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FORMAL PROBLEMS OF TRANSPORTATION IMPACT RESEARCH[1]

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I. Introduction

The subject of this paper is the empirical, inductive approach as a method of determining quantitatively the influence which a transportation system exercises on its environment. Problems referring strictly to methods of statistical analysis have been omitted; they are sufficiently covered in textbooks on this subject. Furthermore, a specific form of impact, namely, the feedback on the transportation system, has not been dealt with. Since some of the more important research problems have not been treated properly or not at all in the impact literature, this paper contains trivial statements in places. Its results are essentially crude and preliminary, but they do provide some formal organization and suggest improvements of the scarce body of inductive impact research methods so far available.

Transportation impact research is commonly considered as the study of the effect which transportation phenomena exercise on other things. Hence, the raw material of such a study consists of the description of transportation features and processes as well as the environment with which they interact. The final goal is the description and explanation of these interactions. Both transportation and environmental phenomena can best be described with the concept of the property space to which the dimensions of space and time are added. Thus, the input information of a transportation impact study can be organized according to the dimensions of space, time and the various properties (variables). The second step will then be concerned with the determination of interrelationships between transportation and environmental variables in space and time. If, in addition, the impact study is to develop predictive power, the final section has to be concerned with the extrapolation of the variables and their interrelationships over the dimensions of time, space, and property scales.

II. The Variables

Since real world phenomena usually display a large degree of complexity, the term variable should be used only for their one-dimensional properties. There is no theoretical way to determine always in advance, which transportation variables exercise influence on their environment, and which environmental variables will be affected. The selection of variables will therefore be

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[1] The support of the Department of Transportation, Federal Railroad Administration (Contract Nr. 7-35524), Washington, D. C., is gratefully acknowledged.

guided by experience and speculation on one side and the researcher's interest in certain variables on the other side. The lack of a priori knowledge usually leads to a repeated change of the set of variables during the course of the study. There are numerous lists of variables in the literature which supposedly cover the essentials of transportation systems and their environment (see, for example, Kanwit, 1967). Transportation variables usually include time, frequency, reliability, cost, physical and psychological comfort, etc., and the environmental variables reach from parameters on population and employment structure to economic output, income and housing, education, voting structure, and physical geographic features. Combinations of these variables are often used to express more complex concepts like accessibility, opportunity, social benefit, etc. The most common problems associated with the variables are those of definition, measurement, and data acquisition. They have been extensively studied and reviewed in a large body of literature (e.g., Thomas and Schofer, 1967; Crumlish, 1966) and will, therefore, not be considered here. After having decided on the set of variables (and their measurements) which are to represent the transportation system and its environment from an impact point of view, the next problem to be solved is the range of time and space within which the data sampling should take place. For this purpose we will design a speculative and mostly conceptual framework which attempts to trace the spread of transportation impact through time and space.

III. Transportation Impact Over Time

To measure transportation variables with regard to the dimension of time they can, at least for practical purposes, be reduced to events which are points on the time axis. This does, of course, not hold for the total environmental impact they generate. People start to react with regard to transportation changes, even when these changes are only perceived as a possible future event. Real estate speculation leading to changes in the land value pattern is probably the best known example. The execution of the transportation changes leads to further consequences: the movement of people living in the right-of-way area, the possible growth of disposable income generated by the investment within the area in which the construction of the new transportation facility takes place, the growth of disposable income resulting from savings in transportation expenditures, and so forth. These are examples of the first round of effects (impacts). The second one might be composed of changes in the commuter sheds, relocation of production activities which seek to adjust to the new accessibility pattern, the increase of overall travel accompanied by growing air pollution, the deterioration of former social relationships and development of new ones (also a result of changes in accessibility) and so forth. From a broader viewpoint, the changes in transportation are themselves only the impact of some other events like increased transportation demand and the decision-making of political bodies. All we are doing here is selecting artificially a truncated chain of cause-effect relationships from the total real world evolution.

Keeping, for the moment, everything else constant, the area whose variables were affected by the transportation change will readjust from a former state of "equilibrium" (i.e., a stable pattern) to a new state, and this readjustment is a process stretching over time. It begins (probably) before the time of the transportation change and rises (probably) quickly to a maximum change per unit time before it declines. Its distribution function might very well have more than one mode, and the later "rounds of impact" penetrate (probably) into an indefinite future. This situation is illustrated in Figure T_1, in which size of transportation change and size of environmental change (assuming they can be quantified and aggregated) are shown as a function which changes over time. t_0 refers to the point in time when the change in transportation becomes effective. The times $t_i (i = -1, 0, +1, \ldots)$ might be thought of as the sequence of years preceding and following the transportation change. It is hypothesized that:

(a) the yearly amount of change in the environment tends toward O with increasing time;
(b) total change generated over time is finite,
(c) the growth rate of environmental change declines with increasing change in the transportation system,[2]
(d) the distribution of environmental change over time is unimodal (a highly questionable hypothesis, especially when one considers that other developments in the environment might reactivate the influence of the transportation change at some later time).

The assumption of "everything else being constant" is, of course, in most cases unrealistic. Other changes take place, which might be in character transportation or non-transportation, economic or jurisdictional or social, and generate their own chain of impacts on the environment, overlapping and interacting with the impacts of a change in transportation as discussed. This is illustrated in Figure T_2. C denotes a change in transportation which takes place at a certain point in time, and Δ(C) shows its environmental impact distribution over time. A, B, and D are other events with their own impact distributions, and "Δ total" represents the total amount of environmental change, which is assumed to increase over the years, but with varying positive or negative increments. In other words, the function "Δ total" represents the evolution of our world. It is the only thing which we can readily--at least in part--observe and measure. It is far more difficult to identify the individual contributions of isolated events, in our case, of the specific changes in transportation, i.e., to identify and measure the impact of transportation changes on the environment represented by numerous variables, which is our final goal here.

In view of the preceding discussion, the sampling and processing of data should conform to the following rules (among others):

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[2] One might, however, reverse the argument by introducing the notion of economies of scale. See Peucker, Th.,: "Transportation Impact Research: A Commentary," presented at the Annual Meeting of the Western Regional Science Association, San Diego, 1970.

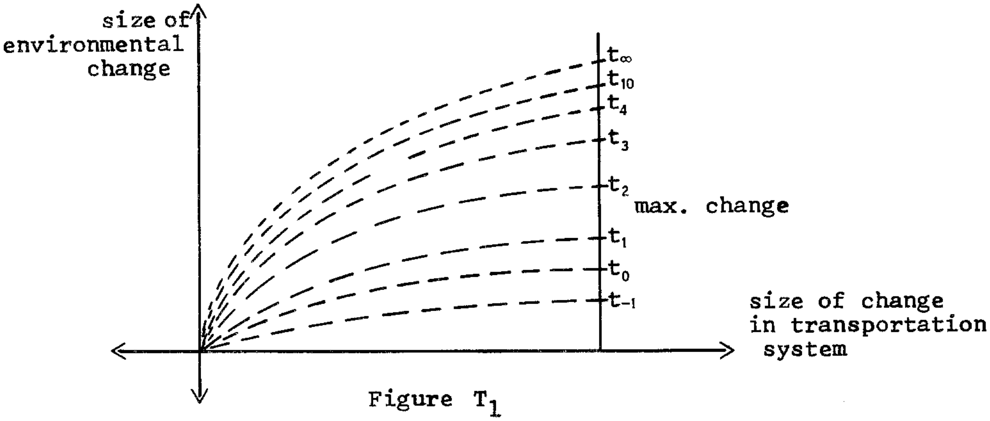

Figure T$_1$

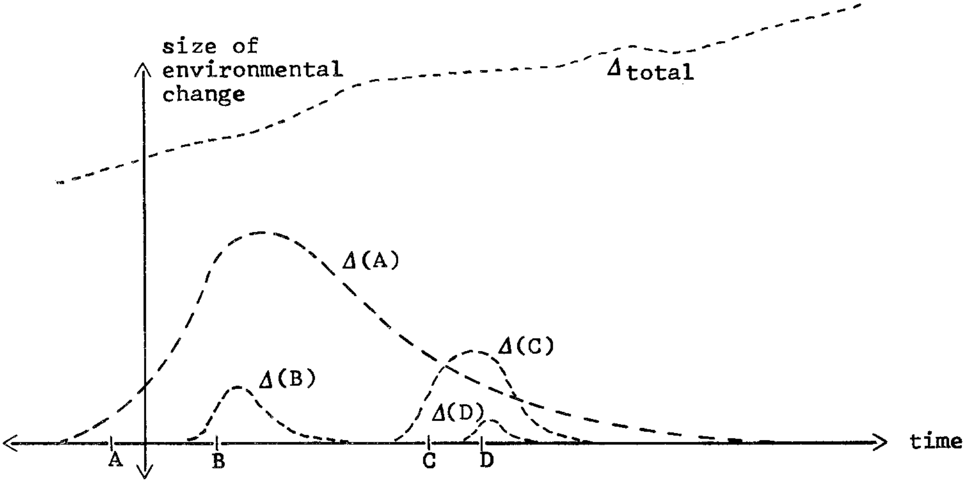

Figure T$_2$

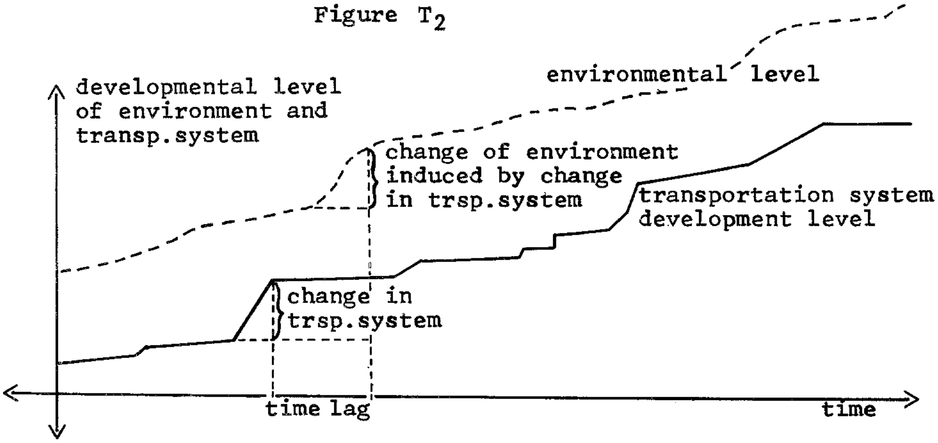

Figure T$_3$

(a) data for the transportation variables should be sampled directly before and after the change(s) in the transportation system;

(b) data for the environmental variables should be sampled for several points in time starting roughly one or two years before the transportation change until either the present or a point in time, where the measurable impact has diminished below some threshold value or has been obscured by the impacts of other environmental processes;

(c) comparison between transportation and environmental variables has to allow for an impact delay, which can vary from a negative up to rather large positive values (e.g., -2 to + 20 years);

(d) data of major events intervening with the transportation impact process should be included.

One might think of at least two approaches which give insight into the impact distribution over time, as generated by a single transportation change.

(1) Changes in the transportation system are sometimes remarkable in size and can be clearly dated. Examples are the innovation of rail transportation and the introduction of air service. The comparison of the time distribution of environmental and transportation changes (both reduced to some selected variables) might reveal some covariation separated by a certain time lag, at least for a few large transportation changes. Under optimum conditions, it would even be possible to read off the true distributions and the average delay of transportation impact, as illustrated in Figure T_3. Fortunately, even smaller transportation system changes can often be isolated in space and time, and therefore serve as case studies for the determination of impact over time (e.g., the change of the New York subway fares). There are, in fact, already a number of impact studies which have concentrated on the effects of those isolated transportation changes, mostly the construction of segments of the interstate highway system. By means of "before and after" investigations using control areas, certain impacts, usually referring to land value and land use at the local scene, have been explored. But nearly all of them are far from being comprehensive and do not permit strict statistical inference nor even a comparison. Nevertheless, a carefully selected sample of individual impact studies based on a standardized methodology would provide a first rough generalization of transportation impact over time on which prediction could be based.[3]

(2) An even more simplified procedure is the application of regression, in which changes of environmental variables are expressed by means of their covariation with the transportation system and its changes on one hand and the state of the environment before the change on the other. Similarly to the "before and after" impact studies, data samples have to be obtained for at least two points in time to allow for the period during which the change in the transportation system takes place as well as the time lag t between the transportation

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[3] For a rough example see Figure 3-20, page 93, in <u>Highways and Economic and Social Change</u>, U. S. Department of Commerce, Bureau of Public Roads, Washington, D. C., 1964.

change and its impact on the environment. The strength of the regression as well as the size of the impact and its distribution over time can then be studied by varying the delay value t.

IV. Transportation Impact Over Space

How far does transportation impact influence the environment? Similar to its distribution over time there is probably no limit, and for practical purposes, the question should be raised only with respect to "major" impacts, i.e., impacts of a predefined minimum size, assuming that quantification of impacts or their surrogates is feasible. Size and distribution of impacts can be manifold: the containerization of trans-ocean freight shipments will mainly affect the ports, but via the freight rates also the size and structure of international trade and therefore, the economies of many participating countries. On a small scale, transportation changes might acquire the right-of-way in settled areas thereby necessitating relocation of residences and working places, they might change the boundaries of consumer markets and of commuter sheds, they might open new resources and recreational areas. In approaching the impact problem by inductive, empirical means, it is therefore to be clarified in what area "distinct" effects resulting from a specific transportation change have to be expected. To sample data everywhere is obviously not an operational solution, and neither is it necessary. The strategy practiced hitherto has restricted the sampling area usually to the communities within or at which the transportation change took place. These places are, however, only a small subset of the total area affected, and not even necessarily the most important ones.

Depending on the type of impact one is looking for, several zones subject to impact can be distinguished. Apart from the zone physically affected, the most obvious impact area is defined by the users of the critical transportation facility and is usually (sometimes misleadingly) called the area of user benefits. Without losing in generality, one can assume that transportation along certain routes will become faster or less expensive (or the opposite). Using a few simplifying assumptions, it is possible to calculate the area containing the origins and destinations of all movements whose time (cost) will change by at least a predefined percentage. Figure S_3 shows an example; the mathematical derivation of the area boundary is given in the appendix.

If detailed data on transport supply and demand are available, the area of user benefits can probably more accurately be determined by means of a trip assignment algorithm which determines the redistribution of all trips after the change in the transportation system. This procedure would permit the computation of the total savings (losses) and the allocation of them over the area affected. It would, however, disregard the redistribution of transportation origins and destinations, which frequently accompanies, with some delay, changes in the transportation system.

Another relevant area is defined by the impacts affecting non-users. Examples of those impacts are shifting land values and land use, shifts in the tax base of communities, shifts in the number and variety of job opportunities and acquaintances. They can be traced back to the original change in transportation conditions, i.e., in the accessibility pattern, and one might argue, that they spread primarily into those areas which have an intensive interaction with the area of changed accessibility. Sampling for impacts affecting non-users should therefore concentrate on the area which experienced a "major" accessibility change plus its "range of influence," i.e., areas with which it has strong ties as expressed by commuting, migration, capital flow, freight traffic, etc. There are, however, even larger areas like economic regions or countries which will be affected by local or regional transportation system changes. It is hard to see how these long-distance impacts can be identified by inductive procedures, because the proportion between "noise level" and the size of the impacts will presumably increase vastly with increasing distance and area of sampling (just to mention one difficulty).[4] A possible approach to determine at least the amount of economic impacts is interregional input-output analysis (see, for example, Mohring and Harwitz, 1962). Tinbergen (1957) and later Roberts (1966) developed models relating economic growth to transportation improvement. Lathrop and Hamburg (1965) and Putman (1967) have designed methods to allocate regional growth in response to, among other spatial parameters, the accessibility pattern. As to the determination of non-economic impacts spreading over larger regions or even countries no systematic approach is known.

V. Inferential Limitations in Statistical Impact Analysis

Once relationships describing the impact of transportation variables on those of the environment have been established on the basis of and within the limits of the data sampled, then the question remains, how valid these relationships are elsewhere, i.e., for other magnitudes of the variables, in other areas and other times.

Projection Over Scale of Variable: Extrapolation of trends observed within the sampled data has often produced false projections. Suppose an impact relationship contains a variable referring to size of settlement (population) for which data have been sampled from villages and smaller cities. It is evident that the relationship does not necessarily hold if it is applied to large metropolitan areas. Generalized, this statement expresses the frequent observation in the social sciences, that "quality might change with quantity," i.e., that for different sizes of the same phenomena, separated by certain critical threshold values, different relationships hold. A first solution to this difficulty might be the use of analogies. We cannot, for example, collect data on impacts which have developed as a result of inter-city high speed ground

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[4] Peucker has suggested a regression type approach based on the assumption that the proportion of environmental development at location B which can be accounted for by a transportation investment at location A decreases with increasing distance between A and B and with increasing stock of investment at B and increases with increasing transportation investment at A (see Footnote 2).

transportation averaging 500 mph, or rely on extrapolated figures, but we might substitute corresponding data from observations related to existing jet plane transportation.

Projection Over Space: How far does a transportation impact relation hold beyond its sampling area, in a spatial sense? Obviously, many relationships derived from North East Corridor data cannot be expected to hold, for example, in the Mississippi states as well; at least a new calibration would be necessary. Aside from this trivial statement it is a large cross-cultural research topic in itself to find out, under what circumstances relationships can be, within pre-established error limits, applied to other areas without changing its form.

For practical purposes one might, as a first approach, assume that the spatial range of validity of a relationship includes all areas which are "similarly structured" as the sampling area. An example is the factor-analytical grouping of standard metropolitan statistical areas by Thomas and Schneider[5] on the basis of a large set of variables. Under the assumption outlined above, regressions obtained from the data of one or several members of a group could then be applied to all group members.

Projection Over Time: The critical question here is, of course, the extrapolation of transportation impact relationships into the future. A possible alternative to the usual trend projections is the more extensive use of the already available information of probably future developments. Many environmental factors, especially macro-economic variables, will be affected only to a minor degree by changes in the transportation system. The reasons are:

(a) numerous activities have a small transportation "input coefficient." This holds espcially for production at an advanced level of economic development, and

(b) in comparison to the already existing transportation system in a highly developed area, the changes brought about by qualitative and quantitative transportation innovations are mostly relatively small.

(a) and (b) lend themselves to the suggestion that the further development of already highly developed regions will only modestly be influenced by the improvements of the transportation system. Since gross areal predictions of trends are available for many variables (mostly economic and population predictions from the Bureau of Commerce), one might consider using these predicted figures as part of the input information and concentrate on the distribution and redistribution within the area as a function of the transportation system and its alterations (Putman, 1967). In general, then, the methods presently available to predict transportation impact relationships are so far only fragmentary and mostly inadequate, containing "shocking gaps" (Crumlish, 1966). Since transportation planning (and therefore urban and regional planning) is affected most critically by this deficiency, research efforts should probably be intensified in the area of systems flexibility as a complement to the

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[5] Unpublished report, The Transportation Center, Northwestern University.

work on impact projections, because a transportation system possessing a high degree of flexibility would permit the planner to respond immediately to unexpected impacts.[6]

VI. The Structure of Transportation Impact and Its Analysis by Regression

The purely formal aspects of regression analysis (including questions of significance, confidence, explanatory power) and the study of related techniques (like analysis of variance and covariance or canonical analysis) lie outside the scope of this paper. But there are several other methodological problems which deserve at least a brief discussion here.

Simplifying real world conditions we assume that the transportation system and its corresponding environmental system are in a state of equilibrium in the sense that they interact but do not change each other. A change in the transportation system will cause a set of response waves which diffuse first through the channels of transportation-environmental relationships and then through the vast network of interrelations within the environment (some of the waves returning to the transportation system as feedback). The result is a series of environmental changes spreading over space and time until a new equilibrium has been achieved. (The literature usually refers to the first impacts as the direct ones and to all others as the indirect impacts.) A small retail establishment, for example, might first lose business because the nearby freeway construction forces part of its customers to move out of its established customer hinterland. As the flow pattern reorganizes on the basis of the new freeway, the retail establishment might get some new customers and lose some others. Years later it might be booming because the improved accessibility of the area has brought new industries and income, or it might be forced to close down because the increased accessibility has accelerated the migration to the nearby urban centers.

Unfortunately, there are usually many other external events with their own chain reactions of impacts, which use the same network of channels, modulating, interfering and transforming the sequence of impacts caused by a change in the transportation system. Keeping them out of the picture for a moment and adding some additional constraints, one can approximate the original equilibrium with a Tinbergen type input-output description. By changing the transportation cost figures, a new output is generated which represents the new equilibrium. The inductive analogue to this essentially deductive model would be a set of regressions providing a comprehensive description of the interrelationships within and between the transportation system and its environment. Both models break down, however, if the often unrealistic concept of constant relationships is given up. Quantitative changes as described above are constantly accompanied by "qualitative" shifts. The consequence for the two

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[6] See, for example, MacKinnon, R. D.: "Uncertainty and Flexibility in Transportation Planning." National Cooperative Highway Research Program, NCHRP 8-4, The Transportation Center, Northwestern University, 1966.

models is the inconsistency of the input coefficients and the regression coefficients respectively (not to mention the possible instability of the orthogonality of the regression variables). Furthermore, the models cannot be constructed large enough so as to implement all other environmental forces, which will therefore distort the transportation impacts as projected by the models. Only a more sophisticated systems-analytical approach, taking into account the dynamics of the real world, might lead to a theory able to simulate the intricate pattern of the real world within acceptable error terms. In practice, one might think of a diffusion model simulating the spread of transportation impact within a framework of other major cause-effect chains to reproduce the evolution of our environment insofar as it is influenced by transportation.[7]

In detail, the criticism of the conventional application of regression analysis to the area of transportation impact refers to the following shortcomings:

(1) The analysis is not process-oriented, i.e., it does not analyze the dynamic structure of the web-like interaction of forces and activities. Instead of dealing with systems of changing interrelations, it tries to establish individual relationships with stable parameters isolated from their environmental dependencies.

(2) It relies strictly on the formal concept of covariation and fails to exploit the existing subject matter knowledge.

(3) Social phenomena are often more successfully treated by stochastic models, rather than by the conventional regression analysis as applied in many impact studies.

(4) It is unable to cope with highly subtle or unique interdependencies (for example, the effect of transportation systems improvement along national borders on the political relationships between the neighboring countries).

(5) It belongs to the large group of scientific approaches which apply known techniques to known data, i.e., it operates within the familiar and established framework. Since the nature of scientific results depends on the approach applied, conventional approaches can endanger the successful exploration of structures in our environment which are not yet discovered and cannot be discovered with the present set of tools and viewpoints.

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[7] Such an approach might very well necessitate completely new strategies relying heavily on research concepts borrowed from disciplines like anthropology and sociology, e.g., study of the development of value systems, cross-cultural studies, etc.

APPENDIX

The Area of User Benefits

Consider an area B, within which the cost per unit flow per mile is fairly homogeneous. Using time as a surrogate for cost, we might assume an average of c_1 mi/hr between any pair of locations in B. Suppose that a (straight) high speed transportation line L has been constructed in B on which the average speed is c_2 mi/hr. Problem: determine the area A defined by the origins and destinations of all trips whose proportion between the new and the former trip time is smaller than or equal to λ.

Let f be the flow between two points P_1 and P_2 in B with distance $\overline{P_1P_2}$ and a travel time P_1P_2/c_1. If f uses the new facility L, its time savings will be largest, if P_2 is located at the end point of L, and if

$$T = \frac{\overline{P_1Q'}}{c_1} + \frac{\overline{Q'P_2}}{c_2} = \text{Min.} \tag{1}$$

where Q' is a point on L and T the new travel time. If a system of coordinates is introduced such that P_1 is located on the y-axis with coordinates $(0, y_1)$ and Q' and P_2 are located on the x-axis with coordinates $(x, 0)$ and $(x_2, 0)$, then

$$T = \frac{1}{c_1}\sqrt{y_1^2 + x^2} + \frac{1}{c_2}(x_2 - x) \tag{2}$$

and

$$\frac{dT}{dx} = \frac{1}{c_1}\,\frac{x}{\sqrt{y_1^2 + x^2}} - \frac{1}{c_2} \tag{3}$$

i.e., the necessary condition for T being a minimum is

$$\cos\alpha = c_1/c_2 \qquad \text{(see Figure } S_1\text{)}$$

Since

$$\frac{d^2T}{dx^2} = \frac{1}{c_1}\,\frac{\sqrt{y_1^2 + x^2} - \dfrac{x^2}{\sqrt{y_1^2 + x^2}}}{y_1^2 + x^2} = \frac{y_1^2}{c_1(y_1^2 + x^2)^{3/2}} > 0 \tag{4}$$

for all x (distances are assumed to be larger than or equal to 0), the point Q'

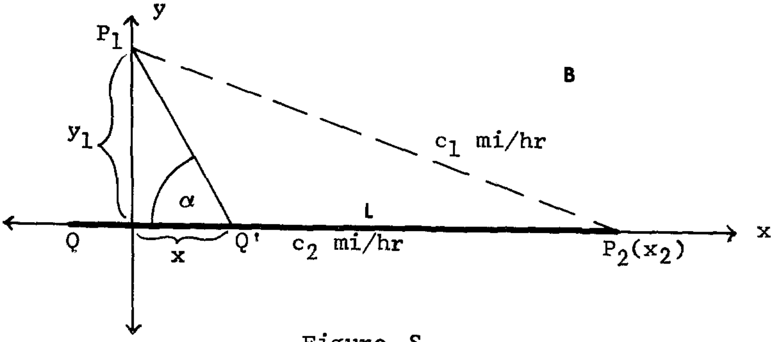

Figure S_1

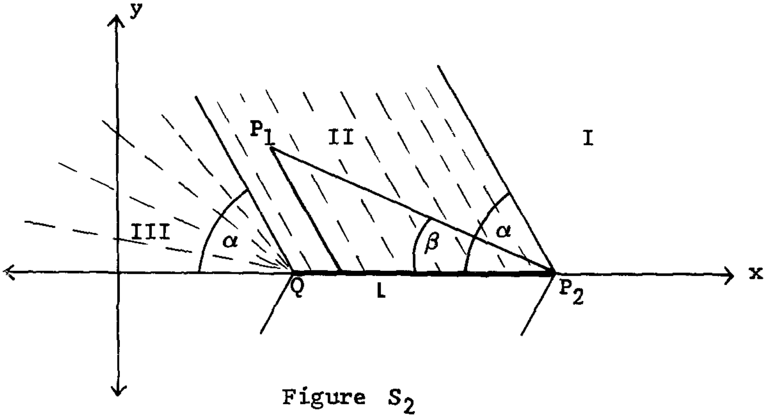

Figure S_2

$\bar{A}$ = Area of traffic saving less than 10%

when using L

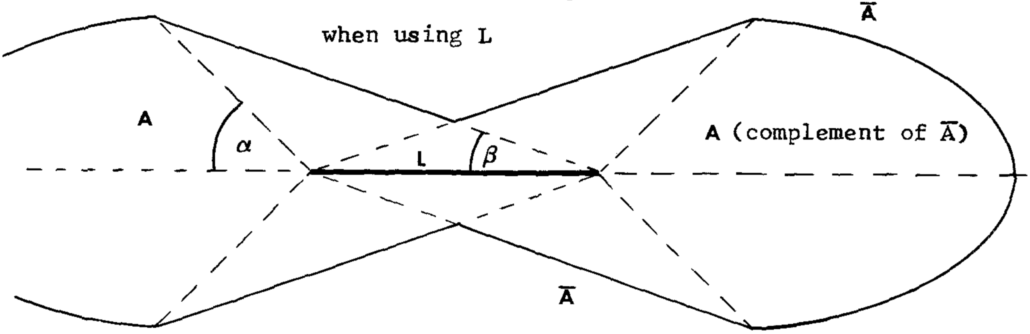

Figure S_3

defined by cos $\alpha = c_1/c_2$ is in fact the one and only one minimum. Of course, there might not always exist a path connecting P_1 and P_2 over two links, one of which is located on L and forming an angle $\alpha =$ arc cos c_1/c_2 with the other. Then the minimum time path is defined by one of the end points Q and P_2 of the line segment L; i.e., the minimum time path is then either $\overline{P_1Q} + \overline{QP_2}$ or P_1P_2.

In detail, the following statements can be made with respect to the spatial distribution of trip time savings (see Figure S_2), when P_2 is again the end point of the new facility L and the location of P_1 varies continuously.

(a) The distribution of savings is symmetrical to the (unbounded) line QP_2.

(b) All trips P_1P_2 with P_1 located in zone I will not benefit from the new facility L (see Figure S_2).

(c) All trips P_1P_2 with P_1 located in zone II can save time by using the new facility, and the savings will be maximized, when the two parts of the route off and on L form an angle $\alpha =$ arc cos c_1/c_2. The trips which experience a maximal reduction of their driving time equal to the proportion λ of their former time consumption are characterized by

$$\frac{\overline{P_1Q'}}{c_1} + \frac{\overline{QP_2}}{c_2} = \frac{\lambda}{c_1} \; \overline{P_1P_2} \tag{5}$$

i.e.,

$$\frac{c_2}{c_1}(x - x_1) + \frac{c_1}{c_2}(x_2 - x) = \lambda\sqrt{y_1^2 + (x_2 - x_1)^2} \tag{6}$$

$$y_1^2 = \frac{1}{\lambda^2}\left[\frac{c_2 y_1}{\sqrt{c_2^2 - c_1^2}} + \frac{c_1}{c_2}\left(x_2 - x_1 - \frac{c_1 y_1}{\sqrt{c_2^2 - c_1^2}}\right)\right]^2 - (x_2 - x_1)^2 \tag{7}$$

Since $\dfrac{y_1}{x_2 - x_1} = \tan$ (see Figure S_2), then (7) becomes

$$\tan^2 \beta = \frac{1}{\lambda^2}\left[\frac{c_2}{c_1} + \tan\beta\,\frac{\sqrt{c_2^2 - c_1^2}}{c_2}\right]^2 - 1 \tag{8}$$

i.e., the angle β is constant for given c_1, c_2, λ; the point P_1 is therefore located on a straight line passing through P_2.

(d) All trips P_1P_2 with P_1 located in zone III make use of the full length of the new facility (see Figure S_2), and the former driving time is reduced to the proportion λ, when

$$\frac{\overline{P_1Q}}{c_1} + \frac{\overline{QP_2}}{c_2} = \lambda \frac{\overline{P_1P_2}}{c_1} \tag{9}$$

i.e., assuming $Q = (0,0)$:

$$\frac{\sqrt{x_1^2 + y_1^2}}{c_1} + \frac{x_2}{c_2} = \frac{\lambda}{c_1} \sqrt{(x_1 + x_2)^2 + y_1^2} \tag{10}$$

By squaring this equation twice one obtains a fourth degree polynomial in x_1 and y_1.

(e) In the foregoing calculations, P_2 has been assumed to be located in one of the two endpoints of the new facility L. Hence, all results so far obtained are symmetrical to the perpendicular bisector of L.

(f) If we consider trips of which neither the origin nor the destination is located in one of the end points of L, then the corresponding area defined by the trips with relative earnings no smaller than $1-\lambda$ is enclosed by the boundaries calculated before. A numerical example is shown in Figure S_3. The area includes all O-D pairs with savings $\geq$ 10%. The parameters are assumed to be $c_1 = 50$ mi/hr, $c_2 = 70$ mi/hr, $\lambda = 90\%$.

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