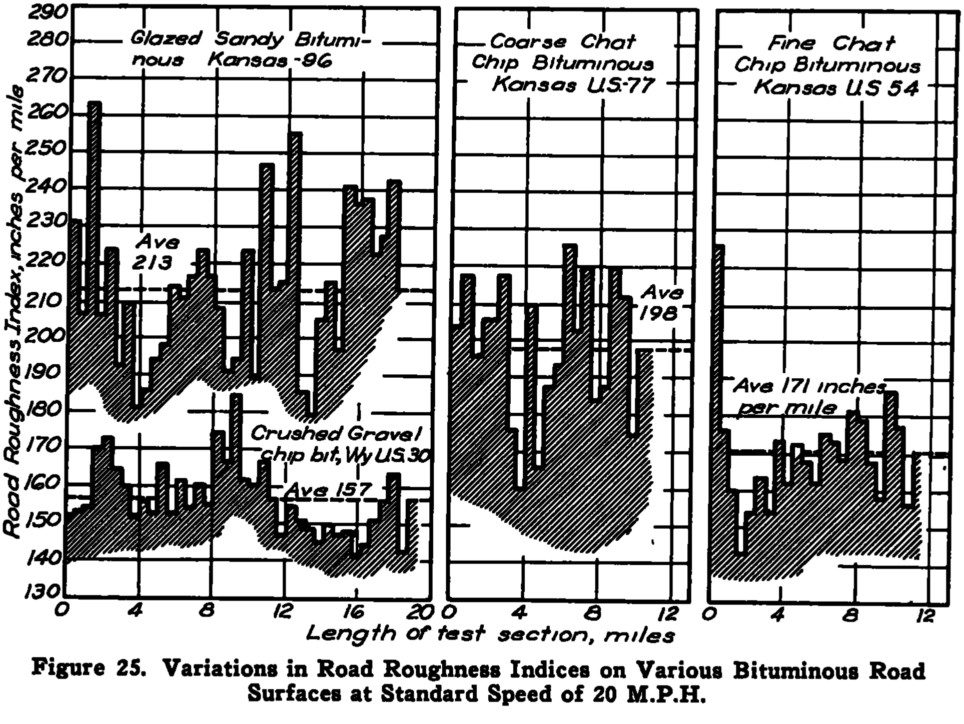

Figure 25. Variations in Road Roughness Indices on Various Bituminous Road Surfaces at Standard Speed of 20 M.P.H.

only made this surface very rough but also very slippery. The lowest average roughness values and the smallest variations on the bituminous types were on the limestone chip and the crushed gravel chip bituminous surfaces in Wyoming. The average values for these surfaces were 154 and 157 in. per mile, respectively. They were built on a stabilized subgrade and a stabilized gravel base over a total width of 36 ft. This high type base construction as well as larger size aggregate and the angularity of the particles contributed to the greater stability and smoothness of these surfaces.

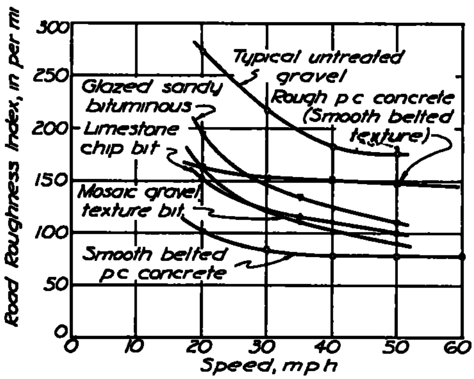

Figure 26. Effect of Speed on Road Roughness Indices for Various Road Surfaces with Various Types of Surface Textures.

An important finding was the marked superiority in smoothness of the concrete pavements as compared to the smoothness of the bituminous, brick, and gravel surfaces on which these tests were run. Included in this study were bituminous surfaces built to high standards of construction The highway engineers in Kansas and Wyoming were very positive in expressing the opinion that these surfaces were equally as smooth as the modern concrete surfaces. Yet the tests showed that roughness values lower than 150 in. per mile were rare on the improved bituminous types while values of 90 to 110 in. per mile were quite common on concrete surfaces built since 1930.

A partial explanation for the consistently higher roughness values on the bituminous surfaces as compared to the concrete surfaces is that the former were for the most part of the traffic-bound type The tire and spring vibrations of the cars and trucks on the traffic-bound roads caused many small ripples which were not noticeable to the casual observer but which were responsible for an increase in the roughness to the extent of 30 to 50 in per mile. Evidence on the effect of these ripples on the road roughness values was obtained by running roughness tests at speeds from 20 to 60 m p.h These tests (Fig 26) show that on concrete roads the decrease in road roughness with an increase in speed was at a much lower rate than on the bituminous and untreated gravel surfaces. At 50 m p h. the roughness values on the three bituminous surfaces ranged from 90 to 110 in. per mile as compared to 80 in per mile for smooth belted concrete The design of the roughness indicator is such that vertical displacements which are not measured by the integrating device can only be accounted for by the increased deflection of the tire The large decrease in the roughness index on the bituminous surfaces therefore was an indication that the tires absorbed a large part of the roughness caused by the ripples as the speed at which the tests were run was increased. It is also quite likely that this explains why many engineers consider the improved types of bituminous surfaces equally as smooth as the modern concrete surfaces

Standards for Road Roughness

In normal peacetime driving the public judges the quality of a road more by its smoothness than on any other basis. The highway engineer should therefore be very critical of this characteristic of road surfaces and should set up suitable standards to evaluate road roughness. It is unlikely that fixed limits can be set up in a set of standards for road roughness which will meet the approval of all engineers Nevertheless, if the limits are not fixed too rigidly, it is reasonable to believe that standards can be established which will be very helpful in rating the smoothness of road surfaces

On the basis of driving tests at speeds of 35 to 65 m.p h on the surfaces included in this study, the drivers of the test cars and the writer have agreed that a roughness index of 100 in per mile or less should be considered as a high standard of surface smoothness, that up to 160 in. per mile should be considered acceptable up to 65 m p.h , but that values in excess of 200 in. per mile indicated a degree of roughness which was definitely uncomfortable to the driver and observer in the test car at speeds of 35 m p h. and higher.

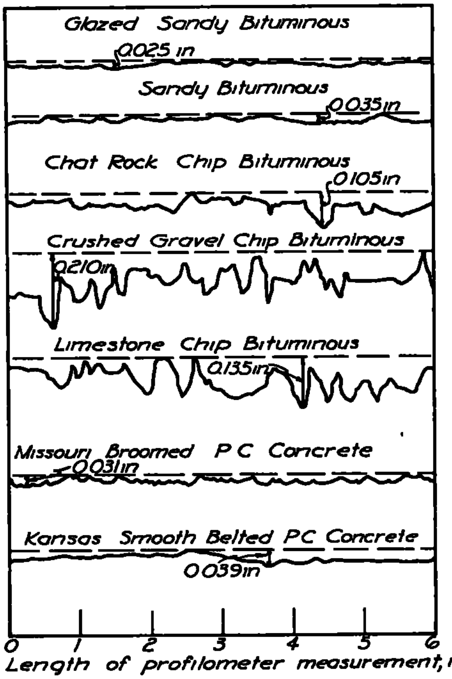

Figure 27. Typical Surface Textures for Various Types of Bituminous and P.C. Concrete Road Surfaces.

While conclusive evidence is not available on the relation of road roughness index to vehicle operating costs, there were indications in the results of the driving tests on the bituminous surfaces with roughness values greater than 200 in. per mile that the gasoline, oil, and tire costs were definitely higher than on the surfaces with roughness values less than 160 in per mile

TABLE 5

PROFILOMETER SURFACE TEXTURE MEASUREMENTS ON VARIOUS TYPES OF CONCRETE AND BITUMINOUS ROAD SURFACES 1941 AND 1942

Surface type and texture	Profilometer surface texture measurements	
	Average maximum depth of surface indentations, inches	Coarseness index
Portland cement concrete		
Missouri broomed	0 103	1 21
Kansas belted	0 085	1 00
Bituminous		
Chat rock chip	0 134	1 58
Crushed gravel chip	0 215	2 53
Limestone chip		
Bleeding	0.110	1 29
Non-bleeding	0.217	2.64
Sandy texture	0.113	1 33
Glazed sandy texture	0 097	1.14

[a] Coarseness index was determined by using an index of 1.00 for Kansas belted portland cement concrete.

SURFACE TEXTURE MEASUREMENTS

Surface texture measurements were made with the profilometer (Fig. 10) for the purpose of obtaining a quantitative measure of the fineness or coarseness of each surface. Typical profilometer records for each surface are shown in Figure 27 and a summary of these measurements is given in Table 5

The records in Figure 27 cover only 6 in. of the 24 in. which made up the complete record. Records were taken at two or three points along the various test sections, each of which were representative of a certain type of surface texture or surface finish. Nine longitudinal records were taken across the road section at points in the wheel tracks and outside and between the wheel tracks Two transverse records were taken, one on each side of the road, to span half of one of the wheel tracks and a part of the space between the wheel tracks In order that numerical comparisons of surface textures could be made the maximum depth of the surface indentations on each 2-ft. record was measured from a straight line drawn approximately parallel to the general slope of the surface and touching the high points in each record. The maximum depth was used in this study to conform with the procedure used in surface texture measurements at Purdue University [4] where it was found that the maximum depths of the profilometer records were in the same order as the average depths and could be measured with a large saving of time when compared with that required to determine the average depths.

In Table 5 the average maximum depth of surface indentations is given for all of the bituminous and portland cement concrete surfaces covered in this investigation. Also given in this table is a comparative coarseness index based on a value of 1 00 for the fine grained Kansas belted portland cement concrete (Fig 2) worn smooth by traffic The average maximum depth of indentation on the Kansas belted concrete was 0 085 in which was the lowest value for these tests The average maximum depth on the limestone chip bituminous surface for sections free of bleeding was 0 217 in which was the largest value measured

The values of coarseness index of the sandy type surfaces were in the range of 1.00 to 1.33 The values for the bituminous surfaces on which bleeding of excess asphalt to the surface was fairly general, were all low as would be expected It was rather surprising to find that the coarseness index of 1 21 measured for the broomed concrete was in the same range as for the sandy surfaces. Examination of the close-up photograph of the broomed concrete surface (Fig. 2) and of the profilometer record (Fig 27) indicated that the surface indentations due to the brooming were not deep but that the broom markings were very distinct with many fine saw-tooth-type ridges across the pavement The coarseness index was lower in the traffic lanes than in sections outside the traffic lanes and in a few cases the broom markings had already been worn off by traffic although the oldest section on this road had been open to traffic only 3 years However, it was observed that even though the broom markings were worn off, the surface retained a sandy texture.

A moderately coarse sandy or rock chip type surface texture has two important advantages related to the safe operation of traffic The first is that such surfaces provide high resistance to skidding The second advantage is that the coarse surface texture diffuses the light at night from the headlights of approaching cars when these surfaces are wet, thereby eliminating the glare that occurs on the wet mirror-like surfaces with a low coarseness index

MEASUREMENT OF COEFFICIENTS OF FRICTION

Four different types of measurements of tire and road friction were made in the 1941-42 tests They were: (1) stopping distance tests from various initial speeds with the four wheels of the test car, Chevrolet No 1, locked, (2) towing-braking tests with a two-wheel trailer in which one trailer wheel was locked while

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[4] Shelburne, T E "Bituminous surface treatment" Purdue University Engineering Experiment Station, Bulletin 82 (1941)

the other wheel was rolling freely, (3) variable braking pressure tests using the two-wheel trailer with the brakes on one wheel applied at air brake pressures from 10 lb. to the maximum required to lock wheel, a special effort was made in these tests to measure accurately the coefficients for the skid impending condition and the locked wheel condition—and (4) the towing-angle tests with the two-wheel trailer in which the coefficients of friction straight ahead were measured for toe-in and toe-out angles on each wheel from 0 to 10 deg.

All of these measurements were made on wet and dry surfaces with new tread and smooth tread tires for each type of measurement.

In the stopping distance tests, the car was brought to the predetermined initial speed and the brakes applied hard instantly, or as nearly so as possible, to lock the wheels. At the instant the brakes were applied, a stopping distance gun loaded with a paint capsule was discharged. The gun was attached to the rear bumper and actuated electrically through the brake pedal. A fifth wheel with a Weston tachometer and speed indicator was used to aid the driver in maintaining the desired speed before the brakes were applied. The stopping distance from the paint mark to the gun on the car after it had stopped was measured with a steel tape (Fig. 12). The tests were run on flat grades and the average coefficients for runs in both directions were computed using the standard stopping distance formula:

$$S = \frac{V^2}{30f}$$

where S = the average stopping distance in feet

V = the initial speed in m.p.h. at which the brakes were applied

f = the average coefficient of friction.

In the braking tests with the two-wheel trailer, an FWD truck was used and the integrating dynamometer shown in Figure 28. The FWD truck carried a 250-gal. water tank and a rotary pump driven by a small gas engine which could spray water on the road at a maximum rate of 11 gal. per minute and at a pressure of 40 lb. per sq. in. in such a way that a path slightly over a foot in width could be sprayed for one or both trailer wheels as needed. A rotary compressor mounted over the truck engine provided air at 100 lb. pressure in a tank on the truck. The trailer brakes were Linderman air brakes with valve arrangements to make it possible to apply brakes on one or both trailer wheels at air pressures ranging from 10 to 65 lb. per sq. in. The air line couplings were of the quickly detachable type to facilitate detaching the trailer when turning around on a narrow road. The trailer was built using a front axle from a $1\frac{1}{2}$-ton Ford truck. The body was of steel and filled with bags of gravel to bring the weight of the trailer up to 1790 lb. which, after deducting the load transfer at the hitch, produced an axle load of 1710 lb. or the same as the axle load on the test cars. The springs on the trailer were leaf springs. Snubbers were also attached to the trailer to prevent excessive vibration and bouncing on rough roads.

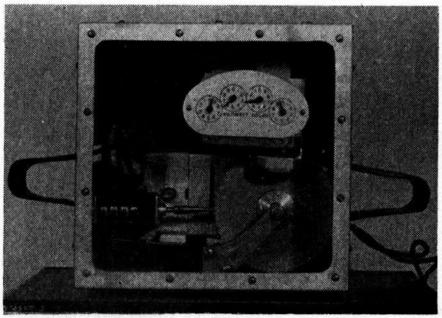

Figure 28. Integrating Dynamometer Used in Towing-Braking Tests

In the braking tests, the integrating

dynamometer was attached to the trailer and tow truck in line with the wheel being braked in such a manner that the entire braking force was transmitted through the dynamometer (Fig. 29). Readings of the two revolution counters on the integrating dynamometer were taken at the beginning and end of each run and from these readings the braking forces and coefficients of friction were determined from a calibration curve. For the locked wheel tests the maximum air pressure was used and the brakes applied with a manually operated quick release valve. The average braking force for each run was measured for 5 to 10-sec. depending upon the speed, which was maintained constant at 10, 20, 30, and 40 m.p.h. At the higher speeds short braking periods were required because the heat due to tire friction was so great that it caused inconsistent results if these values were exceeded. On certain dry surfaces braking for more than 10 sec. burned blisters on the tire tread and damaged it to such an extent that only a limited number of tests were made and then only for short braking periods. The calibration tests showed that a minimum braking time of 5 sec. was necessary to obtain accurate readings with the dynamometer.

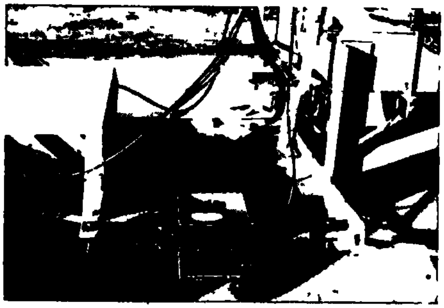

Figure 29. Integrating Dynamometer in Position for Measuring Braking Forces in Towing-Braking Tests.

For the variable pressure braking tests, the desired pressure was obtained by adjustment of the variable pressure valves in the air line to each brake. The pressure in each line was indicated on pressure gauges mounted on the work table on the truck The speed at which each wheel on the trailer was rotating was observed on two Weston speed indicators also mounted on the table. The magneto generator for each speed indicator was attached to the fixed axle of the trailer and was gear driven. Instantaneous speed readings could be taken with an accuracy of 0.1 m p h. which was considered necessary to obtain a true measure of the extent and nature of wheel slippage during braking.

The toe-in and toe-out angle tests were also run with the trailer and dynamometer. The trailer was built using a split tie rod and a gear arrangement operated by a starting motor in such a way that by throwing a switch in the truck the wheels could be toed-in or out at various angles up to 12 deg For the angle tests the dynamometer was attached to a center hitch. The toe-in and toe-out angles were indicated by an arm on a scale on the front of the trailer in plain sight of the observer on the truck.

All of the tests were run on level straight sections of highway with the wheels of the trailer near the center of the wheel tracks of the traffic on the highway. Tests were run in both directions and the results averaged to eliminate the effect of grade. The no load value for the dynamometer was checked several times daily and a complete calibration over the entire load range observed in the tests was run about once a month.

RESULTS OF COEFFICIENT OF FRICTION TESTS

The results of the more important coefficient of friction tests on the various road surfaces are shown in Figs 30 to 36. A complete series of tests covering each of the four types of measurement was not run on all of the 10 types of surfaces

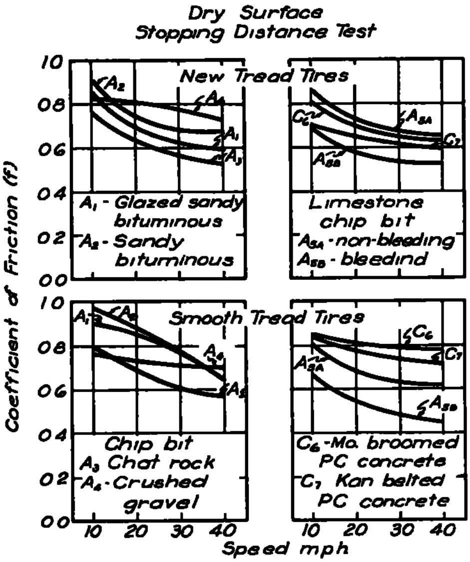

Figure 30. Coefficients of Friction on Various P.C. Concrete and Bituminous Road Surfaces When Dry as Measured by Stopping Distance Method. Tire Size 6.00 by 16 Inch. Ave. Wheel Load 860 Lb.

covered in this phase of the investigation due to lack of time and personnel However, the towing-braking tests and the stopping-distance tests were run on all of the surfaces tested, and all four methods of measurement were used on the types of surfaces selected as most representative for studying every phase of the tire and road friction problem

The results of the stopping distance tests on the surfaces when dry (Fig. 30) and of the stopping distance and towing-braking tests (Fig 31) on these surfaces when wet revealed no unexpected new road surface skidding characteristics which had not been determined in similar tests in previous investigations[5] The decrease in the coefficients of friction with an increase in speed, the high coefficients for the harsh abrasive surfaces, and the

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[5] Moyer, R A Skidding Characteristics of Road Surfaces *Proceedings*, Highway Research Board, Vol 13 (1933)

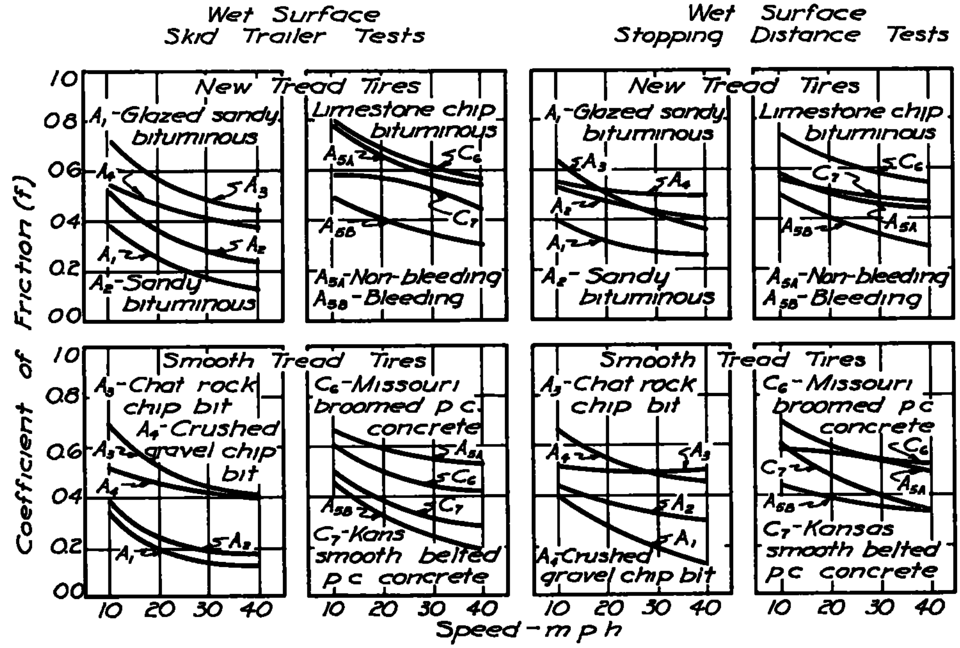

Figure 31. Coefficients of Friction on Various P.C. Concrete and Bituminous Road Surfaces When Wet as Measured by Skid Trailer and Stopping Distance Methods. Tire Size, 6.00 by 16 Inch. Average Wheel Load 860 Lb.

dangerously low coefficients for the glazed surfaces with excess asphalt when wet were clearly evident here as in previous tests The coefficients for all of the surfaces in the dry condition were high and supported the previous finding that dry surfaces free of loose sand or other aggregate presented no skidding hazard. The belted concrete surface worn smooth by traffic gave results very similar to the results in the 1933 tests That is, the coefficients on this surface when wet provided values of 0 30 or less at speeds above 30 m p h. and while this was amply safe for ordinary driving operations, it was not safe for emergency braking and sharp turning operations where coefficients of 0 40 to 0.60 are required The broomed portland cement concrete in Missouri provided the highest coefficients measured in the braking tests on wet surfaces. The coefficients on the chat rock chip, limestone chip (non-bleeding type), and the crushed gravel chip bituminous surfaces were practically all above 0 50 at 40 m p h when wet and were only slightly lower than the coefficients for the wet broomed concrete for which values ranging from 0 55 to 0 80 were measured It should be noted that the values for the wet glazed sandy bituminous and the bleeding limestone chip surfaces were in the danger zone with coefficients below 0 30 and even below 0 20 which is in the range of values for snow and ice

The coefficients for the stopping distance tests with the four wheels locked were plotted for the initial speed rather than for the average speed although it is recognized that the computed coefficients are average values for all speeds from the initial to zero speed and probably should be plotted for the average. However, since it was desired to convey the idea that braking started at the initial speed for which the coefficients were plotted and since the resulting curves checked fairly closely the corresponding curves for coefficients obtained in the towing-braking tests which were run at constant speeds, the method used is preferred by the writer. Considerable weight should be given to the results obtained in the stopping distance tests because the possibilities of error by this method were very small and the results obtained were remarkably uniform It is interesting to note that the ranking of the surfaces for slipperiness in the wet tests was almost identical by both the towing-braking tests and the stopping distance tests.

Figure 32 indicates the wide spread in

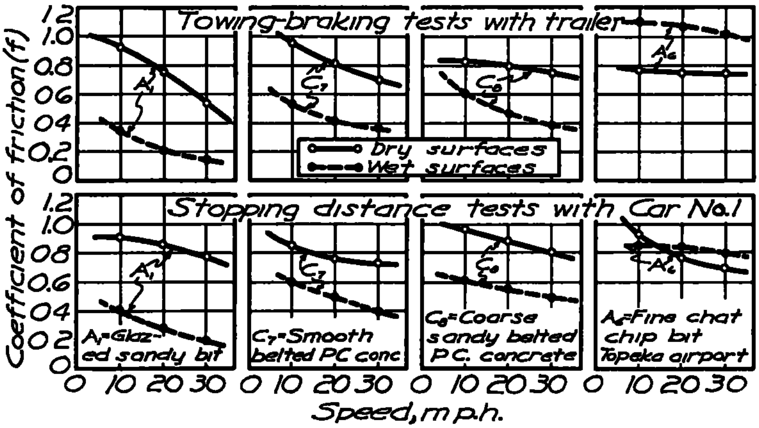

Figure 32. Coefficients of Friction on Typical P.C. Concrete and Bituminous Surfaces (Including One Airport Runway) for the Dry and Wet Conditions as Measured by the Trailer Towing-Braking and by the Stopping Distance Methods. Tire Size 6.00 by 16 Inch, Smooth Tread. Average Wheel Load 860 Lb.

coefficients of friction for typical concrete and bituminous surfaces for the dry and wet condition. The greatest reduction for the dry and wet condition was observed on the glazed sandy bituminous surface which provided values from 0 90 to 0 50 at speeds from 10 to 40 m.p h. when dry and from 0 35 to 0.15 when wet. The contrast here was so marked that it was not surprising to find skidding accidents a common occurrence on this surface during rainy weather. In fact, three skidding accidents were observed in one day during August, 1942, within a 50 mile section of glazed asphalt on which tests were run in the rain. The maximum safe speed on straight sections of this road was in the range of 35 to 40 m.p h. and the test drivers agreed that extra care in driving at 35 m p.h. was required to keep the car from skidding when this surface was wet.

The tests on the runways of the Topeka Municipal Airport provided unusual results in two respects, the coefficients were the highest measured in the 1942 tests and the coefficients for the wet surface condition were higher than for the dry condition These runways were built in 1935 using a seal coat with fine sharp chat chips for cover material. The airport traffic has been light on the runways and the chips have retained their sharpness. There was no indication of excess asphalt on the surface. The coefficients for the runway were very high with values ranging from 0 70 to 1.10. The measurement of higher coefficients for this surface when wet than when dry is not new Similar results were obtained on surfaces of this type in tests by the Oregon Highway Department[6] A serious objection to this type of surface is the high rate of tire wear which in some respects is more costly and causes greater inconvenience in the operation of airplanes than in motor vehicles. Surfaces which provide coefficients as high as were found on this runway are certain to be highly abrasive and it is doubtful if the extra factor of safety against skidding provided by such a surface is required for safe vehicle operation. In the regular driving tests it was found that coefficients in the range of 0.50 to 0 60 at 40 m p h. provide ample protection against skidding in the usual emergency stops or turns and the tire wear on such surfaces should be one half to one third of the wear on the chat chip type surfaces

Typical results of the variable braking pressure tests for four surfaces are given in Figure 33. It is interesting to note the relative values for the coefficients on the same surface at various braking pressures for the dry and wet tests and also to note the maximum values generally obtained for the skid impending condition and the subsequent falling off as the brake pressures were increased and the wheels were locked.

The difference in the coefficients for the skid impending condition and for the locked wheel condition was greater in the dry than in the wet tests This was, no doubt, due to the greater variations in the surface characteristics noted in the wet tests than in the dry tests Any factor such as increased moisture film thickness which might cause a sudden decrease in the coefficient would be certain to cause the wheel to lock where otherwise a high skid impending coefficient would have resulted On the wet slippery glazed sandy bituminous surface, a high skid impending coefficient would have provided an added safety factor It should be noted, however, that the tests on this surface showed a lower skid impending coefficient than the locked wheel coefficient. This reversal of the usual order in the coefficients was due to the corrugated condition of this surface. The excess asphalt caused the bituminous mat to shove and

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[6] Oregon State Highway Department, "Skid-resistant characteristics of Oregon Pavement Surfaces," Technical Report No. 39-5 Salem (1939)

creep and the variations in the tire contact due to the bouncing wheels caused wide variations in the coefficients which in turn caused the wheels to lock much sooner than if the surface had been as smooth as the concrete surfaces.

The higher coefficients obtained on many wet surfaces condition as compared to the dry condition for the same brake pressure as shown in Figure 33 were due to two factors. The temperature of the rubber was an important factor which influenced the coefficients of friction In the wet tests the tread temperatures were at least 50 deg. F. below the tread temperatures in the dry tests Since in previous tests higher coefficients were found at low tread temperatures than at high temperatures, the higher coefficients for the wet condition at the same brake pressure appears to be the logical result. The second factor involved the cooling effect of the water on the brake drums and brake linings which changed the coefficients of friction of these materials to the extent that higher coefficients were obtained in the wet tests than in the dry tests for the same brake pressure. The tests indicated that the heating effects were greater on the smooth tread tires than on the new tread tires. This suggests the value of certain features in tread design patterns and in the tread rubber to promote low tire temperatures as a means for increasing coefficients of friction on wet surfaces. The low tread temperatures would also have the additional advantage of reducing the rate of tire wear and the tendency for tires to fail due to heat blowouts

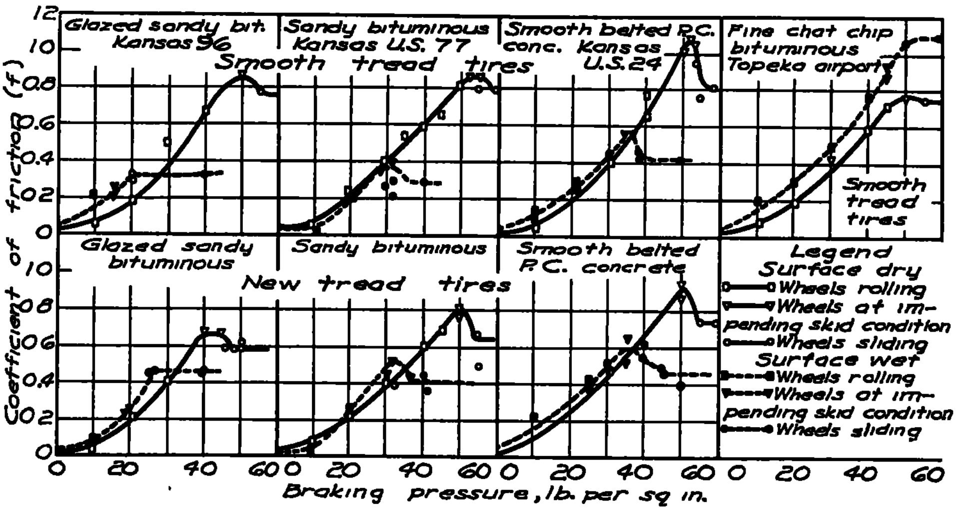

Figure 33. Coefficients of Friction at Various Braking Pressures Measured in the Towing-Braking Tests with Trailer on Typical Bituminous and Concrete Road Surfaces in Wet and Dry Condition. Speed 20 M.P.H. New Tread and Smooth Tread Tires, 6.00 by 16 Inch. Wheel Load 860 Lb.

The data on wheel slippage (Fig. 34) obtained in the variable braking pressure tests revealed some interesting tire and road surface effects. The large increase in tire wear as the amount of wheel slippage increased was corroborated by the skid marks on the road surface when the wheels were locked and the wheels slipped. The least slippage was observed on the dry smooth surfaces such as the belted concrete where practically no slippage was observed for coefficients up to 0 60 for new tires and up to 0.40 for smooth tires.

The usual slippage for the maximum braking force on dry surfaces was in the range of 6 to 10 per cent On wet surfaces the usual range was from 6 to 16 per cent. The greatest slippage was observed for the smooth tires on wet surfaces. For most surfaces, the slippage increased rather sharply from 0 to 6 per cent as the brake pressures were increased and the coefficients of friction approached the maximum values for the given surface.

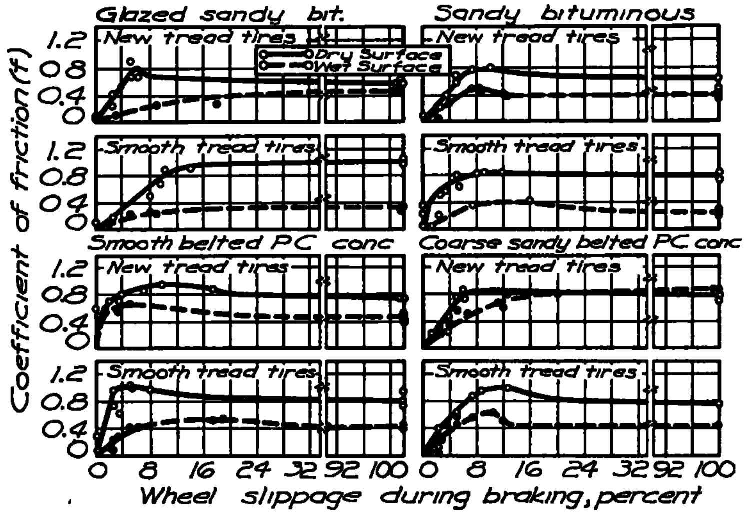

Figure 34. Wheel Slippage and Coefficients of Friction Measured in Towing-Braking Tests with Trailer on Typical Bituminous and P.C. Concrete Surfaces in Dry and Wet Condition. Speed 20 M.P.H. New Tread and Smooth Tread Tires, 6.00 by 16 In. Wheel Load 860 Lb.

Low slippage was observed on smooth surfaces with a low coarseness index and on surfaces which provided high coefficients of friction when wet or dry Surfaces with these characteristics are highly desirable since they cause little slippage for the usual maximum braking coefficients of 0 3 to 0 4 and the increase in tire wear due to moderate braking on such a surface would not be as great as on a slippery surface where the slippage would be much higher for the same braking force

The towing-angle tests (Fig 35) provided a measure of the maximum resistance to skidding sideways of the type developed on curves. In these tests the wheels were continually rolling forward at a given angle with the path of travel and were developing the maximum frictional forces which the surface could provide for the given angle The tendency of tires to slide or slip commonly observed in the braking tests was eliminated almost entirely in these tests The forces were measured in the direction of travel and, therefore, the component of the side skid force in the line of travel was measured instead of the actual side skid force.

The tests indicated that there was a steady increase in the coefficients as the toe-in and toe-out angles were increased from 0 to 10 deg The results of the angle tests on the dry surfaces were approximately the same for all surfaces and were far more uniform than the results of the braking tests on the same surfaces The coefficient for the 10-deg angle was about 0 2 which indicated a side skid coefficient of about 1 0 for the dry surfaces In the tests on wet surfaces, there was a definite reduction in the coefficients for the wet as compared to the dry condition although the change was not as great as in the braking tests. For the wet condition the lowest coefficients were found on the glazed sandy bituminous and the highest on the coarse sandy concrete pavement. The coefficient for the 10-deg angle on the glazed bituminous surface when wet was found to be 0.08 which indicates that the side skid coefficient was about 0.40. The tests at various speeds indicated little change in the coefficients for the various surfaces due to speed.

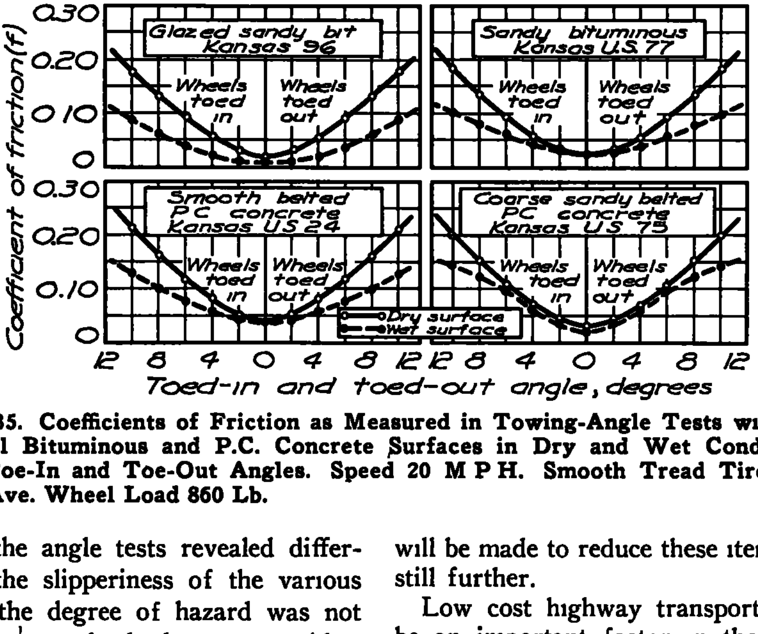

Figure 35. Coefficients of Friction as Measured in Towing-Angle Tests with Trailer on Typical Bituminous and P.C. Concrete Surfaces in Dry and Wet Conditions for Various Toe-In and Toe-Out Angles. Speed 20 M P H. Smooth Tread Tires 6.00 by 16 Inch. Ave. Wheel Load 860 Lb.

While the angle tests revealed differences in the slipperiness of the various surfaces, the degree of hazard was not so evident as in the braking tests. Also, as was found in the angle tests in a previous study run by an entirely different method, the maximum side-skid coefficients were higher than the coefficients obtained in the braking tests on the same surfaces. Therefore, since the frictional requirements are normally greater when braking than when driving on curves and since the friction which the road surfaces can provide is lower for braking than for driving on curves, it seems reasonable to conclude that the best measure of road slipperiness is obtained by means of braking tests.

SIGNIFICANCE OF THE TEST RESULTS IN THE IMPROVEMENT OF POST-WAR HIGHWAYS

A major consideration in the development of transportation after the present war will be economy. The vehicle operating costs for gasoline, oil, tires, maintenance and repairs for the 1941 model cars used in these tests reached the low total of 1½ cents per mile. Improvements in cars and highways can, and no doubt will be made to reduce these items of cost still further.

Low cost highway transportation will be an important factor in the economic and social life of our people after the war just as it was before. Competition with air transportation may prove to be fairly keen but the advantages of low cost per mile, comfort, convenience, and safety should continue to favor highway transportation.

The results of the tests in this investigation indicated the general nature of certain types of improvements in the design and construction of highways which will contribute to lower operating costs, greater comfort, and greater safety. It was shown that the reduction in gasoline costs due to improvements in bituminous and concrete road surfaces is likely to be small The tests indicated that tire costs and car maintenance costs can be reduced if construction methods are used to eliminate the fast rate of tire wear caused by certain sharp hard abrasive types of aggregate and surface finishing methods and if roads are built to high standards of smoothness. The tests on road roughness indicated the importance of smooth surfaces Since riding comfort is important in making motoring attractive, methods of construction and maintenance of types which are known to produce smooth riding surfaces should be adopted generally. Greater safety due to road surface effects may be obtained by constructing and maintaining suitable non-skid type surfaces The tire and road friction tests demonstrated that it is possible to build road surfaces with an ample margin of safety to prevent skidding accidents without making these surfaces so abrasive as to cause excessive tire wear.

While many miles of four-lane divided highways will be built on heavily traveled roads, the two lane highway will continue the predominating type in rural areas and the major efforts of the highway engineer will be directed toward its improvement Tests were run on two surfaces, the broomed concrete in Missouri and a chip treated bituminous surface in Wyoming, which exemplify the type of construction based on sound engineering which should fit into the post-war plans for the improvement of two-lane highways. Stabilized base construction and improved methods in surface construction should assure permanence and a high standard of smoothness on these roads for many years

GENERAL CONCLUSIONS

The results of the extensive tests on the various portland cement concrete and bituminous surfaces covered by this report indicated that in general the differences in vehicle operating costs on these two major road surface types are negligible if they are maintained with moderately smooth riding surfaces.

In the road roughness tests the observers were of the opinion that the roughness index of 100 represented a high standard of smoothness, and that an index greater than 200 indicated definitely uncomfortable conditions

That speed is one of the most important factors contributing to variations in tire wear was indicated by the fact that the wear rate at an average speed of 60 m.p h. was two to four times greater than at 35 m.p.h The variations due to the type of road surface on which tests were run in this investigation were even greater than those due to speed since the wear rates on the harsh abrasive chat chip bituminous surface and on the broomed concrete surface were five times greater than on the softer limestone chip and the sandy bituminous surfaces where a slight excess in the amount of asphalt used in the seal coat contributed to the lower wear. In the present war emergency with the critical shortage of rubber, the use of a seal coat, which provides a slight excess of asphalt up to the point where bleeding creates a slippery road condition when wet, is recommended as an effective and justifiable method to reduce tire wear. Treatments of this type are recommended as justifiable only during the present emergency while the national speed limit of 35 m p.h. remains in effect. The skidding hazard at speeds above 35 m p.h. is a continual cause of accidents on surfaces of this type when wet and steps should be taken to correct this hazard before these surfaces are opened to traffic at speeds above 35 m.p.h.

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