EXPRESSWAY ROUTE SELECTION AND VEHICULAR USAGE

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SYNOPSIS

From experiences gained in conducting three comprehensive Origin and Destination Surveys for the State Highway Commission of Indiana and the subsequent preparation of Traffic Survey and Highway Plan Reports, this paper presents the development of effective methods for the selection of urban expressway routes and the determination of their percent of usage by vehicles.

The selection of expressway routes, because of the intricacies involved, cannot be expressed in mathematical terms, but rather must consider the major desire line graphs as the primary basis for selection coordinated with an intimate knowledge of the city applied to land use, Sanborn and city maps, aerial photographs and an intensive field reconnaisance.

The extent to which vehicles will use the expressway is shown to depend on the "expressway distance" (the length of the expressway portion of the trip), the "access distance" (the length of city streets used to enter and leave the expressway in connection with a trip), and the "adverse distance" (the increased distance required for the trip via the expressway as compared to a more direct route using the city streets). Speeds on the expressway were assumed as twice those on city streets. From these conceptions the expression

$$P = \frac{\left[P_1 + P_2\right] \times P_3}{100}$$

where P = Percent of expressway usage,
P_1 = Factor based on "expressway distance,"
P_2 = Factor based on "access distance," and
P_3 = Factor based on "adverse distance",

provides a rational method for computing the actual percent usage of expressway. Laborious calculations involved in the application of the formula are eliminated by the use of a graph or mechanical device developed in connection with the study.

The methods reported in this paper follow from personal experience gained in conducting three comprehensive origin and destination surveys for the State Highway Commission of Indiana in cities with populations between 120,000 and 400,000 and the subsequent preparation of a basic traffic Survey Report and a Highway Plan Report for each city. In connection with all of this work, it has been our practice to review all available similar reports for other cities and seek the counsel of other engineers engaged in this field.

The completion of the comprehensive origin and destination survey and the Traffic Survey Report containing all the basic data, tables, desire line graphs, and kindred items brings the planner face to face immediately with two all important questions: Where should the routes be located? How many vehicles will use them? For the purposes of this discourse, we will assume the city in question has a population exceeding 100,000 and the anticipated volumes of traffic over a future 20 year period will require the expressway type of facility.

EXPRESSWAY ROUTE SELECTION

The selection of routes that will carry the traffic most efficiently and afford the greatest amount of relief at the lowest comparable costs, presents a complex challenge to the planner. Patterns developed for other cities, if available, will aid immeasurably in visualizing certain possibilities for the city in question. Our studies to the present time indicate scant opportunity for isolating the several involved complex phases into mathematical expressions which will establish even approximate locations. Rather, we have been compelled to bring into the picture every conceivable tool that would aid in the coordination of the city street system as it exists with daring alterations and additions as dictated by survey traffic patterns. The elements absolutely essential to the determination of the final routes include an intimate knowledge of the city applied to the major desire line graphs, land use, Sanborn and city maps and aerial photographs.

A mental picture of the city gained during the field survey and subsequent analytical studies will provide the most desirable background for the preliminary selection of feasible lines. A large city map suspended from the wall will refresh the memory as, in connection with the major desire line graph, we observe the varied patterns and prepare to choose the dominant center lines. The expressway type of facility becomes desirable for movements exceeding 20,000 vehicles per 24-hr. period and we therefore examine the graph and delineate the theoretical center lines of the traffic bands which will equal or exceed this minimum for the design period of 20 years. Narrow strips of draftsman's tape offer an excellent mode of showing these center lines. The selection of center lines which combine two or more bands should be given every consideration. Lines which can be easily recognized as infeasible because of certain known physical barriers should be discarded and efforts concentrated on substitute combinations. The basic survey data in this graphic form depicts the theoretical patterns and therefore demands a maximum of consideration. Throughout the location studies it will be necessary to refer continually to these traffic band patterns, in order to guard against extreme deviations as successive obstacles arise.

The transfer of these basic lines to the land use map involves very careful attention to the characteristics of each section of the city to be traversed. The planner attempts to locate these routes in such a manner as to insure maximum use of vacant, low value and decadent property, so that the right of way cost and disruption of the city may be held to a minimum. In order to make use of existing streets as service roads, center lines should be located preferably at the center of the block or, in the case of wide blocks, between one street and the alley or property line in such a manner as to provide a minimum right of way width of 300 ft. Since the survey traffic statistics in some cases show that approximately 50 percent of all vehicular trips traverse some part of the central business area, the planner will be required to locate the routes essentially approaching its center. We recognize the vital need for an ample system of collection and distribution streets and the utter impossibility from an economic standpoint of acquiring costly business establishments and consequently the attempt is made to traverse within 5 to 6 blocks of the central point. This distance will usually avoid the absorption of main thoroughfares as service roads, and thus permit the main arteries as well as the new facility to serve the city more effectively.

The selection of both potential and final routes should be based on reliable survey data and sound engineering principles rather than preconceived opinions or personal prejudices. The planner should in no way be influenced by knowledge of actual names of property ownership along the several routes. Cemeteries, substantial churches, and schools must be avoided in selecting the routes.

A veritable labyrinth of lines will thus be developed from which the final system must be evolved.

An intensive examination of these lines will reveal certain patterns which have possibilities of definite consideration for the ultimate routes. For the normal city of this class, the system will usually require two major routes approximately at right angles with each other and, in general, paralleling the existing streets. Enlarged oblique aerial photographs taken as an essential part of the survey will prove an invaluable aid to the study and selection of the most desirable lines. Sanborn maps provide detailed information for each block in the city. City plat maps supply necessary street, alley, and block widths. A comprehensive coordination of the aerial photographs and maps by the planner serves to eliminate possible lines and establish several groups of potential routes worthy of exhaustive examination.

In preparation for field investigation these lines are reproduced on combined sections of photostatic reproductions of Sanborn maps (scale 1 in. = 100 ft.). Field maps prepared in this way help the investigator to identify an area quickly and serve as a constant reminder of the nature of the area. Alterations in the lines as dictated by the field studies can be shown in red on these maps for future use in the office. Liberal time should be alloted to this reconnaisance in order that the number of potential lines can be reduced to the absolute minimum for final consideration and comparative studies. By field observations in connection with our route studies in South Bend-Mishawake, Indiana with a combined population of 140,000, we finally ruled out all parallel lines with the exception of a 2-mile section which involved the alternate of acquiring either a restricted railroad right-of-way with a minimum of residential property or adequate right-of-way in a parallel location with a greater amount of residential property. The comparative study revealed a saving in cost of $100,000, and a larger percent of vehicular usage for the latter route. The selection of the final routes in preference to alternate parallel lines can, in many cases, be determined by office and field observations of the relative property values, the advantages of more adequate access points, the adaptability of existing streets for service roads, the greater potential vehicular usage, and the lesser construction costs. For cases where uncertainty exists, exhaustive comparative studies should be performed in which the relation of benefits to costs should be given full consideration. In our studies up to the present time we have had no major case in which an actual benefit-cost ratio study was applied to the preliminary selection of lines. However, for the final routes, we have evaluated anticipated benefits in monetary terms for time saved and reduction in accidents.

In general the direct representatives of the several affected governmental units will have collaborated in the final stages of the line selection to give informal approval to the final routes. Formal approval should be gained in a subsequent conference with the responsible officials. It is our latest practice to arrange conferences with the editors of the newspapers for a preview of our proposed routes so that, if possible, we gain their tentative approval. In all these conferences we request that plans exhibited and discussed be held in strict confidence pending approval of the final report at some later date. The acceptance of this phase of the project by responsible officials paves the way for the next vital step in the evaluation of the system, that of determining the expected vehicular usage of the facility.

VEHICULAR USAGE OF THE EXPRESSWAY

In developing the proper location of the expressway to serve the largest volume of vehicular traffic, we are faced with a number of factors which influence its percent of usage. The city streets will continue to carry all short trips and others which could utilize the expressway for only a short distance (less than one half mile) as well as those trips for which adverse distance would be a prohibitive factor. The expressway will carry varying percentages of all other types of trip dependent on their course with respect to the facility and the serviceability of the existing street system. On our initial project, traffic flows were developed by an experienced recorder choosing a percent of usage by personal judgment. He was guided by an intimate knowledge of the city, the assumption of a 2:1 speed ratio on the expressway as compared with city streets and, from visual inspection of the map, by the relative distance via the expressway and normal street routing. The recorder interpreted the 2:1 ratio to mean that where the time via the expressway equalled the time via a more direct route, 50 percent of the trips would use the expressway; and only in the case where the time via the expressway was one half that by any other route would 100 percent of the trips be considered to use it. Between these limits proportionate percentages of expressway usage were determined dependent on the relative time ratios.

We soon recognized that this method failed to include all factors affecting the movements but rather that it depended almost entirely on the good judgment of the engineer performing the tabulation. In the preparation of subsequent reports, it was therefore decided to explore the possibilities of an empirical formula which, regardless of the recorder, would produce the same results. This research led us to the conclusion that percent of usage is governed by three principal factors which we designated as F_1, F_2 and F_3.

F_1 involves the distance for which a given trip can use the expressway. F_2 considers the relationship between that distance and the total length of trip. F_3 is concerned with the extra or adverse distance necessary to reach and use the expressway.

After considerable discussion, trial and experiment it was determined that F_3 rated equal in importance to the combination of F_1 and F_2 and, further, that F_1 was more important than F_2 by a ratio of 7:3. Optimum values of 70, 30, and 100 respectively were therefore assigned and the composite factor, F, for the ultimate percent of usage set up as:

$$F = \frac{(F_1 + F_2) \times F_3}{100}$$

The essential distances pertinent to potential expressway trips and necessary to develop formulae for the several factors were:

a = Expressway distance, the length in miles of the expressway portion of the trip.

b = Access distance, the length in miles of the city street portion of the trip.

c = Street distance, the total length of trip in miles by the most advantageous route using only city streets.

From these distances:

$a + b$ = total length of trip via the expressway and

$a + b - c$ = Adverse distance - v

Factor F_1 reflects only the influence which expressway distance exerts on the percent of usage. We recognized that there will be a certain amount of inconvenience in entering and leaving an expressway, relatively important for short but of minor consequence for long expressway distances. Drivers would tend to weight the benefits against the inconveniences involved and would, in varying degrees, choose to use the expressway. In light of this conception it was our consensus that percent of usage would be zero for trips with expressway distances of less than one half mile (when a = 5.4) as a sufficient distance by which the saving in time would be ample to nullify the inconveniences. For values of F_1 between those points, a parabolic variation with vertex at the upper limit (70 at 5.4 miles) was selected because it provides a sharp rise in values for the expressway distances near the lower limit where it is apparent the rate of increase would be greatest. The detailed derivation of Factor F_1 based on these assumptions is recorded in Appendix A and develops the formula:

$$F_1 = -2.8a^2 + 30.24a - 11.65$$

for values of a, expressway distance, between 0.4 and 5.4 miles. For lesser and greater values of a, F_1 retains its respective minimum (0) and maximum (70) values.

Factor F_2 shows the extent to which the access distance influences expressway usage. It can best be visualized by observing the relation of the access distance to the expressway distance when the origin and destination of the trip are located on opposite sides of the expressway route. When these points are immediately adjacent to the expressway, it is the obvious and possibly only direct route for the trip. As origin, destination or both move away from the expressway, an increasing number of parallel streets will present to the driver numerous alternate ways to negotiate the trip without resort to the expressway. The greater the access distance becomes, the greater the probability will be that some of these streets, because of their distance from the expressway, will be relatively free from congestion and will therefore minimize the expressway advantages. A relation was therefore evaluated on the basis of the ratio of the expressway distance to the total trip length via the expressway. When this ratio is 1:1, that is when the access distance (b) is zero, Factor F_2 has its optimum value (30). Zero usage was assumed when this ratio reached 1:10 on the premise that percent of usage would be negligible when the total length of trip was ten times the length of expressway which could be used. This zero point could logically have been taken where the ratio was zero (one to infinity) without materially affecting the net result but we preferred to restrict our calculations to a finite limit.

For values of F_2 between the stated limits a straight line variation was used on the premise that usage will vary almost directly with this ratio. The detailed derivation of Factor F_2 based on these assumptions is shown in Appendix B and develops the formula:

$$F_2 = 33.3 \frac{a}{a+b} - 3.3$$

Factor F_3 reflects the effect of adverse distance on the percent of expressway usage. Adverse distance v is the additional distance of travel required via the expressway as compared to that by the existing streets. The speed on the expressway is, in every case, assumed to be twice that on the existing streets. It is our opinion that the variable speeds during the day resulting from traffic volume changes will automatically maintain this average ratio of 2:1. For example we know that increased volumes on the expressway imply the same on the city street with a corresponding reduction of speeds on both facilities and under light traffic, speeds increase but logically in approximately the same ratio.

On the basis of the 2:1 speed ratio, then, from a theoretical standpoint, when the ratio of the adverse distance to expressway distance (v:a) is 1:2 (0.5), the time required via either route would be the same, since, by definition:

$$v = a + b - c \qquad (1)$$

(via expressway route) $T_1 = \frac{a}{2} + \frac{b}{1}$ and $T_2 = \frac{c}{1}$ (via city street route)

$$\text{when } T_1 = T_2;\ c = \frac{a}{2} + b \qquad (2)$$

by substituting in equation (1) the value of c from equation (2)

$$v = a + b - \frac{a}{2} - b \quad \text{or}$$

$$\frac{v}{a} = ½$$

Conditions resulting in equality of time requirement for the two routes would seem to justify an assumption of 50 percent but from a practical standpoint we considered the expressway route somewhat less favorable because of more involved turning movements and therefore arbitrarily set the usage at 40 percent for this condition. Optimum usage is attained when the adverse distance is zero, i.e. when the length of trip is the same via either route. The parabolic function was selected to express the full range of F_3 values with its vertex at a value of 100 when $\frac{v}{a}$ = 0 and with a value of 40 when $\frac{v}{a} = 0.5$. This choice followed from the conviction that the rate of change should be at a maximum below the controlling value of 40 and should decrease gradually as F_3 approached its optimum value. Mathematical projection gave a zero value for F_3 when $\frac{v}{a} = .645$. The detailed derivation of Factor F_3 based on these assumptions is recorded in Appendix C and develops the equation:

$$F_3 = 100 - 240 \left(\frac{v}{a}\right)^2$$

The application of the method to the determination of expressway usage by vehicles is very simple and, for any desired movement, requires the measurement of the primary distances involved in the formula as previously defined: (1) expressway distance a, (2) access distance b; and (3) street distance c. For each potential expressway movement the recorder, by means of a flexible tape, scales the b and c distances on a city map upon which has been depicted the expressway system including all service roads, entrances and exit ramps. Important city thoroughfares were given a distinctive color to aid the recorder in selecting the most favorable routes. Distances a between all access points of the expressway were measured previously and shown in a table to eliminate repeated measurements.

For example: Between two specific tracts we have a movement of 130 trips which, by observation, would involve potential expressway usage. Selecting the access points, consulting the table for a and measuring b and c, we find:

$a = 6.0$
$b = 3.0$
$c = 8.0$
$v = a + b - c = 6 + 3 - 8 = 1.0$

Application in the basic formula produces:

$$F = \frac{\left[70 \text{ (}a\text{ exceeds } 5.4) + 33.3 \frac{6}{6+3} - 3.3\right]}{100} \times \left[100 - 240 \left(\frac{1}{6}\right)^2\right]$$

$$= \frac{[70 + 19] \times 94}{100}$$

$$= 84$$

Trips on the expressway therefore would be 84 percent of 130 = 109 trips they would apply between the selected access points. The remaining 21 trips would use the available city streets.

These final formulae were rigidly tested by applying them to a comprehensive selection of actual trip movements from the South Bend project. The percentages of expressway use thus computed were observed in each case to be so completely satisfactory, that we have adopted this method for all projects. It has facilitated greatly the mechanics of this phase of the work and assured us of consistent accurate results.

The cumbersome work entailed in applying these formulae to the calculation of these factors was eliminated by preparing a graphic calculator from which the three factors could be selected by using the pertinent distances involved in the formulae. Figures 1 and 2 show the use of this device in the determination respectively of Factors F_1, F_2 and F_3. (Note: Figures 1, 2 and 3 are in the back of this book.) Factor F_1 is read directly as a stub item on the left side of the chart. For value $a = 6$, $F_1 = 70$ ($F_1 = 70$ for all values of a above 5.4).

For F_2, the value of $a + b$ on the pivoted arm scale (Fig. 4) is brought to an intersection with the vertical line through the a value on the top scale. The reading where the arm intersects the upper arc is the value for F_2. For our example $a + b = 9$ intersects $a = 6$ showing a value in the upper arc for $F_2 = 19$. For F_3, the value a on the pivoted arm scale (Fig. 5) is brought to an intersection with the vertical line through the v value on the top scale. The reading where the arm intersects the lower arc is the value for F_3. For our example, $a = 6$ intersects $v = 1$ to produce $F_3 = 94$. The recorder completes the combination of the factors on a calculating machine.

Since the development of the described tool for determination of factors, Mr. P. M. Cassidy of the Indiana District Office of the Public Boads Administration, who had consulted with us on this study, further interested himself in the project by developing a mechanical device from a series of nomographs designed and arranged to perform completely the solution of all equations including the additions, subtractions and multiplications involved. Figure 3 is a photograph of the device depicted to show how it would solve the stated example.

The operation of the device is as follows: The left sliding pointer is moved to *a* equal 6.0, the right sliding pointer is moved to *b* equal 3.0, the slider on the tape near the center is moved so that *c* points to 8.0 on the *c* scale. String 1 (revolving about the left pointer) is moved around to position 1 so as to touch the right pointer in which position F_2 is determined (19) from where the string crosses the diagonal F_2 scale. Nineteen is then added mentally to the value of F_1(70) which is given opposite the *a* reading (this addition which is always very simple is the only mental calculation required in this method) and this sum (89) is set on the extreme left hand scale of $F_1 + F_2$ scale. String 1 is then moved around to position 2 so that it passes through the value of 1.0 on the *v* scale (4th from left) and the extension of this line through the intersection with the diagonal F_3 scale gives the value of F_3 equal to 94. It will be noted that *v* was obtained directly by reading in the little opening of the slider on the tape. (It is just coincidence that string 1 crossed the value of *v* equal 1.0 at this point.). String 2 is then revolved (to position 1) so that it intersects the vertical F_3 scale, at the right, at reading of 94 and the percent usage (84) is read where this string intersects the "percent usage" scale near the center; then placing one's thumb on the string at the "percent usage" reading and revolving string 2 around to position 2 so that it intersects the "number of vehicles involved" scale, for the given value of 130 and which had been set to start with, the vehicle usage is then determined from the "vehicle usage" scale which reads 109 vehicles.

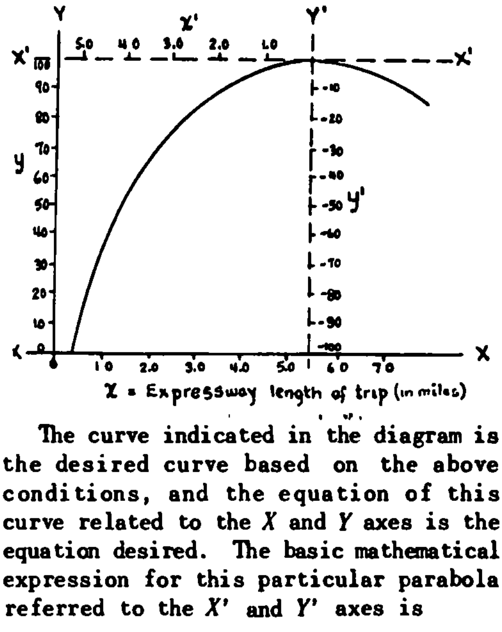
A series of examples run by the use of graph and by the mechanical device revealed a saving of approximately 20 seconds for each operation by the latter method. The recorded time by the graph as 1 min. 20 sec., by the mechanical device 1 min. After a period of actual use of the mechanical device, we anticipate the time per operation can be reduced even below the 1 minute figure. The advantages in addition to saving in time include a greater accuracy and elimination of a certain amount of drudgery connected with the former method. The device requires only one operator to determine and record the flows in lieu of two for the other method.

The selection of expressway routes and the determination of traffic flows thereon constitute a most important part of the development of a highway plan for the city. The methods we have described are presented for the constructive use and criticism of all interested engineers engaged in this field to the end that through the mutually sharing of accomplishments, the greatest progress will follow.

APPENDIX A

DERIVATION OF FORMULA FOR FACTOR F_1

It was the general consensus of those associated with expressway "use" determinations that a factor that would reflect only the expressway trip length should have a value of 0 when the length was 0.4 mile and a value of 100 when the length was 5.4 miles, and for lengths in between the variation should be parabolic.



The curve indicated in the diagram is the desired curve based on the above conditions, and the equation of this curve related to the X and Y axes is the equation desired. The basic mathematical expression for this particular parabola referred to the X' and Y' axes is

$$y' = k\,(x')^2$$

solving this equation for k when $y' = -100$ and $x' = -5$ gives a value for $k = -4$

therefore $\quad y' = -4\,(x')^2$

to change this equation so as to refer to the X and Y axes instead of the X' and Y' axes substitute $y - 100$ for y', and $x - 5.4$ for x', and the equation becomes

$$y = -4x^2 + 43.2x - 16.64$$

This is the basic equation which expresses in percent the "use" of the expressway insofar as the length alone is concerned.

As indicated elsewhere the length factor carries a weight of only 70 in relation to a weight of 30 for Factor F_2 in the final determination of expressway usage, therefore values in the above equation are multiplied by 0.7 to give the proper values to Factor F_1. The equation then becomes

$$F_1 = -2.8x^2 + 30.24x = 11.65$$

or since designation "a" instead of "X" is used to indicate the length of expressway the equation becomes

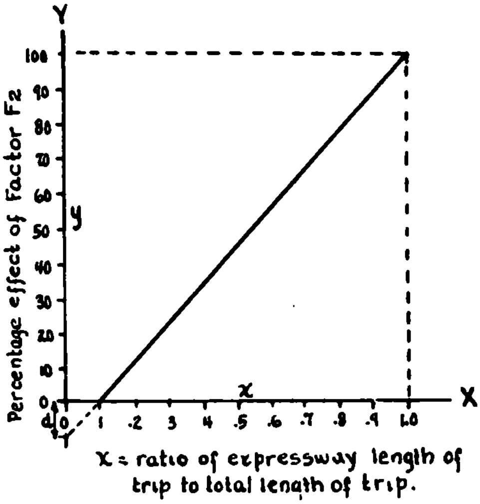
$$F_1 = -2.8a^2 + 30.24a - 11.65$$

Where a is the expressway length of trip in miles.

APPENDIX B

DERIVATION OF FORMULA FOR FACTOR F_2

It was the general consensus of those associated with expressway "use" determinations, that a factor that would reflect the effect of the distance the origin or destination was from the expressway could be expressed by the ratio that the expressway distance was to the total length of the trip and that the values corresponding to various ratios should be as follows: 100% when the ratio was one, zero % when the ratio was 0.1 and in between values to vary as a straight line. The line indicated in the diagram at the right is the desired line, based on the above conditions.



The general equation is $y = mx + d$ where m is the slope of the line and d the Y axis intercept

but $m = \frac{100}{.9}$ and $d = -(.1)\,\frac{100}{.9} = \frac{-10}{.9} = \frac{-100}{9}$

substituting, the equation becomes

$$y = \frac{(100x)}{(.9)} - \frac{(100)}{(9)}$$

further substitution of the value of

$$\frac{a}{a+b} = x$$

the equation becomes

$$y = \frac{100}{.9}\left(\frac{a}{(a+b)}\right) - \frac{100}{9}$$

As indicated elsewhere the F_2 factor in the final usage percentage determination should carry a weight of only 30 in relation to a weight of 70 for the F_1 factor, therefore the above equation should be multiplied by 0.3 to give the proper values to factor F_2.

the equation for factor F_2 then is

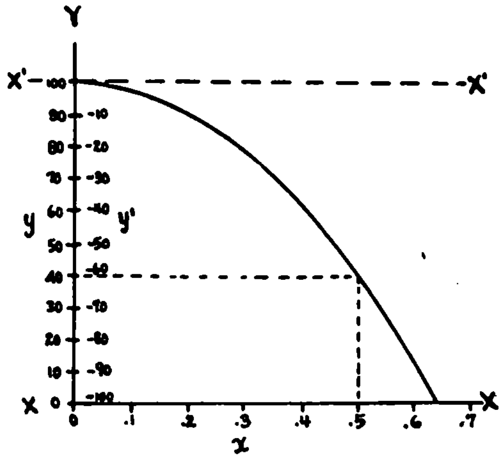
$$F_2 = \frac{30}{.9}\left(\frac{a}{(a+b)}\right) - \frac{30}{9}$$

or $$F_2 = 33.3\,\frac{a}{a+b} - 3.3$$

where a is the expressway length of trip in miles and b is the access distance in miles.

APPENDIX C

DERIVATION OF FORMULA FOR FACTOR F_3



x = ratio of adverse distance to distance of trip on expressway

It was the general consensus of those associated with expressway "use" determinations that a factor that would reflect usage relating the time via the expressway to the time via the more direct route could be expressed by the ratio that obtained between the adverse distance, and the length of trip actually on the expressway, and that the values that these ratios should indicate would be as follows: 100% when the ratio was 0, 40% when the ratio was ½, and 0% when the ratio was .645.

The curve indicated in the diagram is the desired curve based on the above conditions, and the equation for this curve related to the X and Y axes is the desired equation.

The basic mathematical expression for this parabola which has its vertex at the intersection of the X' and Y' axes is

$$y' = k(x')^2$$

when $y' = -60$, $x' = .5$ and substituting and solving for k, $k = -240$ and the equation becomes

$$y' = -240\ (x')^2$$

To change this equation so as to refer to the X and Y axes substitute $Y - 100$ for y', and x for x', and the equation becomes

$$y = 100 - 240x^2$$

Further substitution of the value of $\frac{v}{a}$ for x and the equation becomes that for Factor F_3 which is

$$F_3 = 100 - 240\ \left(\frac{v}{a}\right)^2$$

where a is the expressway length of trip in miles and v is the adverse distance in miles.