

THE DETERMINATION OF URBAN TRAFFIC MOVEMENTS  
WITH ELECTRICAL ANALOGUES

by

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June 20, 1954

Professor Frederick J. Adams  
Chairman, Department of City  
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Massachusetts Institute of Technology  
Cambridge 39, Massachusetts

Dear Professor Adams:

I am submitting herewith my thesis, entitled  
"The Determination of Urban Traffic Movements with  
Electrical Analogues," in partial fulfillment of  
the requirements for the degree of Master of City  
Planning.

I would like to take this opportunity to  
express my appreciation to you for the instruction  
and friendly counsel I have received from you  
and the other members of the faculty and staff  
throughout my two years of study.

Very sincerely yours,

James M. Small  
Box 56  
Belfair, Washington

## THESIS ABSTRACT

Subject: "The Determination of Urban Traffic Movements  
with Electrical Analogues"

Author: James McCarthy Small

Submitted to the Department of City and Regional  
Planning in June, 1954 in partial fulfillment of  
the requirements for the degree of Master of  
City Planning.

The purpose of this thesis is to investigate the use  
of electric analogues as an improved, more rapid method  
for street and highway planning.

The specific objectives are:

1. Through the solution of many experimental problems,  
to propose a method of operation for an electrical  
analogue.
2. To determine and test the best means of applying  
this method to problems.
3. To illustrate the proposed method of operation  
by the means of a street planning problem.
4. To summarize and criticize the work done and  
suggest subjects for further research.

Many tests have been made with example problems to  
determine a practical method of making an electric circuit  
analogous to traffic flow on a system of streets. Road-  
ways are compared on the basis of relative driving times  
for various amounts of vehicle flows.

In the electrical analogue voltage (E) is made propor-  
tional to driving time, current flow (I) corresponds to  
traffic flow in vehicles per unit time, and resistance (R)  
is a variable, depending upon the ratio of driving time  
divided by vehicle flow. Tests of various methods of resis-  
tance assignment to streets are made, with dimensional checks.

The proposed method of operation of an electrical  
analogue is illustrated with an example problem and the  
results are analyzed. Throughout the thesis the inherent  
advantages and disadvantages of an electric analogue for  
street and highway planning are discussed. In the final  
section some unsolved problems are listed and suggestions  
are made for further research.

(Thesis Abstract, page 2)

The author recommends that the electrical analogue not be considered only as a "gadget" for indicating the best solutions to traffic problems. This device, when perfected, shows promise of becoming a very useful research tool, making possible planning studies of types and volumes not presently possible.

Thesis Supervisor:

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Burnham Kelly  
Associate Professor of  
City Planning

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Part I.

INTRODUCTION

1.1 Purpose

It is the purpose of this thesis to investigate the feasibility of the use of electrical analogues as an improved method for the more rapid solution to street and highway planning problems.

The use of analogous electric circuits enables the research worker in some other fields to build working models of his projects and study their characteristics in the laboratory. This electrical analogue is a device to simulate traffic flow on streets and highways with electric flow in wires. Traffic resistance factors will be directly related in some manner to ohms, electric resistance. Current will be applied at traffic origins and taken off at destinations, the current flow in any one wire corresponding to the traffic flow on the matching street.

The work in this thesis, the author feels, is just a beginning to the discovery of the potentialities and full usefulness of such an electrical device. No final results can be shown, partly because the necessary traffic flow data are not available and partly because the magnitude of the problem exceeds the scope of one thesis.

The intent of this thesis is to:

1. Explain the proposed method of operation of an electrical analogue.
2. Formulate a means of applying this method to problems.
3. Test and fully explain this method with a sample problem.
4. Make a general summary and critique and suggest subjects for further work.

In the attempt to develop the method of applying an electric analogue to traffic problems, much of the work in this thesis has been based on assumptions of roadway capacities, vehicle flows and speeds. The author felt that it would be more valuable not to become "sidetracked" on attempts to improve the accuracy of a portion of this work, but to attempt to show, in a broad way, how the electrical analogue method may be applied to planning problems. Thus it is expected that later improvements and changes in techniques will be made. Assumptions used in this thesis are clearly labeled for the benefit of future workers.

It is with the hope that this work may encourage others to carry it on and eventually perfect a valuable new planning tool that this thesis is presented.



## 1.2 Usefulness of the Analogue

In order to fully appreciate the need for such a tool for street and highway planning, it is necessary to understand the shortcomings of the present methods. Traffic engineers of cities generally use an unsystematic trial and error method of attacking traffic problems, basing their decisions on judgment and previous experience. Engineers usually can only guess what the effects of local improvements may be to the overall circulation pattern. These effects may be temporary if the change is a test involving parking regulations, the conversion of a pair of streets to one-way operation, or a change in light timing, but if a street is widened or a new road or bridge built, the change is permanent. It is impossible to build a new route as a "trial" to study its effect on the overall system of streets. Minor changes, such as the removal of curb parking, may be very difficult to achieve politically. The suspicion of merchants toward one-way streets or the removal of curb parking has frustrated the plans of many traffic engineers.

An electrical analogue, when perfected, would provide a laboratory means of obtaining answers before available only by field trial. Such a laboratory device would enable engineers and planners to study all possible solutions to a traffic problem, and then compare results and costs systematically.

In the analogue the test of a new route will mean only the connection of a wire of proper resistance between origin and destination points and the checking of resultant flows on this route and existing roadways. If the capacity of a street is to be increased by the removal of parking or retiming of the traffic lights, the relative resistance of this street to others would be lowered.

The "judgment factor" of experienced engineers will be very necessary in the setting up of the device and the assignment of correct resistors to the streets. This judgment can be incorporated into the analogue and improved upon if test results or field checks indicate errors.

Planning and traffic engineering, both young fields, are conceded to be "under researched." This device, if it is perfected and is successful in achieving more rapid solutions to some planning problems, would certainly have a long-range usefulness to the planning field as well as having immediate benefit to the city.

Sufficient figures on traffic flow are not available at this time to construct a full-sized analogue. More information, comparing road capacities to various vehicle speeds, is needed before such things as "induced traffic" on a new route can be predicted with useful accuracy.

All these things can and must be built into the analogue for good results on all types of problems.

### 1.3 Advantages of the Analogue

Primarily the big advantage of any electronic computing device is speed. The same is believed to be true for this electrical analogue. The answers will be no more accurate than the information and assumptions used, and these theoretically could be used by experienced engineers to arrive at the same results. When the problem is of the magnitude of the assignment of traffic to Boston's streets from the planned "central artery," however, this judgment process may take weeks or months.

As a corollary to speed, it will be possible to pose a much greater number of "test solutions" to problems and find the worth of each. This speed and versatility could be of great assistance also to the research worker. By posing great numbers of problems, it may prove possible to establish the relative efficiencies of various groupings of land uses and the circulation system connecting these land uses. Or, if the electrical analogue proves to be most valuable for rapid approximations, it may be used to establish limits or ranges and leave the final, more accurate work to other devices.

If a city would keep up to date a permanent analogue,

it could prove to be of great value for planning. With future growth estimates and flow figures known, the analogue would show where "problem areas" in the street system will arise and it would provide a laboratory means of testing the necessary changes or additions. When accepted, the analogue might help end public controversy over the location of a new route because costs and benefits of each location could be tabulated and shown.

#### 1.4 Origin and Destination Surveys

The engineer's basic research for street and highway planning consists of the making of an origin and destination survey. By one of several methods<sup>1</sup> a statistical sample of drivers' origins and destinations and numbers of trips is obtained. Desire lines between the zones of the city are plotted, and with the judgment factor again, major desire lines with estimated traffic flows are shown. New or improved streets are planned to conform as nearly as possible to these major desire lines, in location and size. In theory this method considers some but not all of the factors city planners would suggest; in practice the operation is far from perfect but it is being improved all the time.

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<sup>1</sup>(Roadside interview, license plate, return post cards, tag on car, or home interview)- Institute of Traffic Engineers, Traffic Engineering Handbook, New Haven, Conn., 1950

Existing street traffic flows usually do not reflect actual travel desires and are certainly poor indicators of future street needs. A good origin and destination survey shows the needs for today's streets but too often present travel desires only are made the basis for permanent street systems. In a growing city a nearly empty zone today may contain a major shopping center, industry or subdivision in the future. Thus origin and destination surveys should clearly be coordinated with city general plans when they are used for roadbuilding.

The effect of the roadway system on the achievement of general plan goals is of major importance. As is pointed out in Local Planning Administration,<sup>1</sup> the street system forms the major framework of the city and is perhaps its most important single element. The traffic problem is largely the worry of traffic engineers and police. The intensity and type of land use of street-abutting property must be controlled so as to distribute traffic and prevent the generation of more traffic than a street can carry. This is of major concern to city planners. There may be a limited amount that can be done to established portions of cities, but if the growth areas and rebuilt portions can

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<sup>1</sup>International City Managers' Association, Local Planning Administration, Edwards Brothers, Inc., Ann Arbor, Michigan, 1950, p. 90

be planned with an efficient land use pattern and a street system that properly serves these uses, cities in the future may be made more efficient and pleasant places in which to live and work.

#### 1.5 Operation of the Analogue

The electrical analogue for traffic flow is pictured tentatively as being set up quite similar to an origin and destination survey. A city would be divided as nearly as possible into zones corresponding to land use groups.<sup>1</sup> Origin and destination data, either present or projected into the future, are known. The circulation system, consisting of major streets, either actual or theoretical, is superimposed upon the zone map. The first step will be the initial assignment of traffic from zones to routes. Electric resistors, corresponding in some manner to actual resistances to traffic flow, will be assigned to each section of street. Electric current, the flow in amperes corresponding to the number of trip origins at each point, will be "applied" at origin points and "taken off" at destination points. If resistors have been correctly assigned to the streets, traffic flow can be read directly with an ammeter as current flow in each wire.

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<sup>1</sup>For more information on this subject, see: Grossman, David A., A Theory of Urban Structure, Unpublished M.C.P. Thesis, M.I.T., Cambridge, Mass., 1953

Combined with a city plan, which should give the best available "guesstimates" about future origins and destinations, a city electrical model could show weak spots in the circulation system, and provide a sound basis for future street planning.

A better method of channeling major desire lines from origin and destination data may also be discovered. This would remove a time consuming task from the process of interpreting origin and destination data. For any large scale work, other than local improvements, work will probably begin with origin and destination survey type information. Hence any improvement in the present techniques of arriving at major desire lines and traffic assignment would be very useful.

#### 1.6 The McIlroy Analyzer

One example of the successful operation of an electrical analogue, somewhat similar to this situation, is the McIlroy Analyzer,<sup>1</sup> an electrical device for the analysis of flows and head losses in complex fluid networks (such as city water mains and trunk lines). Several of these analyzers are in operation, and they enable trained technicians to completely analyze the water systems of medium

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<sup>1</sup>McIlroy, Malcolm S., Studies of Fluid Network Analysis and the Basic Design of an Electric Analyzer for Fluid Distribution Systems, E.E. Sc.D. Thesis, M.I.T., Cambridge, Mass., 3 vols, 1947

sized cities in a few days - a job which would require months by the Hardy-Cross system, and therefore is so costly it is seldom done.

McIlroy developed special non-linear resistors to represent pipelines of the fluid network. The relation between voltage across and current through a resistor so designed is directly analogous to the relation between friction head loss and flow rate in pipes. Each non-linear resistor consists of a specially proportioned straight tungsten filament with nickel supporting leads enclosed in an evacuated glass bulb. The complete assembly, called a "fluitron," is easily constructed by any manufacturer of incandescent lamps.

It appears at this point that such resistors, with different characteristics, will be needed for a working model of a traffic-flow analyzer. As traffic flow increases on a road the average speed of vehicles is reduced. This situation can be reproduced by the use of certain elements in the filament of the resistor, notably tungsten. Increasing the current through such a filament causes a rise in temperature, which in turn increases the resistance of the filament, as required. A type of circuit-breaker or other control device may be used to set a maximum flow, corresponding to the possible capacity of each roadway, to



allow no more current to go through.

The following paragraph from volume 1 of McIlroy's thesis is quoted because it is an example of a working analogue that has objectives quite similar to those of this thesis if roadways could be substituted for pipelines:

"This thesis<sup>1</sup> demonstrates beyond reasonable doubt that the construction of an electric network whose elements perform in a manner quantitatively analogous to fluid flow laws is entirely practicable. This method of analysis will permit the rapid solution of problems previously considered too difficult to undertake. It will provide a straightforward rapid means of investigating the effects on network performance of a variety of assumptions of loads, source pressures, or pipeline arrangements. It brings into the laboratory or engineering office a quantitative equivalent of the actual fluid distributing system on which any operating condition of the actual or projected system can be reproduced to scale or studied in detail. Its inherent flexibility should establish the analyzer as a powerful aid to practicing engineers, whose decisions often involve the wise

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<sup>1</sup>McIlroy, op. cit., (Note: subsequent work has borne out the above).

investments of large sums in improvements or extensions of piping networks."

The fact that the McIlroy Analyzer is a practical device for fluid flow research is certainly not proof that a similar device can be built analogous to traffic flow. Fluids in a pipeline obey natural laws, which are well defined. Traffic flows apparently do not obey any set law; approximations by experienced engineers of future traffic flows commonly contain large errors. Another basic difference is that fluids, entering a pipe network under pressure, have no particular destinations, such as automobiles have.

Continuing research by engineers and such agencies as the Highway Research Board is contributing to our knowledge of street traffic flows. The problems solved successfully in the development of the McIlroy Analyzer indicate to the author that there is a good possibility that the difficulties in the development of a traffic flow analyzer can be similarly solved.

Traffic engineers could easily establish individual speed-flow relationships for their major streets with counters and speed-meters. One such meter, recently developed, consists of two pressure tubes, approximately eighteen feet apart, to be placed across a lane of traffic.

According to the time delay between impulses on the tubes, speed is shown on a meter. An addition to the meter which would automatically record the speeds and flows would be very helpful.

#### 1.7 Non-Linear Resistors

The determination of how many types of non-linear resistors may be needed for traffic flows is considered beyond the scope of this thesis. Before any such determinations can be made, considerable speed-flow relations for many routes will have to be available.

#### 1.8 Analogue for Two-Way Streets

One wire in the analogue cannot be used to represent a two-way street. Electric flow can only go one way at one time in a wire and an attempt to induce two-way flow will cause the currents to be added algebraically and cancel each other out.

For a group of intersecting streets, apparently two wires will be needed for each two-way street. These wires will probably need to be of the type that will allow electricity to flow in one direction only. This subject is discussed with diagrams in a later section.

One other possibility is suggested here. If the turning movements are not large on major intersecting

streets, morning peak hour flows can be considered separately from the afternoon peak hour flows in the opposite direction. With a single-line network currents could be reversed, origins becoming destinations, and vice versa, for measurements of the other peak hour flow.

Methods for determining just which streets can be eliminated from consideration in the analogue will be necessary. Many smaller trunk lines are ignored in the McIlroy Analyzer but their combined effects are estimated.

#### 1.9 Current Source Concept

For this electrical analogue, in place of the usual "constant voltage" source, it appears more reasonable to use a "current source" which supplies a current of constant amplitude regardless of the voltage range. The current source, by definition,<sup>1</sup> will have a high internal resistance compared to the external resistance of the network. This consideration will not affect the solution of problems by electrical equations, as is done in this thesis, but would have to be taken into account in the building of a model.

#### 1.10 One-Way Streets

One-way streets can be duplicated in the analogue by the use of special wire that allows electricity to flow in

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<sup>1</sup>Walter C. Johnson, Transmission Lines and Networks, McGraw-Hill, New York, 1950, p. 245-6.

one direction only. The resistance will be lower on these streets, compared to two-way streets, because of their greater capacity.

#### 1.11 Route Selection

How do individual drivers select routes when a choice is available? Normally it can be logically assumed that drivers will take the route that will get them to their destination soonest. Certainly time is the dominant factor, but distance, safety and comfort are other considerations that should be taken into account. Some drivers are aware that operating expenses for their cars amount to approximately four cents a mile, so there is a tendency to use the shortest available route, even if it is not known if it will save time.

Traffic flows on most of the nation's toll roads and freeways have far exceeded predictions. Part of this extra traffic, it is believed, is due to the fact that drivers are willing to pay extra and even go out of their way for the privilege of using a safer, more comfortable highway.

The author believes that while these factors may not be resolved completely for some time, enough is known at this time to make satisfactory approximations. These are

outlined in part II of the thesis, in which some of the preceding postulations are tested by the means of applying the electrical analogue method of solution to an illustrative problem.

## Part II. APPLICATION OF THE ANALOGUE TO PROBLEMS

### 2.1 Relation of Traffic Flow to Electric Flow

A primary objective of this thesis is to establish a means of assigning electric resistance to individual streets in the analogue in order that current flows will be proportional to traffic flows on each route. First, a general basis for predicting amounts of traffic flow on routes must be established and then a means of paralleling these flows under all conditions by current flow in the electric analogue must be found. At all flow levels assigned resistors must correctly apportion the analogue current between routes in the same manner as traffic is distributed on the corresponding streets.

It is here assumed that drivers will select their routes on the basis of driving time alone. Therefore, if two parallel routes have equal speed limits, drivers initially will select the shortest route between their origin and destination. As the flow on this route increases average speeds are reduced and other drivers may find that an alternate, less congested route will save them driving time.

Several recent studies on route selection by drivers indicate that much more research will be needed before the relative importance of factors of time, distance, comfort,

safety and others can be compared. A recent pamphlet by the Highway Research Board<sup>1</sup> contains the following conclusion following a study of driver selection of alternate routes:

"It is conceivable that if a sufficient number and variety of existing facilities were thus studied, mathematical equations could be developed to aid in predicting traffic usage on any planned facility by careful selection and adjustment of these known equations much in the same fashion as now employed in selection of a Weir formula or earth-compaction curve."

While conclusive answers are not available from these studies, it is evident that driving time is the most important factor drivers consider in route selection. Another conclusion from the same source states:<sup>2</sup>

"Motorists, in travelling from one point to another in the study area, apparently regard travel time as more important than distance in selecting a route of travel. Of all the trips examined, only 38 per cent saved distance by the freeway, while 81 per cent saved time."

In the problem included in this thesis the author

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<sup>1</sup>Highway Research Board, Bulletin #61, "Traffic Assignment," 1952, p. 14.

<sup>2</sup>Highway Research Board, op. cit., p. 20.



assumed that drivers will pick their routes on the basis of driving time alone and that flows on alternate routes will divide so that driving time between origin and destination will be the same for each route. When more is learned about route selection other factors may be added to time but any modification of this factor will not affect the method of solution outlined in the following problem.

## 2.2 Possible Methods of Resistance Assignment

One method of simulating traffic resisting factors with electric resistance is to install resistance in direct proportion to the actual driving time for each homogeneous section of roadway between the origin and destination. Since possible speeds vary with amounts of traffic flow, the assigned resistance must vary with these amounts of traffic flow for accurate results.

Another method is to assign resistance per unit length of roadway in inverse proportion to the practical capacities of the roadways in question. The practical capacities are computed with the Highway Capacity Manual,<sup>1</sup> and the resistance is thus related directly to the physical conditions of the street or highway.

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<sup>1</sup>U.S. Bureau of Public Roads, Highway Capacity Manual, U.S. Government Printing Office, Washington, D.C., 1950

The practical capacity of a roadway is defined by the Highway Capacity Manual as being "the maximum number of vehicles that can pass a given point on a roadway or in a designated lane during one hour without the traffic density being so great as to cause unreasonable delay, hazard, or restriction to the drivers' freedom to maneuver under the prevailing roadway and traffic conditions."

A third method would be to assign resistance so that current flow would parallel the observed flows on streets and highways. It was hoped that this method could be used as a check on the others, but no reliable flow figures, relating speeds and capacities for roadways have been found. A combined traffic counter and speed-meter, mentioned in 1.6 of this thesis, would greatly facilitate obtaining this type of information.

The resistance assignment method found to be most satisfactory is derived in paragraph 2.4 and explained in the example problem. This method is based on the previous assumption that the total traffic flow will divide so that driving time is always kept equal on parallel routes. In the electric analogue, voltage (equal to current multiplied by resistance, or  $E = I \times R$ ) is always equal on parallel circuits. Driving time is therefore made proportional to voltage in the analogue. The Highway Capacity Manual is

used to determine rates of flow at practical capacity and the maximum capacity of each street.

### 2.3 The Highway Capacity Manual

Since reliable traffic flow figures were not obtainable, the Highway Capacity Manual seemed to offer the best compromise source of material. The traffic flow tables and formulas therein are derived from a combination of theoretical research and averages of actual traffic flows, compiled over many years in all sections of the country. While most engineers agree that this manual is the best and most complete treatise on roadway capacity yet written, they also stress that it is being constantly improved, and that solutions to all types of traffic problems cannot be found in any manual. This book seems especially to fail in the case of downtown city traffic, where flow inhibiting factors often appear too complex for analysis.

An interesting indication about the usefulness of this manual is that while one finds it on nearly every highway engineer's desk, city traffic engineers do not regard it as being very useful for their problems. There is an obvious danger to the application of general averages (such as this manual) to specific situations and problems.

This manual was deemed satisfactory for use in thesis

problems because method is being tested and exact calculations or refinements are not attempted. Future analogues will probably have to be tailored to fit each set of streets.

A general understanding of the Capacity Manual method of computing roadway capacities is helpful for the comprehension of the following sample problem. To avoid unnecessary duplication in this thesis, it is suggested that the serious reader refer to or be familiar with parts IV and V of the Manual.

#### 2.4 Evaluation of Methods of Resistance Assignment

Many trial problems were solved which assigned resistance per unit length of roadway in inverse proportion to the practical capacities of the roadways. This method gives reasonable results when simple problems of two alternate roadways of similar lengths are solved. However, in problems involving a network of roads of different lengths connecting several origins with one destination, the results were not considered reliable.

This method does not appear to be dimensionally satisfactory, either. In the analogue electric current is proportional to vehicles-per-hour traffic flow. If resistance per unit length is inversely proportional to capacity:

$$\frac{R}{\text{unit distance}} : \frac{l}{\text{vehicles/time}} = \frac{\text{time}}{\text{vehicles}}$$

$$\text{and } R : \frac{\text{time x distance}}{\text{vehicles}}$$

The electric analogy to this relationship is voltage equals resistance multiplied by current flow, or  $E = I \times R$ . Combining the two, dimensionally,

$$E : \frac{\text{time x distance}}{\text{vehicles}} \times \frac{\text{vehicles}}{\text{time}} = \text{distance}$$

E, voltage, is always equal on two parallel electric routes. It follows from this relationship that the lengths of the routes would have to be equal, which is not the case.

The method of making resistance directly proportional to driving time is examined dimensionally next.

$$E = I \times R$$

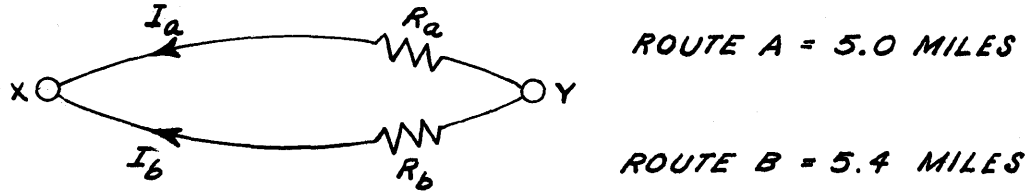
$$E : \frac{\text{vehicles}}{\text{time}} \times \text{time}$$

$$E : \text{number of vehicles}$$

The number of vehicles on each parallel route need not be equal in this case either.

If resistance in ohms is assigned directly in proportion to driving time, traffic will not be divided so that driving time will be kept equal between alternate routes.

The following example illustrates this:



Connecting destination, X, with origin, Y, are two routes. Route A with traffic flow  $I_a$  and resistance  $R_a$  (equal to driving time) is 5.0 miles in length. Route B is 5.4 miles in length. The two routes are equal in possible speeds but not necessarily equal in capacities. Route A will carry most of the traffic until average speeds are reduced to the point that traffic can flow on route B and arrive at the destination at the same time. Other conditions being equal, route A will always carry more traffic than B because of its shorter length.

The assumed condition in paragraph 2.1 was that any level of flows will be divided into amounts that keep the driving time between origin and destination equal on the two routes. Then any driver at Y can select either route and arrive at his destination, X, at the same time. If driving time is kept equal, the resistors will be kept equal at all times. If  $R_a = R_b$ , current  $I_a$  will equal  $I_b$  at all times. This obviously cannot be the case. Current flows

$I_a$  and  $I_b$  must be proportional to the respective amounts of traffic flow on routes A and B, and these can differ widely (depending on length, speed and capacity of the roadway) as long as the driving time on the two routes is kept equal.

In the electric analogy the one thing that is kept equal in both paths is not current or resistance separately, but their product.  $I \times R$  is always equal in parallel electric circuits connecting one input with one output. If it is desired to keep driving time equal in each of the paths, then time can be made proportional to current flow multiplied by resistance.

Driving time :  $I \times R = \text{voltage}$

The current flow in amperes must be proportional to vehicular flow per unit time. Dimensionally,

Driving time :  $\frac{\text{vehicles}}{\text{time}} \times \text{resistance}$

This relationship gives this new method of resistance assignment:

Resistance :  $\frac{\text{driving time}}{\text{vehicle flow}} = \frac{\text{time}}{\text{vehicles/time}} = \frac{(\text{time})^2}{\text{vehicles}}$

The complete electric analogy is now:

$E = I \times R$

$$E : \frac{\text{vehicles}}{\text{time}} \times \frac{(\text{time})^2}{\text{vehicles}} = \text{time}$$

Voltage is thus proportional to time.

In a problem resistance (R) would be computed by checking driving times (E) at different flows (I) and plotting  $R = \frac{E}{I}$  for different values of I.

Dimensionally this analogy appears to be reasonable and will be tested in the following problem. This problem is included to test the preceding relationship and to illustrate the proposed method of solution of traffic problems with an electric analogue.

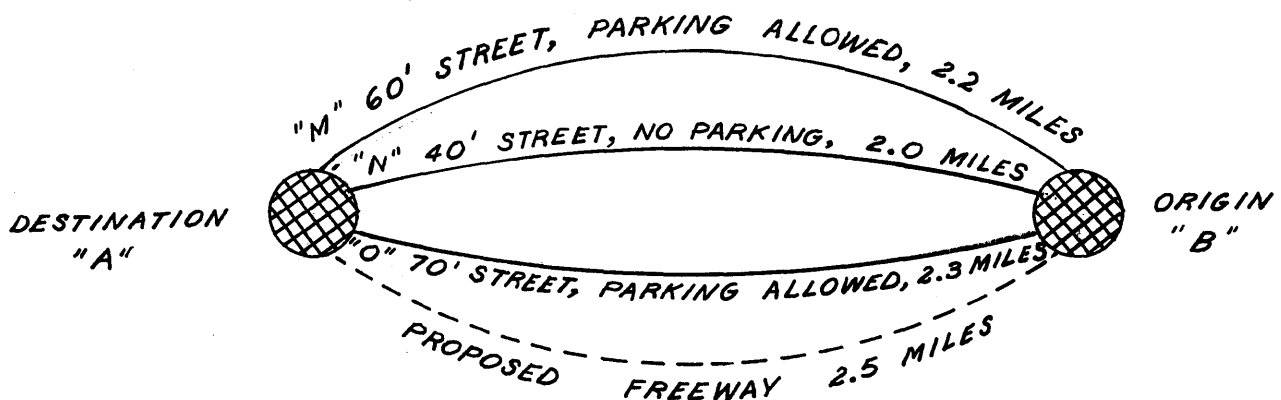
The author has not had electrical equipment available for test purposes and the solution of complex problems by electrical equations is very time consuming and requires many pages of calculations and explanation. While the one problem cannot illustrate completely all phases of the operation of an electrical analogue, it is felt that it will give the reader a picture of the method of solution of problems. The routine steps of solutions, after the problems are posed, are generally not included.

It should be remembered that after an analogue is set up the answers to problems such as the following can be obtained readily by varying the input currents and reading



resultant circuit flows with an ammeter. As was stated in chapter I, the primary advantage of the analogue for problems such as the following will be speed and versatility.

## 2.5 Illustrative Problem



In a given city the downtown center "A" is connected with one origin area "B" by three city routes, "M," "N," and "O." At present the routes are operating at roughly practical capacity during peak hours.

Origin and destination survey projections, coordinated with the city general plan, indicate that a 15% increase in traffic flow can be expected on these streets in the next five years. This increase is expected to load the streets to near "possible" capacity, creating occasional severe congestion during peak hours. It is desired to find how this severe congestion can best be avoided. Planners wish first to evaluate changes in parking regulations, then to

check other ways of increasing street capacities and see how each of these changes will distribute the traffic flow.

The survey projections further indicate a 20-year increase in traffic flow of 60% in this area. This may require major changes to the street system and since a freeway is ultimately planned to go through these two points, it is desired to predict how much traffic from origin B will use the 2.5 mile section of planned freeway.

Traffic lights on the three existing routes are progressively synchronized and green 2/3 of the time. Only flows in the direction B to A are being considered.

| <u>Route</u> | <u>Capacity Manual<br/>Intersection Capacity</u> | <u>Flow if Light is<br/>Green 2/3 of the Time</u> |
|--------------|--|---|
| M            | 1450 vehicles/hour                               | 966 vehicles/hour                                 |
| N            | 1340   | 894   |
| O            | 1660   | 1107  |
|              |  | <hr/> 2967  |

It is assumed from reference to a travel-time study of the streets of Boston<sup>1</sup> that for these streets the following average speeds will occur at the listed flows:

| <u>All Routes</u> | <u>Practical<br/>Capacity</u> | <u>20% under<br/>Pr. Cap.</u> | <u>20% over Pr. Cap.<br/>Possible Cap.</u> |
|-------------------|-------------------------------|-------------------------------|--|
| M, N, O           | 18 m.p.h.                     | 21 m.p.h.                     | 12 m.p.h.                                  |

<sup>1</sup>Bone, A.J., Highway Research Board Proceedings, "Travel Time and Gasoline-Consumption Studies in Boston," Dec., 1951.

Flows 20% greater than practical capacities will be considered "possible capacities." The possible capacity of an intersection approach is the maximum number of vehicles that actually can be accommodated under the prevailing conditions with a continual backlog of waiting vehicles.<sup>1</sup> No greater flow can be forced through the streets and all drivers will be subjected to delay and inconvenience. In the analogue an electrical device will prevent greater flows from passing in any wire.

Resistance is computed by dividing the travel time in hours by the vehicular flow. For example the first resistance for route M is computed in this manner:

$$\frac{.105 \text{ hour}}{774 \text{ veh/hr}} = .0001358$$

Absolute values of resistance have no importance. Only their relative values are used in this problem and all the derived absolute values such as the above are multiplied by  $10^7$  to obtain whole numbers.

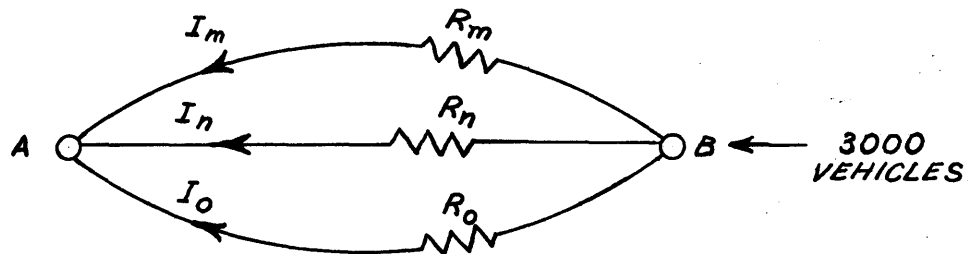
$$.0001358 \times 10^7 = 1358 \text{ ohms resistance}$$

| <u>Route M</u>                 | <u>Average Speed</u> | <u>Vehicle Flow</u> | <u>Travel Time</u> | <u>Ohms Resistance</u> |
|--------------------------------|----------------------|---------------------|--------------------|------------------------|
| up to 20%<br>under<br>pr. cap. | 21 mph               | 774 veh/hr          | .105 hr            | 1358 ohms              |
| pr. cap.                       | 18                   | 966                 | .122               | 1262                   |
| poss. cap.                     | 12                   | 1160                | .183               | 1578                   |

<sup>1</sup>U.S. Bureau of Public Roads, op. cit., p. 71.

| <u>Route N</u>                 | <u>Average Speed</u> | <u>Vehicle Flow</u> | <u>Travel Time</u> | <u>Ohms Resistance</u> |
|--------------------------------|----------------------|---------------------|--------------------|------------------------|
| up to 20%<br>under<br>pr. cap. | 21 mph               | 715 veh/hr          | .095 hr            | 1329 ohms              |
| pr. cap.                       | 18                   | 894                 | .111               | 1242                   |
| poss. cap.                     | 12                   | 1072                | .167               | 1558                   |
| <u>Route O</u>                 | <u>Average Speed</u> | <u>Vehicle Flow</u> | <u>Travel Time</u> | <u>Ohms Resistance</u> |
| up to 20%<br>under<br>pr. cap. | 21 mph               | 885 veh/hr          | .109 hr            | 1232 ohms              |
| pr. cap.                       | 18                   | 1107                | .128               | 1157                   |
| poss. cap.                     | 12                   | 1328                | .192               | 1447                   |

A normal peak hour load for the system is approximately 3000 vehicles. For the first problem, 3000 amperes are applied at B and taken off at A. Non-linear resistors will vary with the amount of current flow through them, giving two variables in each line, each dependent upon the other. With an actual analogue the system would become stable as soon as the resistors warmed up, and current flows could be read with an ammeter.



The solution is obtained by successive approximations:

| <u>Route</u> | <u>Flow</u> | <u>Resistance</u> | <u>Driving Time</u> | <u>Practical Capacity</u> |
|--------------|-------------|-------------------|---------------------|---------------------------|
| M            | 967 veh/hr  | 1266 $\Omega$     | .122 hr             | 966 veh/hr                |
| N            | 971         | 1260              | .122                | 894                       |
| O            | 1062        | 1151              | .122                | 1107                      |
|              | <u>3000</u> |                   |                     | <u>2967</u>               |

It appears that this method of resistance assignment results in the desired equal driving times. This method will be tried and checked throughout this problem.

Route N, the shortest route, is somewhat congested as would be expected. A driver at B can theoretically select any of routes M, N, or O and arrive at his destination, A, at the same time.

In an actual problem these flows would be checked with traffic counters on the streets to see if the real traffic flows approximate the analogue solution. For this problem it is assumed that they do.

It has been estimated that a 15% increase in traffic will occur in approximately five years. In this problem possible capacities will be considered maximum and if a solution indicates a greater flow in a wire, all above possible capacity will be diverted to other routes.

If no changes are contemplated in the streets in the next five years, the resistors will remain the same. The

applied current at B will be (1.15 x 3000) 3450 amperes.

The resultant flows, again by successive approximations, are:

| <u>Route</u> | <u>Flow</u> | <u>Resistance</u> | <u>Driving Time</u> | <u>Practical Capacity</u> | <u>Possible Capacity</u> |
|--------------|-------------|-------------------|---------------------|---------------------------|--------------------------|
| M            | 1123 veh/hr | 1340 $\Omega$     | .166 hr             | 966 veh/hr                | 1160 veh/hr              |
| N            | 1072        | 1558              | .166                | 894                       | 1072                     |
| O            | <u>1255</u> | 1230              | .166                | <u>1107</u>               | <u>1328</u>              |
|              | 3450        |                   |                     | 2967                      | 3560                     |

Again, the problem solution gives equal driving times for each route and reasonable flows. The planners consider it desirable in this case not to have average peak hour flows greater than at the practical capacity of the streets. Since the demand on this system of streets will be 3450 vehicles per average peak hour in five years, it is desired to find the most practicable way to increase the street capacity to handle this load at practical capacity.

Some of the following remedies may be suggested:

1. Elimination of parking during rush hours
2. Conversion of two or more streets to one-way operation
3. Street widening (expense is usually prohibitive)
4. Elimination of turning movements or truck traffic
5. An increase in the percentage of green time on traffic lights (Capacities of intersecting streets will be reduced.)

6. Elimination of bus lines from some streets

The planners decide that items 3, 4, 5 and 6 are not practicable in this situation, and the city engineer feels that it will be easier to put item 1 into effect than item 2. Hence it will be tried first.

The removal of parking on routes M and O will increase their practical capacities as shown:

| <u>Route</u> | <u>Prac. Cap. with Parking</u> | <u>Prac. Cap. without Parking</u> |
|--------------|--------------------------------|-----------------------------------|
| M            | 966 vehicles per hour          | 1240 vehicles per hour            |
| O            | 1107 "                         | 1353 "                            |
|              | <u>2073</u>                    | <u>2593</u>                       |

This will change the specifications for routes M and O to:

| <u>Route M</u>                 | <u>Average Speed</u> | <u>Vehicle Flow</u> | <u>Travel Time</u> | <u>Ohms Resistance</u> |
|--------------------------------|----------------------|---------------------|--------------------|------------------------|
| up to 20%<br>under<br>pr. cap. | 21 mph               | 992 veh/hr          | .105 hr            | 1058 $\Omega$          |
| pr. cap.                       | 18                   | 1240                | .122               | 984                    |
| poss. cap.                     | 12                   | 1488                | .183               | 1230                   |
| <u>Route O</u>                 | <u>Average Speed</u> | <u>Vehicle Flow</u> | <u>Travel Time</u> | <u>Ohms Resistance</u> |
| up to 20%<br>under<br>pr. cap. | 21 mph               | 1083 veh/hr         | .109 hr            | 1005 $\Omega$          |
| pr. cap.                       | 18                   | 1353                | .128               | 946                    |
| poss. cap.                     | 12                   | 1624                | .192               | 1182                   |

Resistors with these changed characteristics are now installed in routes M and O. The projected five year flow of 3450 vehicles is tested by applying an electric current of 3450 amperes at B and checking the resultant flows in routes M, N and O.

| <u>Route</u> | <u>Flow</u> | <u>Resistance</u> | <u>Driving Time</u> | <u>Practical Capacity</u> | <u>Possible Capacity</u> |
|--------------|-------------|-------------------|---------------------|---------------------------|--------------------------|
| M            | 1225 veh/hr | 985 $\Omega$      | .120 hr             | 1240 veh/hr               | 1488 veh/hr              |
| N            | 945         | 1235              | .120                | 894                       | 1072                     |
| O            | 1280        | 948               | .120                | 1353                      | 1624                     |
|              | <u>3450</u> |                   |                     | <u>3487</u>               | <u>4184</u>              |

The problem solution again gives equal driving times for each route, and reasonable flows. As would be expected, flows are below practical capacity on longest route O, at practical capacity on route M and somewhat above practical capacity on route N.

Next, routes M and N will be converted to one-way operation, route M being in flow direction B to A. Capacities of route M with parking allowed and route N without parking are nearly equal, so parking will be allowed on routes M and O for this test. Route N will have no flow in direction B to A, and is not considered.

Specifications for route M:



| <u>Route M</u>                 | <u>Average Speed</u> | <u>Vehicle Flow</u> | <u>Travel Time</u> | <u>Ohms Resistance</u> |
|--------------------------------|----------------------|---------------------|--------------------|------------------------|
| up to 20%<br>under<br>pr. cap. | 21 mph               | 1616 veh/hr         | .105 hr            | 650 $\Omega$           |
| pr. cap.                       | 18                   | 2020                | .122               | 604                    |
| poss. cap.                     | 12                   | 2424                | .183               | 754                    |

A resistor with these characteristics is now installed in route M and route N is disconnected. The electric current of 3450 amperes is again applied at B, and flows measured on routes M and O.

| <u>Route</u> | <u>Flow</u> | <u>Resistance</u> | <u>Driving Time</u> | <u>Practical Capacity</u> | <u>Possible Capacity</u> |
|--------------|-------------|-------------------|---------------------|---------------------------|--------------------------|
| M            | 2225 veh/hr | 650 $\Omega$      | .141 hr             | 2020 veh/hr               | 2424 veh/hr              |
| O            | 1225        | 1210              | .141                | 1107                      | 1328                     |
|              | <u>3450</u> |                   |                     | <u>3127</u>               | <u>3752</u>              |

The problem solution again gives equal driving times for each route and reasonable flows. Capacities of the two routes one-way, with parking allowed, is not as great as it was for the three routes with parking banned.

The projected 20-year increase in traffic flow of 60% will be considered next. The demand on the system will now be (1.60 x 3000) 4800 vehicles during peak hours. It may be feasible to handle this flow at possible capacities if parking is removed from all routes and routes M and N are converted to one-way operation but for the purposes of

this problem the proposed four-lane freeway will be considered. Routes M, N and O will revert to their original conditions.

Nothing is known about the other traffic demands on the freeway. For this problem it will be assumed that the flows given in the following table will not be the total flow on the freeway but only the added flow from origin B. If no other traffic used the freeway, nearly all the drivers at B could use this high-speed facility and save time.

Specifications for routes M, N and O are the same as they were for the first part of this problem. Freeway specifications are:

| <u>Average Speed</u> | <u>Vehicle Flow</u> | <u>Travel Time</u> | <u>Ohms Resistance</u> |
|----------------------|---------------------|--------------------|------------------------|
| 28 mph               | 1500 veh/hr         | .0892 hr           | 595 $\Omega$           |
| 25                   | 1800                | .1000              | 556                    |
| 22                   | 2100                | .1137              | 541 $\odot$            |

In this portion of the problem as in the others, the solution is obtained by repeated approximations from graphs of resistance vs. vehicular flow and travel time vs. vehicular flow.

| <u>Route</u> | <u>Flow</u> | <u>Resistance</u> | <u>Driving Time</u> | <u>Practical Capacity</u> | <u>Possible Capacity</u> |
|--------------|-------------|-------------------|---------------------|---------------------------|--------------------------|
| M            | 880 veh/hr  | 1276 $\Omega$     | .113 hr             | 966 veh/hr                | 1160 veh/hr              |
| N            | 900         | 1242              | .113                | 894                       | 1072                     |
| O            | 950         | 1180              | .113                | 1107                      | 1328                     |
| F            | 2070        | 542               | .113                | 1800                      | 2100                     |
|              | <u>4800</u> |                   |                     | <u>4757</u>               | <u>5560</u>              |

The above answers are checked in the following manner:

$$I_M + I_N + I_O + I_F = 4800$$

$$I_M R_M = I_N R_N = I_O R_O = I_F R_F$$

$$1276 I_M = 1242 I_N = 1180 I_O = 542 I_F$$

$$I_N = \frac{1276}{1242} I_M = 1.026 I_M$$

$$I_O = 1.080 I_M$$

$$I_F = 2.352 I_M$$

$$\underline{\quad\quad\quad} 4.458 I_M$$

$$5.458 I_M = 4800$$

$$I_M = 880$$

$$I_N = 902$$

$$I_O = 950$$

$$I_F = 2070$$

The first graphic solution checks very closely with the above flow figures. The freeway is obviously the preferable route, and it reduces flows on routes M, N and O to near or

below practical capacities. With the above freeway load from B, plus some from other sources, it would appear wise to plan the freeway to be a total of six, rather than four lanes.

## 2.6 Conclusions to the Illustrative Problem

The example problem was included for two purposes. It was necessary to check the theoretically-derived method of resistance assignment with problems to be certain that this method does keep travel time equal between alternate routes, and the problem illustrated the proposed method of solution of a simplified traffic problem with an electrical analogue. The problem assumptions were kept as reasonable as possible and in every case the derived flows seemed accurate.

A summary of the steps of the solution to the problem follows:

1. The capacities and average driving speeds of each route are derived, preferably from field counts combined with "test runs."
2. Variable resistor specifications (ohms resistance per vehicular flow) are computed.
3. The electrical analogue is constructed and the present peak hour load is applied to the system to see if it checks with observed flows.
4. The predicted 5-year traffic load is applied to the

present streets to see how serious the congestion becomes.

5. Parking is removed from two routes during rush hours, new resistance values are computed, and the 5-year traffic load is again tried on the system.

6. Two of the routes are changed to one-way operation and resultant flows with the same traffic load are checked.

7. The proposed freeway is added to the system and resultant flows are observed on the four routes from the projected 20-year traffic load.

The solution methods used in this problem are rather long but a laboratory experiment with proper equipment could be conducted very easily. Rapid solutions to complex problems could also be achieved with the aid of electronic computers.

Resistors with these required specifications might be very difficult to actually construct. The selection of resistors, whether they be non-linear or linear through short flow ranges, is beyond the knowledge of the author. The construction of an electrical analogue probably is not feasible until more experimental work is done. A more rapid means of solving complex problems, involving the simultaneous solution of many equations or the solution of problems with variable resistors, would be of considerable aid.

Part III.      SUGGESTIONS FOR FUTURE WORK

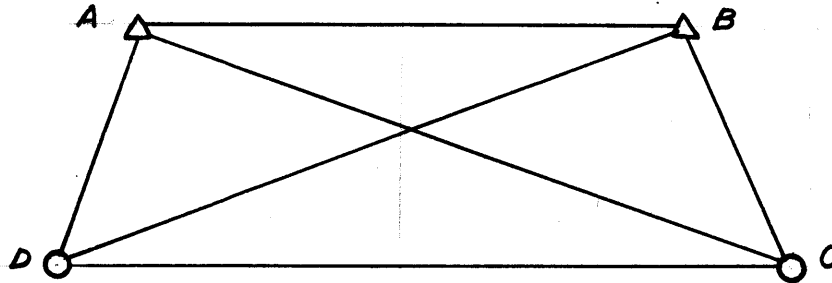
While working on this thesis, the author has not had time to explore several points, which have been suggested or have become obvious through the work, that should be clarified. Some of the points are possible further applications of an electric analogue. Others must be solved or improved upon before the electric analogue will be a practical device for the solution of street planning problems.

Some of these points have been brought out in the preceding sections; others that are considered very important are listed in this chapter in the approximate order that the author would have worked on them had more time been available.

3.1 Multiple Origins and Destinations

Many problems, such as the illustration problem in part II, have been solved by the analogue method that involved one origin and one destination. Other problems with several origins and one destination were solved without difficulty. However when more than one destination is involved, an inherent problem becomes obvious in the analogue. In traffic a driver may travel from his origin past many other destination points to his particular destination. His trip is a portion of the total flow on

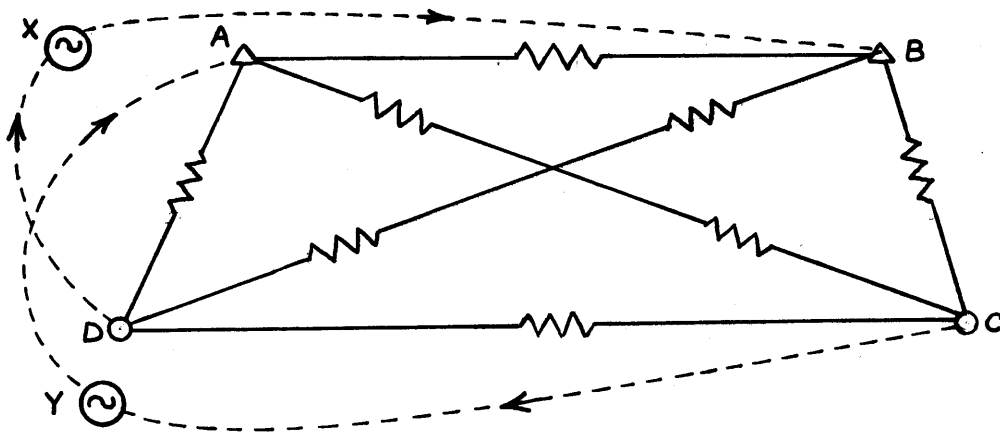
each of the routes he drives. In the electrical analogue no current from a certain origin can be "assigned" to go to a certain destination point.



This situation is illustrated by the above sketch. The triangles A and B are solely origin points, and the circles C and D are only destination points. It is assumed that all of the traffic from A is going to destination C and all of the traffic from B is going to destination D. Other conditions being equal, most of the traffic will use routes A-C and B-D until the routes are congested. In the electric network, however, what is to prevent the current from origin A from going to output D via A-D, and current from origin B going to output C via B-C?

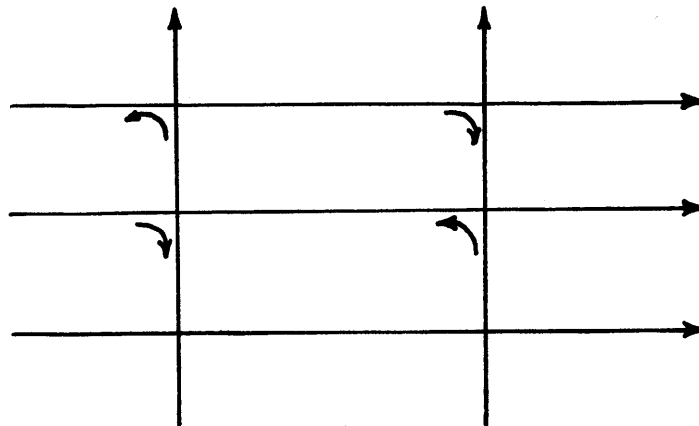
The problem is further illustrated by schematically showing two current sources for the two inputs. At low traffic flows, the operator would want current flows to

travel mainly in the paths B-D-X-B and A-C-Y-A. While the currents in each loop must be equal, it seems to the author that other current paths are possible that would not correspond to vehicle flow, especially if many more origin and destination points were involved. This situation will need further study by an electrical engineer.



### 3.2 Two-Way Streets and Intersections

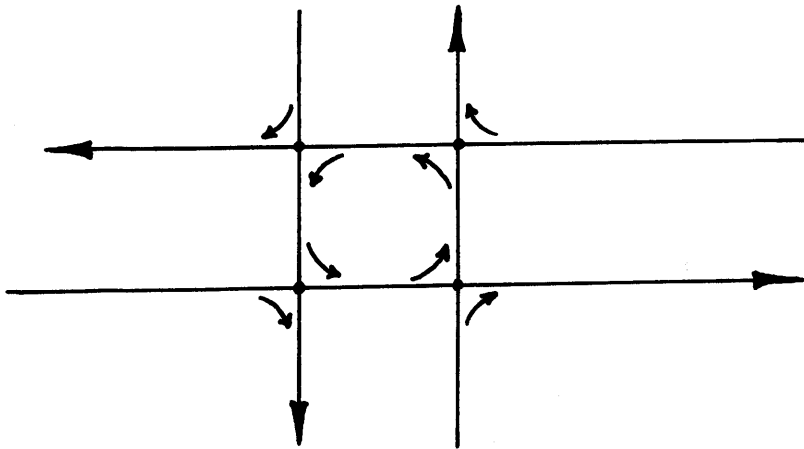
As was stated in part I, apparently two wires will be needed to represent each two-way street. If only one-way flows are considered at one time in a single-wire system, there is apparently no means of providing for turning movements.





In the preceding illustration, if each street is represented by a single wire and only one-way flows are being considered at one time, there is no way of providing for the turning movements shown.

Intersections of two-way streets, simulated by a wire for each direction of flow, have not been studied in detail. Apparently all the wires must be connected if all the turning movements are to be provided for:



This is equivalent electrically to joining all the wires together at a single point. The results of this situation need to be explored further. This raises the point of how detailed and precise the analogue need be. This will depend of course on the problem and the desired degree of accuracy of the results.

It does not seem necessary for an analogue to duplicate every street in a city. A traffic flow analyzer will

probably ignore most city streets and parallel the heavily traveled "through" routes for most operations.

### 3.3 Application of the Analogue to Various Situations

No traffic situations (with the possible exception of city centers) have been encountered for which the analogue method does not appear to be applicable for the duplication and study of problems. Regional problems, consisting of several cities connected by a network of roads, have been easier to set up in analogue form than situations on city streets because of fewer intersections and other conflicting factors.<sup>1</sup> When traffic-assignment figures are determined, possible toll-road locations in a region could be studied, and resultant traffic flows determined.

The electric analogue should prove to be especially valuable for studies involving the location of new routes or facilities such as bridges or tunnels. The testing of new routes with an analogue in operation would mean only the connection of wires of proper resistance across the possible location points and the resultant flows on the new facility could be recorded along with the flow changes on the existing routes.

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<sup>1</sup>These problems were limited to consideration of one destination at a time because of the difficulty mentioned in paragraph 3.1.

### 3.4 Non-Linear Resistors

The main drawback to this proposed analogue method appears to be the type of non-linear resistor that is required. Since every route in a city could theoretically have a different travel time/vehicular-flow relationship, the number of types of resistors required seems very large.

The author has found linear resistors to be satisfactory for some problems when the single resistance operates over a limited flow range only. Considering the accuracy of the data and assumptions regarding traffic flows, especially predictions of future traffic flows, an attempt at exact results is somewhat meaningless.

The best method of applying resistance in these amounts must be left to those doing further work and those skilled in the use of non-linear resistors.

### 3.5 Theoretical Planning Studies

Theoretical studies have not been explored, but an electrical analogue in operation could certainly be well utilized by research workers in between the "problem" solutions and future planning work. While this is admittedly speculation, many studies of great interest to planners could be carried out on an analogue. Some of the more obvious ones are:

1. Relative efficiencies of trial groupings of land uses.

2. Relative efficiencies of different street circulation patterns.

3. Civil defense dispersion studies.

Most of the author's conclusions have already been stated in part I so that the reader would have a better basis for understanding the illustrative problem in part II. This last portion will therefore be limited to a review of the originally stated objectives of this thesis and final conclusions.

#### 4.1 A Review of the Original Objectives

1. The proposed method of operation of an electric analogue was outlined in part I and illustrated by its application to the problem in part II. The concept of having an analogue simulate flows from every origin and destination zone in a city simultaneously may have to be altered because of difficulties mentioned in part III or other reasons unforeseen at this time. The postulations made in this thesis concerning methods of operation are untested by an actual analogue and some may have to be changed later.

2. Most of the work in this thesis involved solving experimental problems to test various methods of resistance assignment so that traffic flows could be paralleled by electric current on any system of roadways. The most reasonable method of resistance assignment found is the

one derived in section II and explained in the example problem. This method has worked well in a few sample problems and the relationship appears to be dimensionally analogous to the equivalent electrical terms. However the method has not been sufficiently checked with theoretical problems, nor with actual problems, to prove it satisfactory.

3. The illustrative problem results were summarized at the end of part II. The method and solution were both satisfactory in this case as well as others that were tried. The main criticism, perhaps, is the lack of further trials on a variety of problem types. Time has not permitted this for this thesis but it is a logical next step in the study of this device.

#### 4.2 Final Conclusions

This thesis represents a beginning - it is hoped a good beginning - to the study and development of electrical analogues for the use of planners. The device is not developed to the point where it would be suitable for use in city engineering or planning offices even if proper variable resistors were available. If further research is favorable, a pilot model should be set up at a research center where considerable traffic information is available and thoroughly tested.

It does not appear that the electrical analogue method would save any time on small or detailed problems. A problem such as the one in this thesis would likely be as easy to solve by conventional techniques. Only when the analogue can be applied to large and complex situations such as the street network of an entire city will its true worth become apparent. When the difficulty mentioned in section 3.1 is overcome, the analogue method can be applied to a large problem for test purposes.

For operation it has been suggested that flow problems be sketched out on paper and the electrical equations solved with an electronic computer for the flows on individual streets. Then no electric network or variable resistors would need to be constructed. However, besides the limitation of always being dependent upon an expensive computer, this would greatly limit two main advantages of the analogue - speed and flexibility. Every time a problem was slightly changed new equations would have to be written, and solved by the computer. The flexibility of being able to add a new route by connecting a wire between two points, or varying street capacities by changing resistors, and immediately reading the results, would be gone. While "test" problems may be solved in this manner, it is believed that the electrical analogue method will only be practical

for research or actual problems when the network is constructed and used in the general manner outlined in this thesis.

The electrical analogue should not be considered only as a "gadget" for indicating solutions to traffic problems. This device, when perfected, shows promise of becoming a very useful research tool, making possible planning studies of types and volumes not presently possible.

The purposes of this thesis have been to summarize what the author has learned from his work, illustrate the best approach of the analogue method to planning problems that has been found to date, and suggest directions for further work. It is hoped that this has been accomplished.

The suggestions and encouragement of many faculty members and others have been of great assistance throughout this study. The author would like especially to express his thanks to his thesis adviser, Professor Kelly, and also to Professor Lynch and Professor Wetmore of the City Planning faculty. Professor Reza, department of Electrical Engineering, and Professor Bone, department of Civil Engineering, have also helped a great deal, as have several engineers in the cities of Boston and Providence.



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