THE ECONOMICS OF HIGHWAY ALIGNMENT DESIGN

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SYNOPSIS

In selecting the location for any highway extension or improvement it is essential that some method be developed for determining the economic value of curvature and/or central angle This paper is a summary of researches along this line made by the Oregon State Highway Department and shortly to be published together with certain other data as Technical Bulletin No 15, "The Effect of Surface Type Alignment and Traffic Congestion on Vehicle Fuel Consumption" From a large number of test runs utilizing different vehicular types and highways presenting a wide variety of alignment conditions it was possible to relate to alignment characteristics both fuel consumption and average traffic speed While these researches are far from exhaustive they do indicate a logical method of approach.

It was found that the central angle index (total central angle per mile) furnishes a convenient and fairly accurate method of rating alignments and of determining the relative economic value of alternate locations.

It was also found that there is a definite resistance to the translation of any vehicle over curved alignment which resistance may be expressed in pounds per ton and may amount to as much as that over a 3 per cent tangent grade.

Certain curves are indicated which may be employed with fair accuracy to calculate the effect of alignment on speed and on vehicle fuel consumption.

In the selection of the alignment design (ordinarily referred to as the location) for any proposed highway extension or improvement certain questions immediately arise: How may alternate alignment designs be rated for comparison and compared? What economic value can be placed upon reduction in curvature? For given traffic conditions, what first cost may be justifiably incurred for reducing the total central angle per mile in a given project by a certain definite amount? It is to these inquiries that this paper is directed in an attempt to offer, if not a complete solution, at least a method of attack

FUNDAMENTAL CRITERIA

The basic criteria for the comparison of any highway extension or improvement are (1) its economic justification and (2) its financial feasibility. Of these, the first is obviously the paramount consideration for if a project fails to find economic justification, there is little need to investigate it further. The present investigation will therefore be confined largely to this phase.

Economic justification is most readily measured by the ratio of benefits to costs If this ratio (the benefit quotient) is greater than unity the project finds justification; if it is less than unity there is no logical reason for considering it

Aside from general community and special land benefits, the principal benefits growing out of improved facilities for highway transport are: reduction in vehicular operation expense and savings in time for operators, passengers, and recipients of motor transport service. These benefits, in general, accrue by virtue of (1) reduction in distance between termini, (2) reduction in rise and fall, (3) improvement in gradients, (4) improved roadway surfaces, (5) elimination of stops and congestional friction and (6) better alignment conditions.

In reference to the first five of these items considerable data are available in the literature but little, if any, attempt has been made hitherto to determine and evaluate those benefits directly attributable to alignment.

Aside from tire wear and vehicular maintenance and depreciation, which are exceedingly difficult of exact determination, any change in alignment conditions modifies the benefit schedule in that it modifies the rate of fuel consumption and it changes attainable safe traffic speeds In an attempt to relate these latter two factors (fuel consumption and maximum safe speed) to highway alignment, a series of tests were inaugurated by the Oregon Highway Department in 1937 under the general direction of the writer and the immediate supervision of Mr. John Beakey, Traffic Engineer for the Department. These researches, among others, are completely described in Oregon Technical Bulletin No 15 entitled "The Effect of Surface Type, Alignment, and Traffic Congestion on Vehicle Fuel Consumption" now in process of preparation, and the paragraphs which follow are largely extracted therefrom.

TESTS

The field procedure consisted essentially in the making of a large number of runs over measured test sections covering the widest possible range of alignment conditions for the purpose of determining fuel consumption and maximum safe speed values. Three test vehicles were employed, (1) a 1938 Ford Sedan (gross weight 3,380 lb), (2) a 1937 Buick "60" (gross weight 4,240 lb.), and (3) a 1939 Chevrolet Dump Truck (gross weight 12,425 lb). A description of the testing equipment and the method of preparing each vehicle for the test runs will be found in Technical Bulletin No. 15. Prior to the test runs each vehicle was checked for all mechanical and engine adjustments and the carburetor set for a maximum economy air-fuel ratio The fuel was measured by a constant displacement fuel meter equipped with a graduated transparent metering cylinder calibrated to read to thousandths and (by estimation) to ten thousandths of a gallon.

Atmospheric conditions were recorded before each series of runs. Barometer and psychrometer readings were generally obtained from portable instruments while wind velocities were obtained by means of an anemometer or from local weather bureau stations or airports. Tests were run only where the wind velocity was very low. Constant operating temperatures for the test vehicle were established by driving it a considerable distance before the runs were started. Tire pressures were then checked and adjusted In all preliminary driving the fuel was routed through the fuel meter in order to stabilize the temperature of that instrument.

For each test section and for each test vehicle enough test runs were made at each speed to establish a well stabilized average. Runs were made in both directions to compensate for the effects of wind and any slight change in gradient. Many of the tests were run at night in order to eliminate the interference of heavy traffic and to take advantage of the more uniform conditions of temperature and atmosphere and lower wind velocity.

Test runs were made at constant speed beginning with the lowest value which could be made to yield consistent results and increasing by ten-mile-per-hour increments to the maximum speed at which the section could be negotiated with safety It was sometimes necessary to cut the last speed increment to five miles per hour. The speedometer of the test vehicle was employed only as an aid to constant speed driving, the true speed being computed from the elapsed time as measured by a one-tenth second stop watch

METHOD OF RATING ALIGNMENT

The maximum horizontal curvature permitted by the design standards now employed by the Oregon Highway Department are as indicated in Table 1

A study of the data in Table 1 indicates that, even with modern design standards, both the total central angle per mile and the degree of curvature may vary through a wide range. The length of the individual curves will likewise vary. Any method of alignment rating which takes into consideration both the length and the degree (radius) of the individual curves would, of necessity, be exceedingly cumbersome. For this reason it has been previously suggested (see Oregon Technical Bulletin No. 7, 1938 Revision) that alignments be rated and compared on the basis of the total amount of central angle per mile. This suggestion immediately raised the question as to whether or not the factors of length and degree of individual curves could be neglected without introducing errors of material magnitude in the comparison.

The results of the preliminary tests were quite satisfying in this regard. First it appeared that, for any given amount of central angle per mile, the effect of the length of the individual curves was slight, that is to say, a few long curves would, within reasonable limits, produce the same effect as a larger number of shorter ones having the same total central angle. Second, it appears that, since sections of curved alignment having a large total central angle per mile invariably have a large number of sharp curves, the total central angle index, to a considerable extent at least, automatically takes care of the degree of curvature. Even for those sections having varying standards of curvature for the same total central angle, the influence of the degree of curvature is comparatively small. This last point is nicely illustrated by a comparison of Figures 3 and 5. The former represents conditions encountered on test sections constructed to old alignment standards where individual curvature was sharp, while the latter represents conditions encountered on test sections constructed to modern alignment standards, the individual curves being of longer radii and more adequately superelevated. Obviously fuel requirements, even for the tangent sections, were not identical owing to the effect of roadway surface and atmospheric conditions, but if the two sets of graphs are superimposed in such a manner as to bring the two tangent graphs into coincidence, the other graphs representing fuel consumption values vs. speed for varying amounts of total central angle will be brought into practical coincidence.

TABLE 1

OREGON STATE HIGHWAY DEPARTMENT

Maximum Horizontal Curve Permitted by Minimum Standards for Design of Highways Depending upon Traffic Density, Character of Traffic, Assumed Design Speed, and Topography

Item	Volume of traffic anticipated per hour[a]					
	500	200	50	25	15	10
Level country						
Safe speed, m p h	70	60	55	50	40	35
Maximum curve in degrees	3	6	7	10	14	16
Rolling country						
Safe speed, m p.h	60	50	45	40	35	30
Maximum curve in degrees	6	10	12	14	16	24
Mountainous country						
Safe speed, m p h	50	45	40	35	30	20
Maximum curve in degrees	10	12	14	20	24	56

[a] Mixed traffic including both passenger vehicles and trucks.

In view of the foregoing it was felt that the central angle index (total central angle per mile) could be employed with fair accuracy as a basis for rating alignment conditions, especially when comparing or evaluating alignment designs constructed to the same general standards.

TEST SECTIONS

The first general requisite in the selection of test sections was that the total central angle per mile should vary in fairly uniform increments from zero (tangent alignment) to the maximum encountered on sections in actual use (in these tests 1760° per mile). It was also convenient (if not absolutely necessary) to select sections which were practically level and provided with a high-type pavement surface in good condition. For a few of the tests it was necessary to use sections on a grade, in which instances the data obtained were corrected by subtracting the excess fuel required by virtue of the gradient. In a few cases it was also necessary to adopt sections somewhat less than one mile in length because mile-long sections having the desired amount of central angle could not be located. Extremely short sections, however, were not considered in any of the tests, since it was found that errors were introduced. These errors arose by virtue of the fact that these lengths were not sufficient to average out variations in fuel measurement such as that due to the effect of centrifugal force on the level of the fuel in the carburetor float chamber. Figures 1 and 2 are strip maps of two of the test sections selected.

RESULTS

Before the data obtained with the test vehicles are presented some discussion of the constant speed method of testing is perhaps in order. This method was adopted in order to render the results comparable with those determined by future tests or on other investigations and the question immediately to arise was whether or not this method represented operation under actual conditions. To meet this inquiry a limited number of observations were made of the speed at which various sections were negotiated under operating conditions.

It was found that the majority of drivers operate at nearly constant speed decelerating against compression and accelerating again over a relatively small-speed interval. Only a few drivers applied brakes when entering a curve. It was therefore concluded that tests made at constant speed would be quite closely representative of actual operating conditions in the majority of cases

It was also determined (from test runs) that on the less tortuous alignments the maximum average speed attained by variable speed operation would exceed the maximum constant speed attainable by as much as five or six miles per hour. On the extremely tortuous alignment sections there was practically no difference in the top speeds attained by the two methods of operation.

From all of the foregoing it would appear that the method employed in making the test runs may be considered as fairly representative of actual operation.

Fuel consumption-speed curves developed with the 1938 Ford Sedan on seven test sections including a tangent section are shown in Figure 3. The total central angle per mile for the seven test sections was as follows: 0 (tangent), 186, 338, 509, 665, 1027 and 1760 deg., but the speed-fuel consumption curves have been interpolated for even 200-deg. increments from zero to 1600 deg. and extrapolated for 1800 deg.

These same data arranged a little differently are shown in Figure 4. Here total central angle per mile is plotted as abscissa while ordinates are plotted as speed and the "relative index of fuel consumption," this latter being simply the ratio of fuel consumption on any given align-

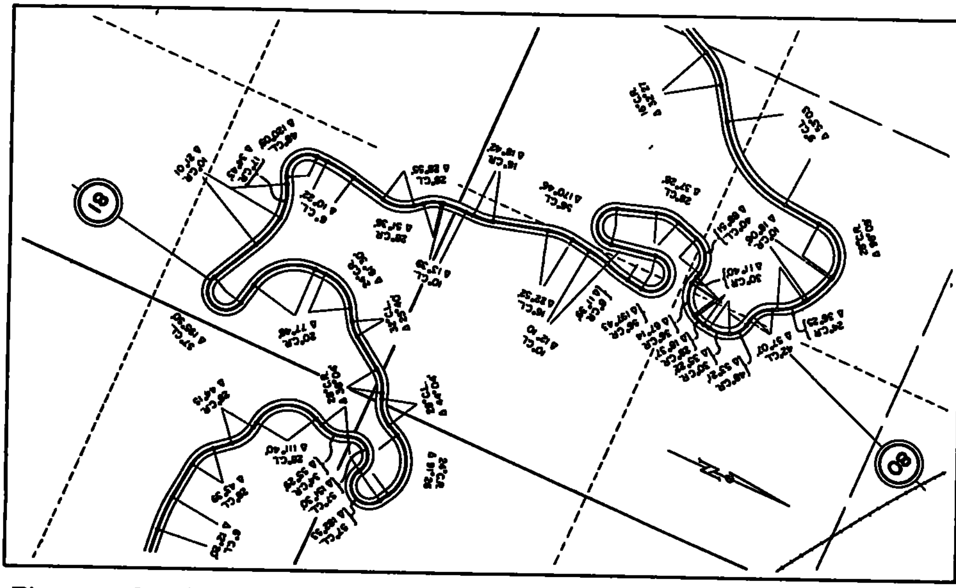

Figure 1. Old Standard Alignment Test Section M.P. 80 to M.P. 81, Upper Columbia River Highway, Length of Section 1 Mile, Total Central Angle Per Mile=1027 Degrees.

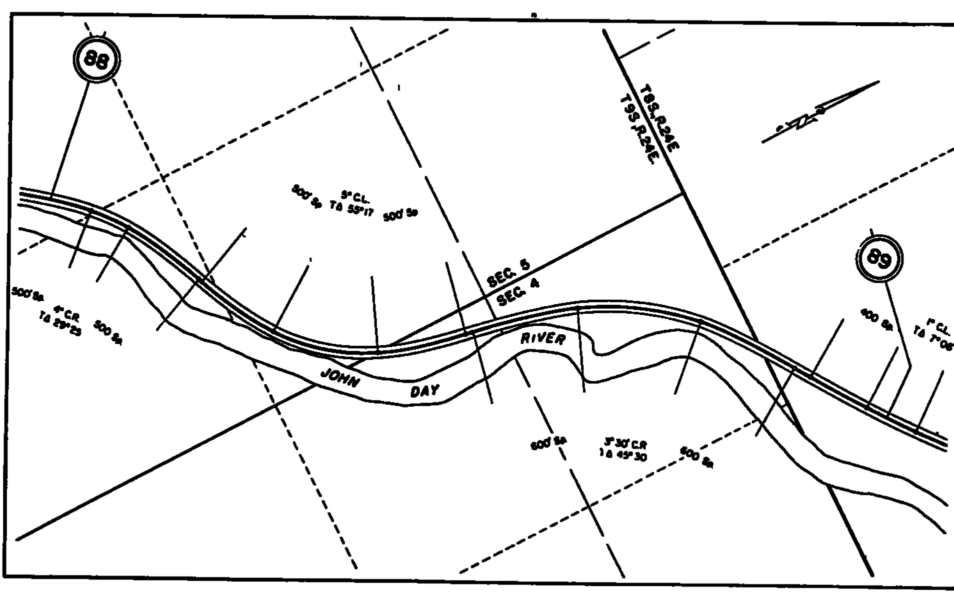

Figure 2. New Standard Alignment Test Section M.P. 88 to M.P. 89 on Ore. 19 North of Spray, Length of Section 1 Mile, Total Central Angle Per Mile=130 Degrees

ment to that experienced at the same speed on tangent. In Figure 4 are indicated graphs for the average observed traffic speeds and for the maximum speed attainable in these tests Relative fuel consumption is also indicated for constant speeds of 20, 25, 30, 40 and 50 m.p h.

The test data plotted in Figures 3 and 4 were obtained over sections of highway built to relatively old alignment standards. In contrast to these graphs those in the newer sections being located at a higher elevation.

If, however, Figures 3 and 5 are superimposed in such manner as to bring the fuel requirement curves for tangent alignment into coincidence, the various graphs spaced at 200-deg. increments of central angle will also be brought into practical coincidence, this justifying the employment of the central angle index as a criteria for rating alignments regardless of the degree or degrees of individual

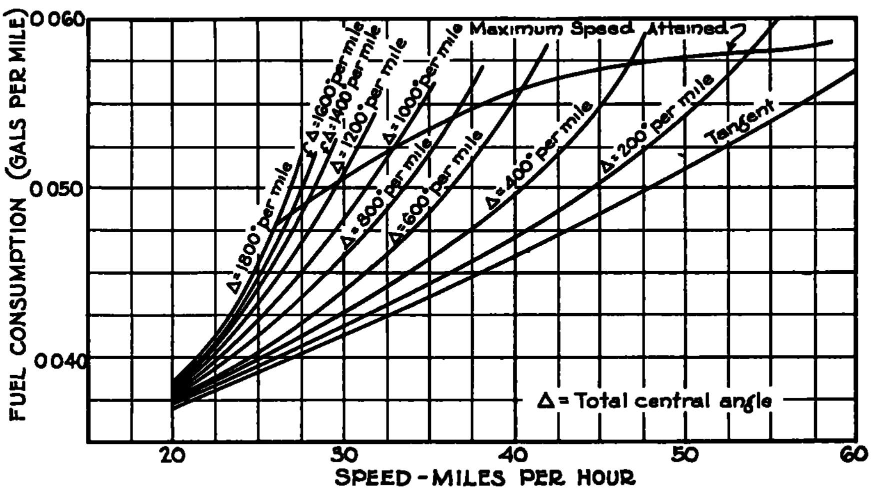

Figure 3. Fuel Consumption of 1938 Ford Sedan on Curved Alignment Shown in Increments of 200 Degrees of Central Angle Per Mile. Data Developed from Tests on Sections Constructed to Relatively Old Alignment Standards.

Figure 5 were developed from tests on sections constructed to modern alignment standards (indicated in Table 1), standards which provide, in general, for spiral transition curves and a more adequate superelevation.

A comparison of the two sets of graphs indicates that, in general, a slightly higher speed was attained on the newer sections. Also, the fuel consumption on these newer sections is distinctly lower even for the tangents, this latter condition being attributable to the better wearing surfaces involved and (to a certain degree at least) to the differences in air density, curvature involved, or the length of the individual curves. Obviously the above assumption is not strictly true since the degree of curvature, and the length of the individual curves involved, does have an effect both on speed and on fuel consumption. A comparison of the graphs shown in Figures 3 and 5, however, would lead to the belief that the use of the central angle index as the sole rating criterion, neglecting these last factors, will be sufficiently exact for purposes of economic analysis.

Figures 6 and 7 indicate fuel requirements plotted against speed for the 1937

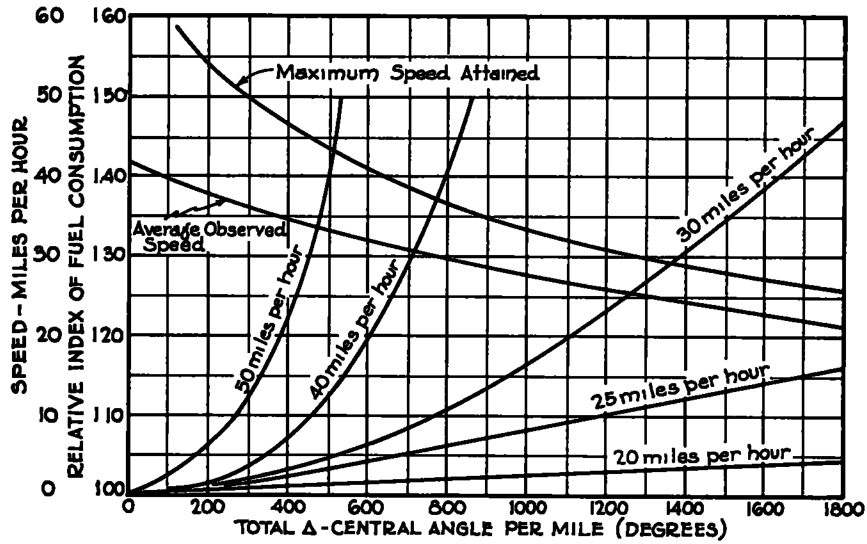

Figure 4. Relative Indices of Fuel Consumption and Maximum Constant Speed Attained on Each Test Section as a Function of Total Central Angle Per Mile (1938 Ford Sedan—Old Alignment Standards).

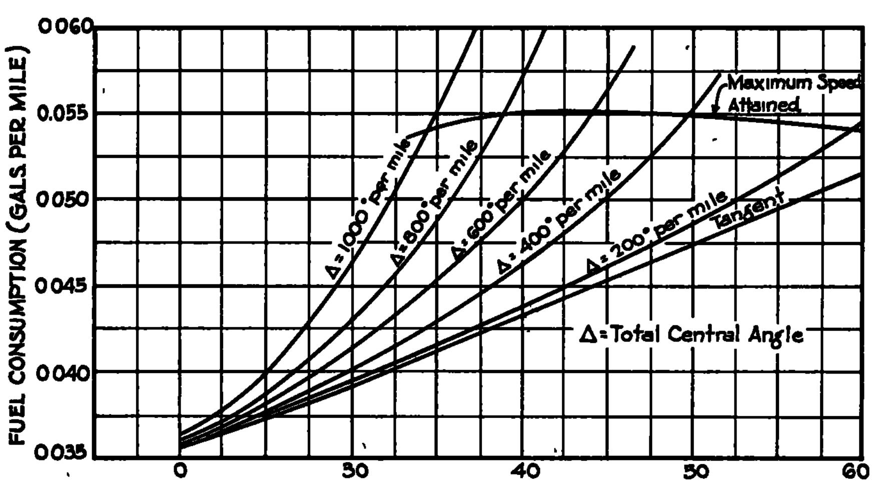

Figure 5. Fuel Consumption of 1938 Ford Sedan on Curved Alignment Shown in Increments of 200 Degrees of Central Angle Per Mile. Developed from Tests on Sections Constructed to Modern Alignment Standards.

Buick "60" test car. Figure 6 is for sections built to modern alignment standards, while Figure 7 is for the old alignment sections. Again, as in the case of the 1938 Ford, the modern alignment standards indicate a lower fuel consumption and a higher attainable speed. Again, however, it must be remembered that a great portion of these differences may be attributed directly to the superior surface types and better atmospheric conditions (higher altitude with consequent reduction in air resistance).

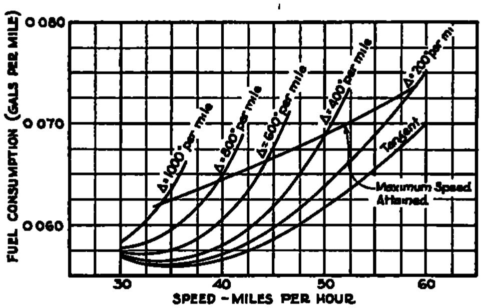

Figure 6. Fuel Consumption of 1937 Buick at 200-Deg. Increments of Central Angle Per Mile on Sections Constructed to New Alignment Standards.

Similar data for the 1939 Chevrolet Dump Truck are indicated in Figure 8 It was not possible to run this test vehicle over the more tortuous alignment sections since the gradients involved did not permit high-gear operation.

Figure 9 is a series of graphs indicating (for the 1938 Ford Sedan) horse power vs. fuel consumption at various speeds on various tangent grades. Since, for the same speed, equal fuel requirements indicate equal power requirements, it is possible, by relating the fuel requirements on level sections of varying central angle per mile to those for tangent sections of varying gradients, to determine the additional power required (and from this latter value the additional tractive effort) necessary to negotiate level sections of varying central angle index.

Figures 10 and 11 indicate these data for the 1938 Ford Sedan.

An inspection of Figures 9, 10 and 11 will indicate that there is a definite resistance to the translation of a vehicle moving over a level section of curved alignment, which resistance increases with the speed and, for any constant speed, increases with the central angle index (the total central angle per mile). This resistance may be as much as that developed in negotiating a tangent section on a 3 per cent grade.

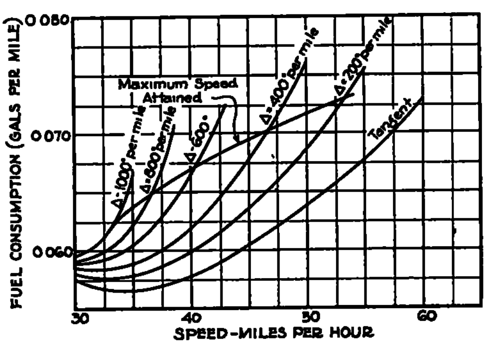

Figure 7. Fuel Consumption of 1937 Buick at 200-Deg. Increments of Total Central Angle Per Mile. Tests on Sections Having Old Alignment Standards.

TENTATIVE CONCLUSIONS

The foregoing researches are far from exhaustive. Further data are necessary to establish definite and reliable relationships. They do, however, indicate a logical method of approach and it is believed that they warrant the following tentative conclusions:

(a) The central angle index (the total central angle per mile) furnishes a convenient and fairly accurate method of rating alignments and determining the relative economic value of alternate alignment designs (locations) for any given set of traffic conditions.

(b) There is definite resistance to the translation of any vehicle over curved alignment which resistance may be expressed in pounds per ton of vehicular

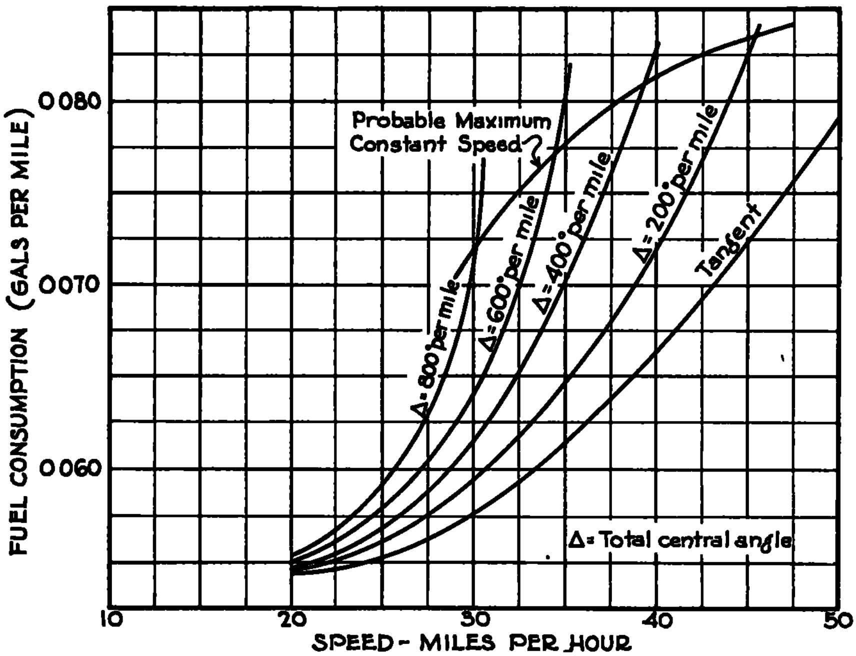

Figure 8. Fuel Consumption of 1939 Chevrolet Dump Truck at 200-Deg. Increments to 800-Deg. of Central Angle

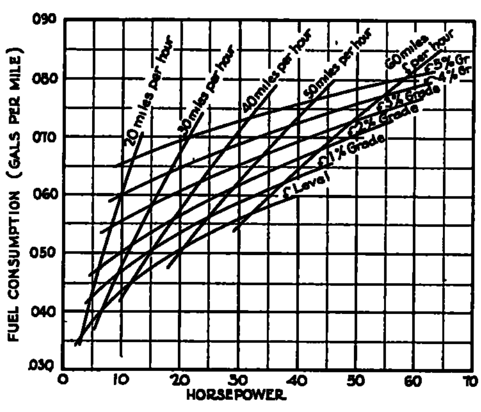

Figure 9. Fuel Consumption Vs. Horsepower for 1938 Ford Sedan

weight This may amount to as much as the resistance of a 3 per cent tangent grade

(c) The curves indicated in Figures 3 and 5 or Figures 6 and 7 cannot be directly compared for the reason that the effect of differences in surface type and air density would, of necessity, be included in the comparison. In general, Figures 5 and 7 should be employed for modern design standards and high-type surfaces, while for secondary roads, Figures 3 and 6 should be employed. In the absence of further data on truck performance, Figure 8 may be used in either case.

THE ECONOMIC COMPARISON OF ALTERNATE ALIGNMENT DESIGNS (LOCATIONS)

Before considering a specific problem it may be well to restate certain fundamental principles of engineering economics If the term B represents the total of annual benefits accruing to the patronage of any project by virtue of its construction and use, and if C represents the total annual expense involved in its construction, maintenance, and operation, the quotient $Q_B = B/C$ represents its economic warrant. If this quotient value is

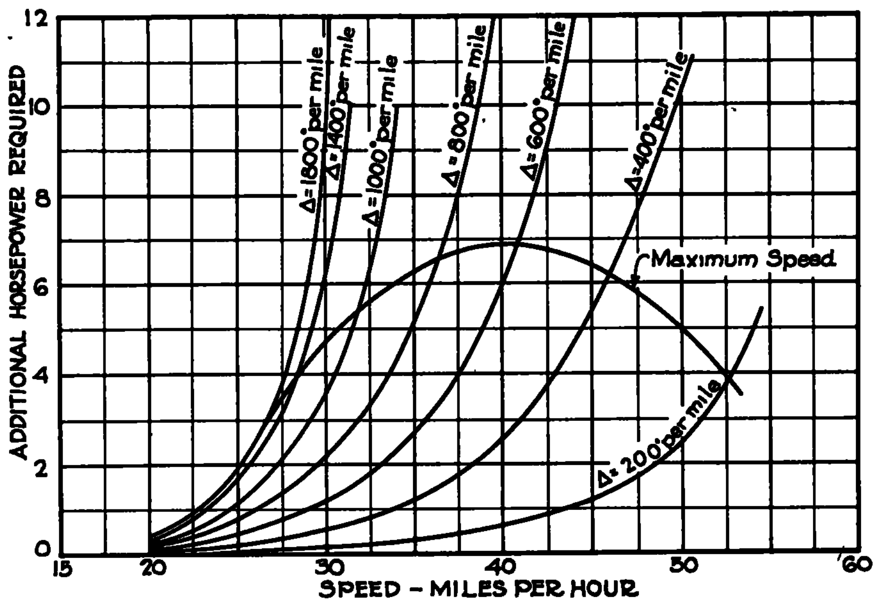

Figure 10. Horsepower Required to Overcome Alignment Resistance at 200-Deg. Increments of Total Central Angle Per Mile, 1938 Ford Sedan

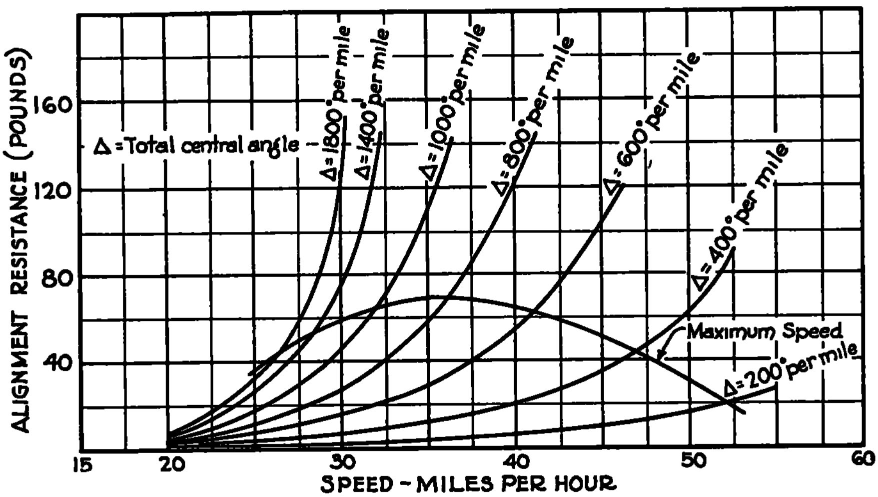

Figure 11. Average Effective Alignment Resistance Plotted at 200-Deg. Increments of Total Central Angle Per Mile, 1938 Ford Sedan

greater than unity the project finds justification, otherwise it does not.

Now let us suppose that there are two alternate designs being considered, and that the first design has a favorable benefit quotient (*i.e.*, $Q_B > 1.0$).

Let C represent the annual cost of the first design, and
B represent the annual benefits to be derived from it.
Let ΔC represent the *additional* cost of the alternate design, and
ΔB the *additional* benefits which may be expected.

For the first project $Q_B = B/C$

For the alternate $Q'_B = \frac{B+\Delta B}{C+\Delta C}$

To justify the selection of the alternate design it is apparent that $Q'_B \gtreqless Q_B$

That is to say:

$$\frac{B+\Delta B}{C+\Delta C} - \frac{B}{C_1} \gtreqless \text{Zero, or}$$

$$\Delta B/\Delta C \gtreqless Q_B$$

Expressing it in another way, the additional cost of the alternate design will not find economic justification if it exceeds $\Delta B \div Q_B$ where ΔB represents the additional benefits derived from the alternate design and Q_B represents the original benefit quotient.

The above reasoning is rather elementary but it will serve to clarify the method of solution outlined below We may now proceed to consider a specific problem.

Let us assume that a ten-mile section of highway reconstruction is under consideration utilizing modern design standards. Location No. 1 shows an average of 300 deg. of central angle per mile The total annual costs have been computed as well as the total annual benefits and from these data the benefit quotient Q_B has been determined to be 1.80. This quotient value is quite satisfactory; that is to say, the project as located finds ample economic justification but further reconnaissance indicates the possibility of an alternate line involving only 200 deg. of central angle per mile. The average annual traffic to be expected during the service life of the project is estimated to consist of 500,000 passenger vehicles and 60,000 commercial trucks and busses.

How much additional expenditure is justified for the alternate line (assuming no legal or topographic speed restrictions)?

From the curves we secure the data in Table 2.

Utilizing these data and an average time value (assumed for sake of illustration) of one cent per minute for passenger cars and two cents for trucks, we compute the benefit increment ΔB as follows:

500,000 passenger cars at 0 88 cents .	$4400 00
60,000 trucks at 2 06 cents..	1236 00
Total ΔB	$5636 00

$\Delta B - Q_B = 5636 \div 1\ 80 = \$3131\ 00$

This is the increment of annual cost which can be justified for the alternate

TABLE 2

Item	For design No 1 ($\Delta = 300°$)	For alternate design ($\Delta = 200°$)	Difference
Average speed of passenger cars·			
From Figure 5	54 5	59.5	5 0
From Figure 7	54 5	59 0	4 5
Average . .	54 5	59 25	4 75
Average time required per trip (10 mi.) ..	11 01 min	10 13 min.	0 88 min.
Average speed of trucks (Fig 8) . ..	42 2	45 5	3 3
Average time required per truck trip (10 mi.) .	14 21 min	13 18 min.	1.03 min.

location. Assuming that annual maintenance and operation costs for the two lines will be equal (which is logical) the above sum may be employed in toto for interest on and amortization of new capital.

Utilizing the well-known formula

$$A = (\Delta C)\left[\frac{r(1+r)^n}{(1+r)^n - 1}\right]$$

with (n) assumed as 30 years and (r) at 3 per cent we find the justifiable amount of additional capital expense A to be:

$$\$3131.\left[\frac{(.03)(1+.03)^{30}}{(1+.03)^{30}-1}\right]\$61{,}395.$$

or about $6139.00 per mile.

It is apparent that if the alternate line involves any great increase in earth work quantities the above sum would be insufficient. This is to be expected since a reduction of 100 deg. of central angle per mile without any accompanying shortening in distance would seldom justify a large additional capital outlay. In practice a line revision of this character is generally accompanied by a material shortening in distance which latter factor creates benefits which will carry a large proportion of the expense

When the problem involves the replacement of an exceedingly tortuous alignment such as is encountered on many sections of old, mountain road conditions are entirely different. A glance at Figures 3 to 8 will substantiate this. Here the time savings are tremendous and large expenditures find ample economic warrant.

In the foregoing analysis no consideration was given to the modification of fuel consumption values. These obviously must be included to present a complete economic picture. A glance at Figures 5, 7 and 8 however will disclose the fact that for the lighter cars (Fig. 5) fuel savings are negligible while for the heavier cars (Fig. 7) and the trucks (Fig. 8) the savings are negative (that is to say fuel consumption values are increased) and very small. In the interest of brevity, therefore, they will be neglected in this problem although, as stated, they should be included in any actual comparison of alternate locations.

In this connection it may be well to call attention to the fact that there is a distinct (though quite small) saving in vehicular operating costs accruing by virtue of improved alignment that has not been considered here. Reference is made to the decrease in tire wear and vehicular maintenance and depreciation. Data are not available whereby these factors may be evaluated but, from the deductions made in Oregon Technical Bulletin No. 7 (Revised Edition) (page 465), it would appear logical to assume a general reduction in vehicular operating expense of about 0.01 cent per ton-mile for each 200 deg. reduction in total central angle per mile. At 20 cents per gallon this would be equivalent to a reduction of 0.0005 gal. per mile in fuel consumption. This saving may be employed to offset, to some extent, the increased fuel consumption resulting from the higher operating speeds over improved alignment.

The problem considered assumed no restrictions as to speed, consequently the fuel-consumption benefits were largely negative; that is to say, fuel consumption was, in general, increased rather than decreased with reduction in the central angle index although, as stated, the amount involved was small. In problems involving constant top speed conditions are entirely different. Here the fuel-consumption benefits are positive and of considerable magnitude. For example, in Figure 4 it is indicated that, for a maximum top speed of 50 m.p.h., a reduction in central angle index from 400 to 200 deg. would reduce the fuel-consumption index from 1.22 to 1.06 or 16 per cent of its value for tangent alignment. Utilizing an average fuel cost of 1.32 cent (See Oregon Technical Bulletin No. 7, page

267, Revised Edition) this would amount to 0.21 cent per car-mile. This saving, for an annual traffic of 500,000 cars, would yield a total of $1,050 per mile, which, in the ordinary case, would constitute an economic justification for considerable additional capital outlay.

SUMMARY

This discussion is, of necessity, somewhat sketchy but space will not permit further elaboration or the inclusion of other illustrative problems. It should be apparent that the curves indicated herein may be employed in a variety of ways and for the solution of a wide range of problems involving the economics of alignment design. It should also be clear that only through the employment of curves or data sheets of this character can the problem be intelligently approached. The tests described are far from conclusive. Further research is needed and it is hoped that the present paper will serve to stimulate interest and point the need for further work.

DISCUSSION OF ECONOMICS OF HIGHWAY ALIGNMENT DESIGN

PROF. R. A. MOYER, *Iowa State College:* The Iowa Engineering Experiment Station has conducted tests on curves along somewhat similar lines as the tests reported by Mr. McCullough. We have conducted the tests by relating tractive resistance and gasoline mileage to the degree of curve rather than to the total central angle per mile. However, I do not believe that our tests have been carried far enough to be able to report on them or to compare our results with the results of the Oregon tests as given in this paper.

MR. W. W. MACK, *Delaware State Highway Department:* Mr. McCullough's paper indicates a resistance due to curvature equivalent to a 3 per cent grade.

PROFESSOR MOYER: That is correct. According to the report the added resistance on curves may amount to as much as the resistance on a 3 per cent grade on a tangent and that would make it equivalent to 60 lb. per ton.

MR. MACK: If I remember correctly the railroad practice is to allow 0.04 of 1 per cent reduction in grade for each degree of curvature. Using the railroad rule this would require a 75-deg. curve to produce resistance equivalent to a 3 per cent grade, which to me seems hardly possible.

PROFESSOR MOYER: The 3 per cent value seems large to me and it wasn't entirely clear to me just how Mr. McCullough arrived at this value by the central angle method. However, I am confident that the tests were carefully conducted and that with the methods they used for running the tests they were able to develop a fairly satisfactory correlation between the central angle per mile and the extra resistance to translation caused by curvature.

In our studies we have measured the total resistance to translation on various curves such as on a tangent or 0-, 5-, 10-, and 15-deg. curves over a wide range of speed up to the maximum at which we believed it safe to run the tests. At the speeds where there was no side friction force and where the centrifugal force was balanced by a gravity force due to superelevation, our tests showed no increase or only a slight increase in resistance. At the speeds at which a side friction factor of 0.15 was developed and which is the maximum speed for which the majority of rural highway curves are designed today, the increase in resistance amounted to less than 20 lb. per ton or therefore less than the resistance on a 1 per cent grade on a tangent. However, if a side friction factor as high as 0.30 was developed our tests indicated that the increase in resistance ranged from 60 to 80 lb. per ton or the equivalent of a 3 to a 4 per cent grade. When a side friction factor as high as 0.3 is developed the speed is so great that the tires start to squeal and the driver is taking all kinds of chances on losing control of the car on the curve. Speed surveys have indicated that for the usual rural highway curve, 85 to 90 per cent of the traffic is operating at a speed below that for which a side friction factor of 0.15 is required and that only a very small percentage, if any, will delevop a side friction factor as large as 0.30. Actually, however, it is my belief that all cars develop some friction at one or more wheels of the car when operated on a curve no matter what the speed. Slow moving cars tend to slide in toward the center of the curve and fast moving cars tend to slide out on the curve. Just what the average friction factor is I am not prepared to say but I am confident that the tire wear on curves is an important factor. When the tires squeal on curves the wear approaches that developed in a quick stop in which our tests on tire wear have shown the rate to be about seven times the normal wear.

As far as the extra fuel is concerned, our tests and the Oregon tests have shown that the increase is slight except at the extreme speeds on sharp curves. The important point brought out in this paper, as I see it is the large loss in time caused by curvature, especially for a location in which the curvature amounts to 1000 deg. in central angle or more per mile. The time losses due to curvature can be determined with a fair degree of accuracy and it seems to me further studies should be made to measure the time factor, to analyze it and to evaluate it.

PROF. J. TRUEMAN THOMPSON, *The Johns Hopkins University:* Professor Moyer mentioned tire wear. It would be interesting to see the loss of rubber plotted against the central angle. The problem of rubber loss is serious in an allied field. Recently I was told by the landing gear expert of a large aircraft manufacturing company that every time a large bomber or transport ship lands, 4 or 5 lb. of rubber are lost by the tires.

MR. C. B. McCULLOUGH, *Author's closure*. Mr. Mack's inquiry is pertinent and of considerable interest. He apparently is seeking a correlation between the values of "alignment resistance" as defined and determined in these tests, and those derived by the time-honored method of grade compensation for curvature. In a textbook published over 40 years ago the author, E. Russell Tratman, states that curvature compensation is "variously taken at from 0.03 to 0.05 per cent per degree" and, even at this date, the above figures had become well established by years of continuous usage.

Figure 11 indicates the alignment resistance in pounds for the 1938 Ford Sedan test vehicle and it is apparent that the results will not correlate with any standard formula for curvature compensation, inasmuch as they vary with traffic speed and with total central angle over a wide range. For example, a total central angle of 1000 deg per mile corresponds to an average rate of curvature of approximately 19 deg. Using the average of the values quoted by Tratman, the equivalent tangent grade would amount to 19×0.04, or 0.76 per cent. It will be noted from the figure that at a speed of 30 m.p.h. the observed alignment resistance for the test vehicle amounted to approximately 45 lb. Dividing this figure by the weight of the vehicle (3,380 lb.) derives a value of 26½ lb. per ton, which is slightly greater than the resistance over a 1 per cent tangent grade. If the speed were to be increased to 35 m.p h. the total alignment resistance would amount to about 110 lb. total, or a little over 65 lb per ton, which is slightly greater than the resistance over a 3 per cent tangent grade.

For an alignment involving a total central angle of 400 deg. per mile, the average rate of curvature would be slightly over 7.5 deg., which, according to the Tratman formula, would correspond to the resistance of a tangent grade of 0 3 per cent. In contrast to this the alignment resistance indicated in Figure 11 for a speed of 50 m p h amounts to nearly 36 lb per ton, or the equivalent of a 1 8 per cent tangent grade

The assumption of other traffic speeds obviously derives results varying widely from the above values. All in all, therefore, there appears to be no definite correlation between these test data and any arbitrarily assumed value for curvature compensation It may be possible with further experimental data to derive new formulas for compensating grades for curvature. However, it would appear that no single percentage value will ever be applicable as the amount of compensation will always remain a function of traffic speed and total curvature.

The experiments described in this paper are obviously far from complete and much more data are needed before any definite formulas or conclusions can be established. However, it would appear that this type of research will eventually yield data of material benefit and serve a very useful purpose in our postwar construction planning