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PUBLIC AND PRIVATE TRANSPORTATION:

COSTS OF VARIOUS MIXES

by
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ABSTRACT

Title of Thesis: "Public and Private Transportation: Costs of Various Mixes."

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The question of the efficiencies of various modal splits is a very important question, but it is also an extremely large one. Certainly, it is not a question to which there is a single answer; rather, the key to its solution lies in the accumulation of bits and pieces of pertinent knowledge.

This thesis is concerned primarily with the costs (as opposed to the benefits) of the urban transportation system, and the prime variables investigated are modal split and urban form. Six different forms of the city, in abstracted form, are described by specifying their geometry and the locations and densities of residences and working places. A previous study, for each of these six cities, has, utilizing an electronic computer, generated traffic flows over a free surface (i.e., there are no defined transportation networks), and counts of the flows have been taken, in various directions, through each one-mile square block of area.

The current experiment, utilizing this basic data, defines transportation networks for the six cities, and assigns to these, for a range of five different modal splits, the traffic flows for public and private transportation. Unit costs are then specified, and for each of the thirty combinations of modal split and city form, computations are made of capital and maintenance costs, of operating costs, and of time costs.

The validity of the experiment is, of course, quite limited, but within the confines of these limitations, the following observations were made. Increasing the percentage of public transportation generally decreased the per capita capital costs and operating costs of the total transportation systems, but increased the average door-to-door journey times. Public transportation was more economical in areas of higher densities. Subway construction (excluding right-of-way costs) was uneconomical at even the maximum densities used in this experiment.

Per capita capital and maintenance costs were lowest in the many-centered city and highest in the homogeneous city. And the average trip times and operating costs for the door-to-door journey were lowest in the central city and highest in the ring city. It does seem likely, however, that these observations are very strongly influenced, not only by the unit costs, but also by the densities of the cities.

ACKNOWLEDGEMENT

The author would like to extend his thanks to Professor Aaron Fleisher of the M.I.T. Department of City and Regional Planning. His debt to Dr. Fleisher is threefold: for his original suggestion of the basic topic of this thesis; for the use of the results from his experiments on travel and the form of the city; and especially, for his sage advice during the development of the entire thesis.

Thanks is also extended to Mr. Ronald Rice for the use of some calculations supplemental to his S.M. Thesis.

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INTRODUCTION

1. Discussion of the modal split problem

Frequent reference is made these days to the "transportation problem," and much work is being done in the field of transportation research. But just what is the "transportation problem?" Before one can seek out any solutions, he must know specifically the questions to which he is seeking the answers. And certainly, the "transportation problem" is an exceedingly complex one.

One of the questions it frequently poses inquires as to the efficiencies of the various modal splits; i.e., given two or more modes of travel between two points, what will be the comparative costs and benefits associated with the various possible combinations of amounts of travel by the different modes. There are many criteria which must be considered before any solutions to this question can be attempted: construction costs of the transportation facilities; aesthetic and financial effects on property near-by and adjacent to the transportation facilities; transportation operating costs; speed of travel; comfort and convenience levels; social acceptability. Then, too, the evaluation of the various criteria will vary greatly according to the perspective through which the problem is being viewed; by the individual traveler or user of transportation, for example, or by the planners or decision makers in metropolitan management.

From the point of view of the transportation user, travel is a cost item (costs being measured in terms of money, time, and discomfort) to be expended for a return of some type. That is, the transportation user will attempt to minimize the sum of his transportation costs in relationship to the rewards and gains he will reap at the destination of each trip, such as financial gains and residential and recreational satisfactions.[1] Consequently, the mode of travel chosen by the traveler will depend on many interrelated factors, especially: the different modes of travel available to him; his car ownership status; the quality of transit service relative to the degree of congestion he is likely to encounter on the roads; and the parking facilities available at his destination.[2] (It will also depend to some degree on the amount of transportation being purchased by the consumer. Some people purchase so little transportation that mass transportation will always be more economical. There are, too, other persons who, for reasons of age or disability, cannot drive. However, most people do purchase enough transportation so that they will allocate their trips according to the relative costs of the alternative modes of travel available).

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[1]R.L. Creighton, D.I. Gooding, G.C. Hemmens, J.E. Fidler, "Optimum Investment in Two-Mode Transportation Systems," (paper presented at the 43rd annual meeting of the Highway Research Board, January, 1964).

[2]J.D. Carroll, Jr., R.L. Creighton, J.R. Hamburg, "Transportation Planning for Central Areas," Journal of the American Institute of Planners, February, 1961.

The transportation planners, though, who must decide where, when, and what kind of transportation facilities should be built, must view the modal split problem in a broader light than the individual transportation user. The planners must weigh the costs and benefits accruing to all interested parties: not only the transportation users, but also the adjacent property owners, the persons who would be displaced by construction of the transportation facilities, and the general public (which supplies the revenue with which the government operates).

It is in this perspective that the present thesis is viewing the problem of the modal split. More specifically, it is attempting to develop a technique and produce some results, using a range of modal splits and one particular set of "typical" standards and assumptions, which can be of some service to the transportation planner and designer.

It is true that much material has already been produced which offers recommendations on the modal split question.[3] It is also true that much of this material is of a rather generalized nature. For example, it can be said that in medium to low density areas, individual modes of travel will generally be cheaper, while in very high density areas, the group modes of travel may well be equal to or even lower in cost than the individual transportation modes.[4]

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[3]Some of these studies are cited later in the text, particularly in sections I.1 and III.2.
[4]R.L. Creighton et. al., op. cit.

This is certainly useful information, but it does require considerably more information than this to decide on a specific type of transportation system for a city. Then, too, conclusions are often based almost entirely upon historical data, which is a necessary, but not a necessarily sufficient criteria upon which to project trends in transportation.

These should not be construed as criticisms, but rather as observations; the nature of the modal split problem is not generally such as to be readily conducive to specific, reliable, easily obtainable answers or conclusions. The historical evidence relating to travel patterns and modal split may seem clear enough:

> ...It is well known that high densities and star-shaped settlement patterns with extensive transit systems have characterized those large cities which experienced heavy growth before the advent of the automobile as a major transport carrier. The growth of cities since the development of the automobile has been at lower density and has been less centralized.
>
> This tendency of recent growth to be at low densities, with decentralization of nonresidential activities and with provision for parking, clearly makes mass transit more difficult to provide. First, any mass-transportation line will run through terrain which has a lower population and hence a lower number of potential passengers per square mile. Second, the dispersion of nonresidential activities works against the centripetal-centrifugal movement characteristics of a highly centralized region. With more dispersed work places available, there will be a reduction in the potential number of centrally oriented passengers per square mile. The CBD with its high density, centralized, nonresidential activities, fulfills the ideal conditions necessary for efficient, economical mass transit.[5]

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[5] J.D. Carroll, Jr. *et al.*, *op. cit.*

Or, in other words, transit travel may be said to be predominantly focused on the central business district, whereas automobile travel is diffused throughout the urban area. It is also true that in all but a few large cities, the automobile at present accounts for more than 85 percent of all urban travel, and is usually the dominant form of transportation for persons entering the downtown area.[6]

But historical experience is limited, and the abstraction of even the observed experiences into an hypothesis on the effects upon the city of different modal splits is not a simple procedure.

> While it often is asserted that highway oriented urban transportation systems are the undoing of cities and, conversely, that mass or, better, rapid transit their salvation, there is little historical evidence to support a conclusion one way or the other on this issue....CBD's and central cities have both prospered and languished with and without rapid transit. Furthermore, relatively less rapid growth has occurred in CBD's than either central cities or SMSA's as a whole whether or not rapid transit is available. At best, rapid transit appears to slightly decelerate the tendency toward relative dispersion and provides a very minimal aid, and certainly no guarantees, in preventing an absolute decline in a CBD.[7]

Because, then, of the inconclusiveness of the historical evidence, because of the great variance of costs and values from city to city, and because of the over-all complexity of the problem, the modal split question must be construed as being the aggregate of many smaller, more

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[6] Wilbur Smith and Associates, "Future Highways and Urban Growth," New Haven, Conn.: 1961.

[7] J.R. Meyer, J.F. Kain, and M. Wohl, "Technology and Urban Transportation," Executive Office of the President, Office of Science and Technology, 1962.

specific questions, and great care must be exercised in answering any of these questions. The current thesis is attempting to deal with the question of what costs are associated with different modal splits for different forms of city. The answers obtained will be, of course, partial answers; many assumptions of unit costs and operating criteria have to be made, so that the conditions under which the study is being conducted, while intended to be realistic, nevertheless embrace only a minute proportion of the innumerable sets of conditions which are conceivable. The results, then, must be treated with caution; the inferences drawn from these must be quite limited in their scope of application. Still, they should add just that much more to the slow accumulation of bits of knowledge in the transportation field.

2. Further directions of the thesis

As noted, transportation must be measured in terms of costs, with respect to the quality of service provided. Unfortunately, both costs and quality of service contain many quantities which cannot be easily measured and evaluated in an objective, systematic manner, (e.g., the waiting period for public transit, noise levels, the views provided on the journey, the comfort of seating--or standing--facilities, the ability to smoke or read or listen undisturbed to the radio). Consequently, rather than grasp for the elusive and intangible without first investigating the more feasible and promising, this thesis will concentrate on some of the more readily definable and measurable costs of urban transportation systems--in general, those to which a monetary measure can be most easily applied. These include physical costs (construction plus maintenance costs) for the transportation facilities, operating costs, and time costs (although these costs are given simply in units of time--no attempt is made to apply a monetary value to them).

Of course, any set of costs must assume some level of quality of facilities and services provided. In this thesis, the nature of the transportation facilities is considered to be generally equivalent to modern, present-day, bus, rail, and highway standards. A full, more detailed description of the qualities of the transportation facilities and services would be difficult to draw, lengthy, and not always very meaningful in light of the degree of precision of the cost figures being used.

There are many variables involved in the modal split problem. Primary among these is the transportation system itself; the modal split can embrace many different forms of travel. In this thesis, however, the modal split will hereafter be used to refer to the split between public and private transportation. Private (automobile) transportation and public (mass) transportation will, in turn, embrace various forms of individual modes and group modes of travel, respectively.

Among the other major variables in the modal split problem are land use patterns and densities, population characteristics, and transportation technology. It would be cumbersome indeed to investigate all of these in a single study. Consequently, in addition to modal split, only city form will be dealt with in this thesis as a major variable. The general form of the American city today is comprised of the dense core or central business district surrounded by lower density "urban sprawl." But there are many other possible basic city forms than those of the central city type of scheme. Some of these may develop unexpectedly. Some may be fostered and nurtured by government action if found suitable in terms of transportation and other factors. And some may never show their faces in real life.

But since one cannot tell beforehand into which of these categories any particular city form will fit, and especially since it is strongly felt that the form of the city is a very significant variable in the urban transportation problem, the analysis in this thesis will be performed for each of several very different (abstracted) city forms, and comparisons will be drawn.

PROCEDURE

1. Background

A common instrument for carrying out the purposes of transportation studies is the model. The model, by definition, is a device used to reduce a problem to a more manageable, more workable scale. In engineering and the hard sciences, this reduction may be in a purely physical sense; the model may aspire to achieve, as closely as possible, exact duplication of the prototype in every quality except physical size. In the "softer" sciences, however, such is not generally the case. The problems here are not so clearly defined, the forces and their effects are not so predictable, and the methods of solution are not so obvious. The model achieves workability not through physical reduction, but through simplification; through approximation and reduction of the number of variables (usually quite large) which enter into the problem.

The experiment performed in this thesis utilizes models. They are models of cities and they are not original with the author of this thesis. These models were constructed by Aaron Fleisher in connection with some research he has performed in the transportation field.[1] Eight different city forms are defined, of which six are utilized in this thesis: the central city, the quasi-central city, the many-

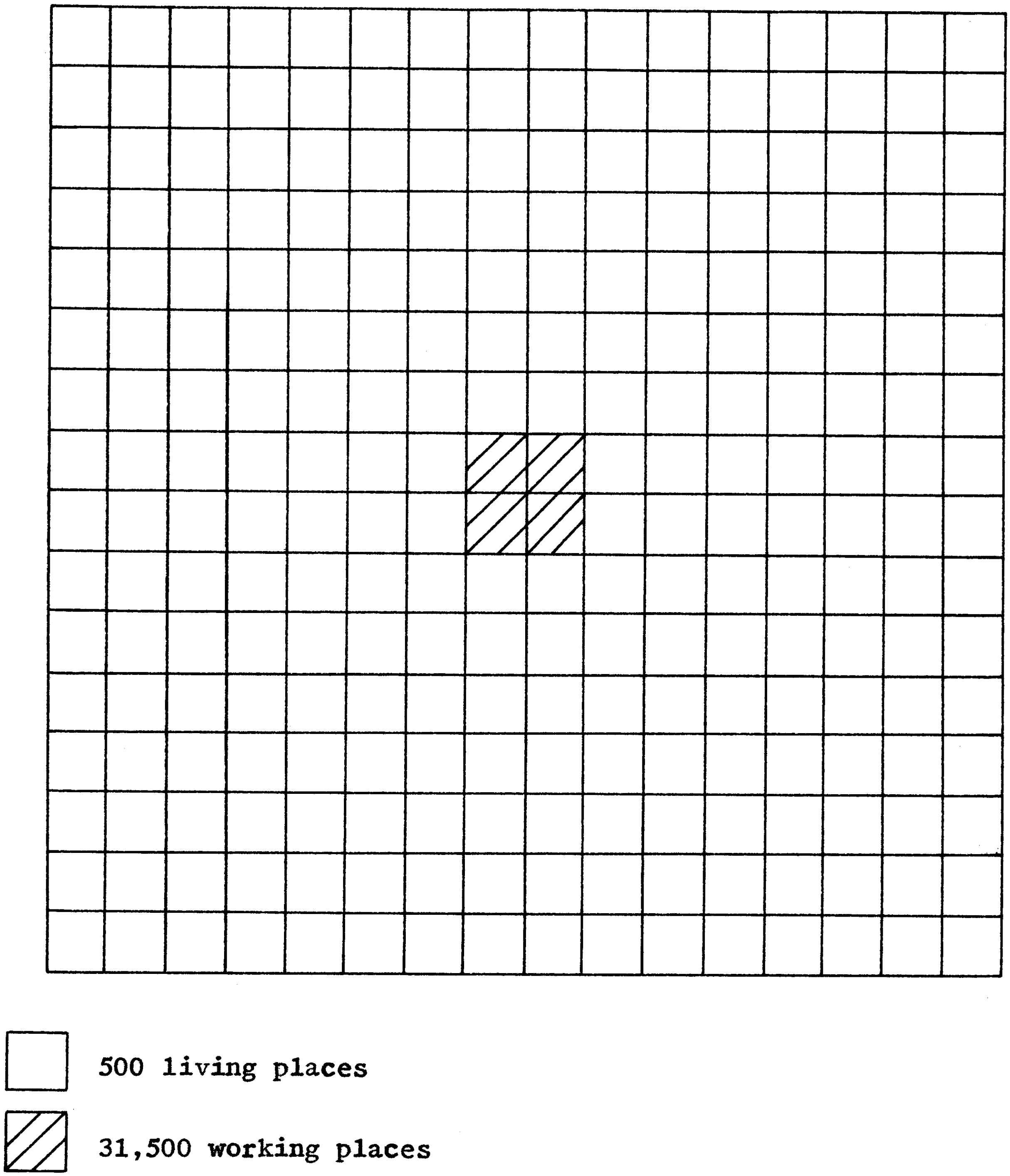
[1]Aaron Fleisher, "Experiments on the Form of the City and the Qualities of Travel" (unpublished draft), M.I.T.-Harvard Joint Center for Urban Studies, 1963.

centered city, the layered city, the homogeneous city, and the ring city.[2] These cities are defined by specifying only the places of residence and the places of employment, and it was only the work trip which was being analyzed; more specifically, the evening rush hour consisting of the journey from working place to home.

In addition to city form, the other major variable in the original experiments was the individual's travel decision. Four decision functions were defined, expressing four different sets of preferences with respect to the desired length of the journey to work.[3] Trips were distributed, in accordance with the decision function, from working places to residences for each of the thirty-two combinations of city form and decision function, and counts were made of the traffic flow as it passed through each mile-square block or area. These included a count of total flow (in all directions) as well as breakdowns into north, northwest, west, southwest, south, southeast, east, and northeast directions. (Trips were distributed over a free surface; i.e., they were not confined to any particular transportation network).

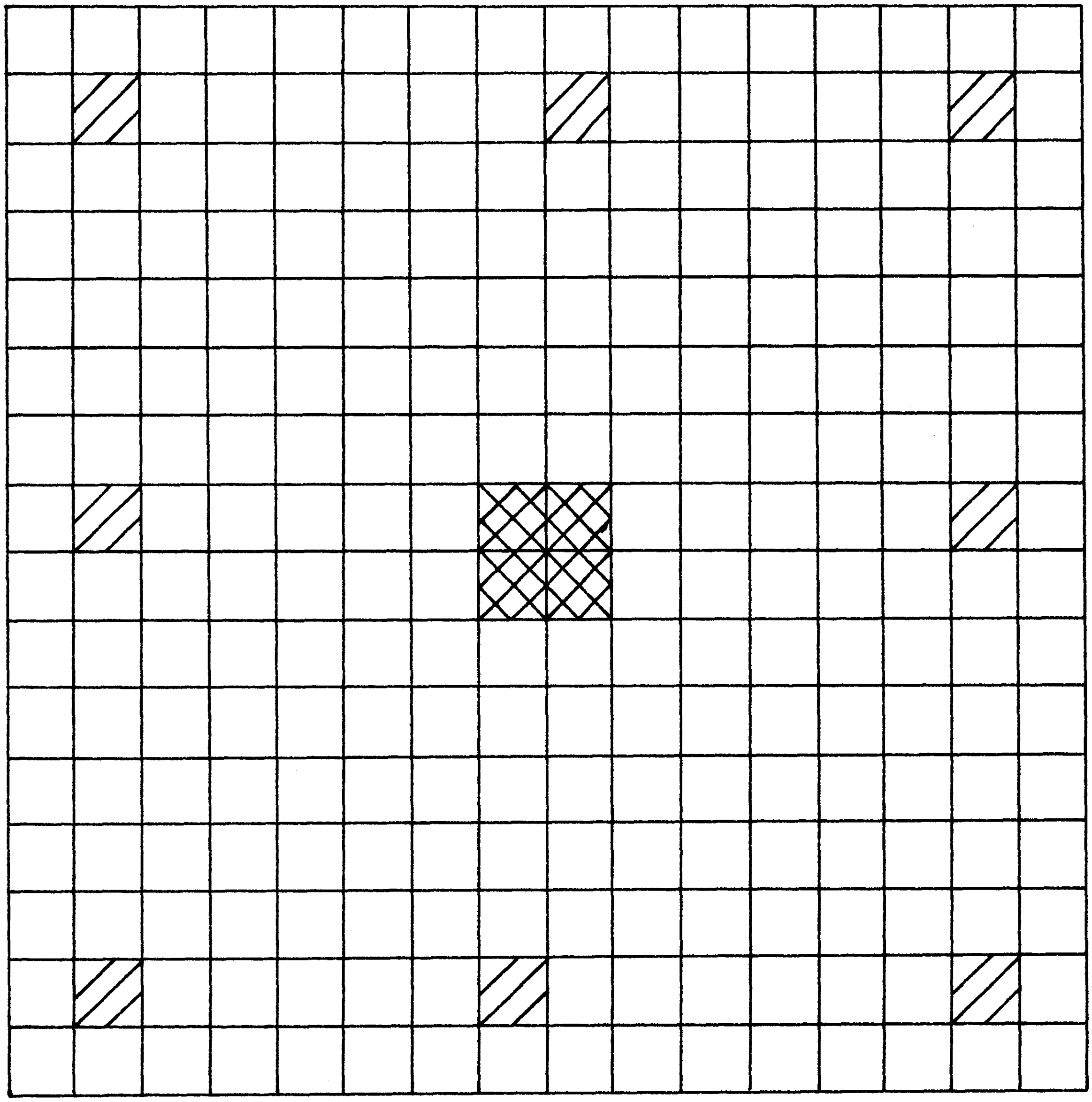
These traffic counts, then, gave a picture of the traffic flows throughout each of the cities for each of the decision functions. In addition, a computation was made

[2]These are illustrated in Figures 1 through 6. The other two forms of city described by Fleisher are two forms of asymmetric cities.
[3]See Figure 7.



Total population = 126,000 workers.

Figure 1. The central city.



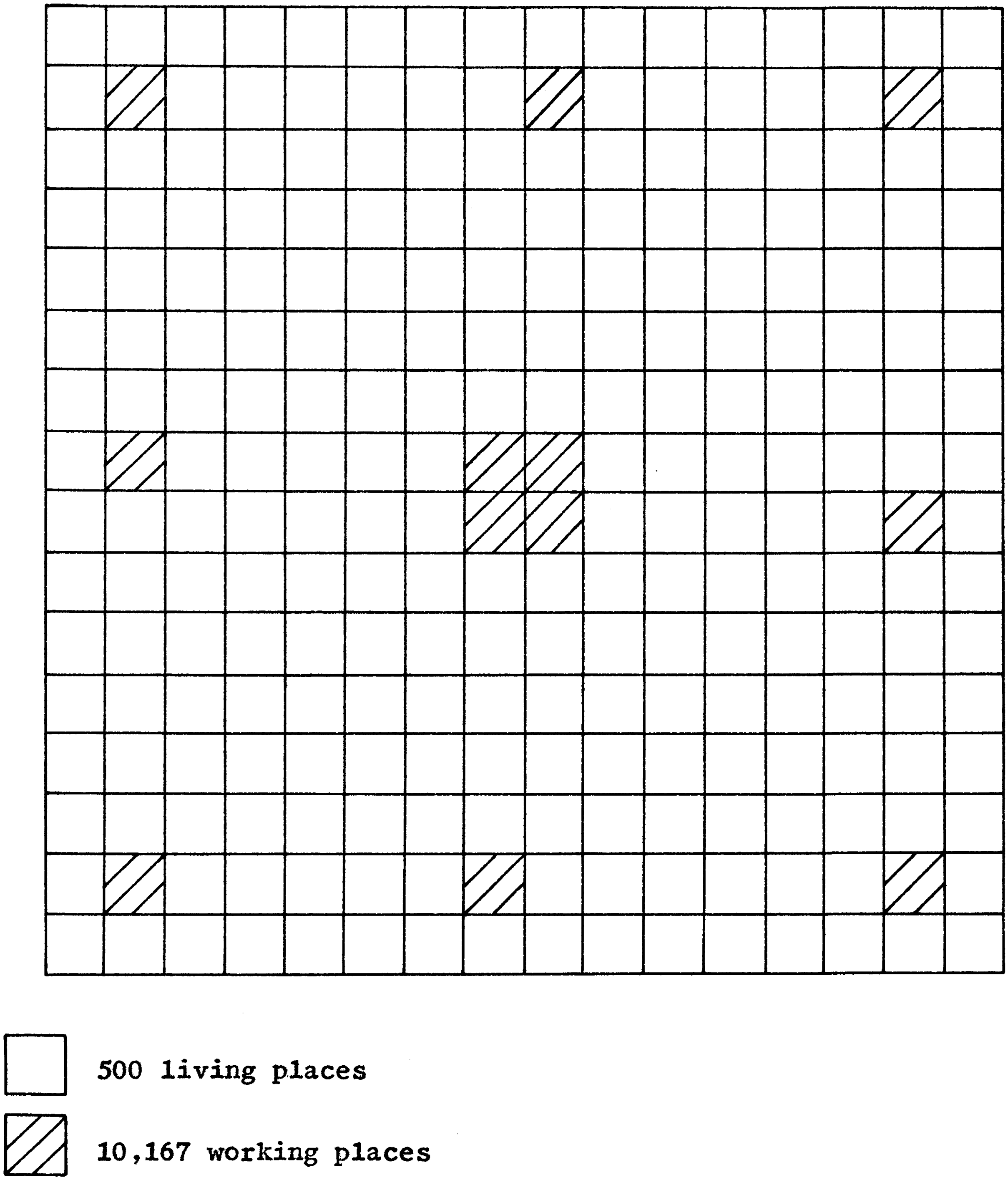
500 living places

6,100 working places

18,300 working places

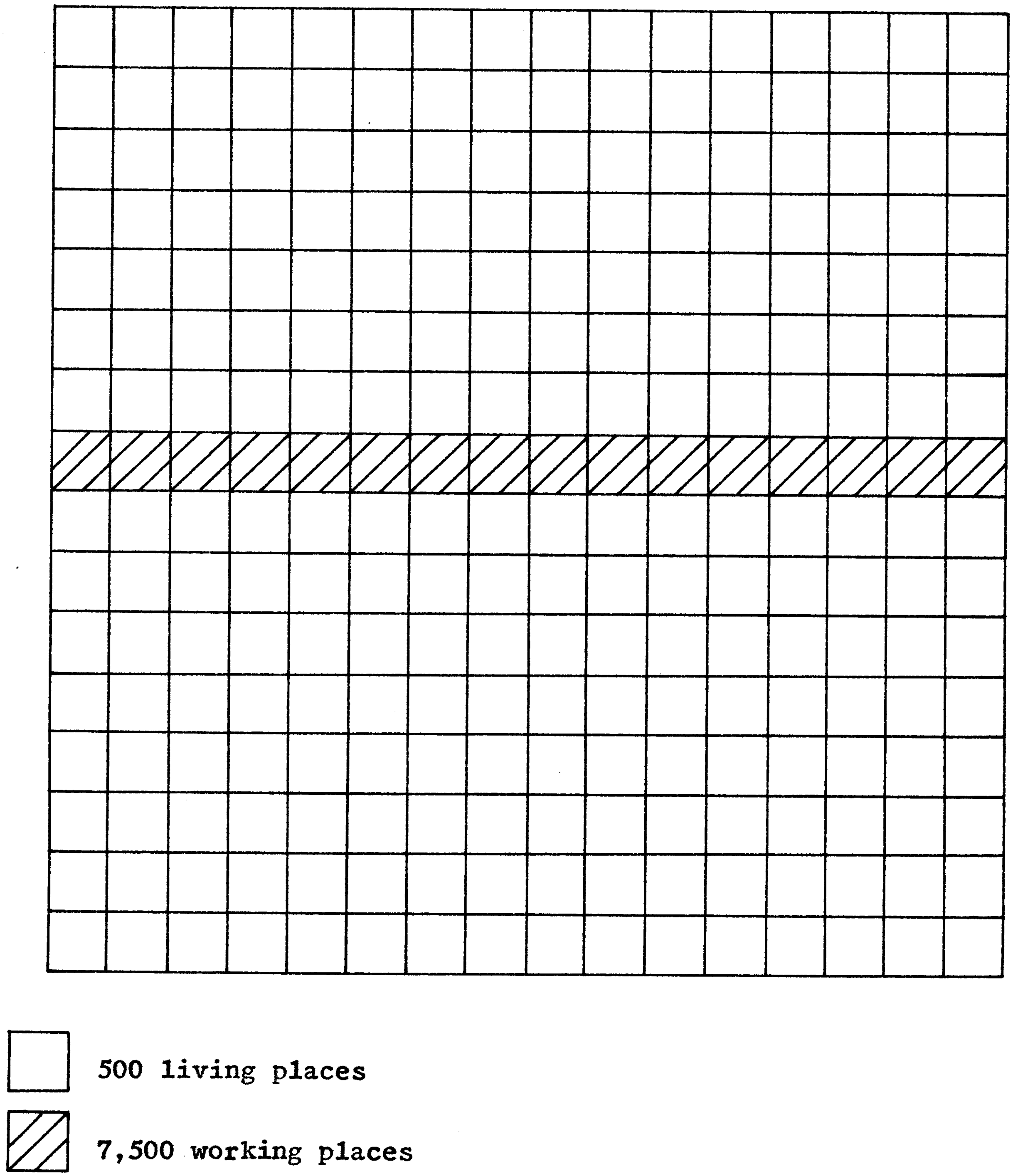
Total population = 122,000 workers.

Figure 2. The quai-central city.



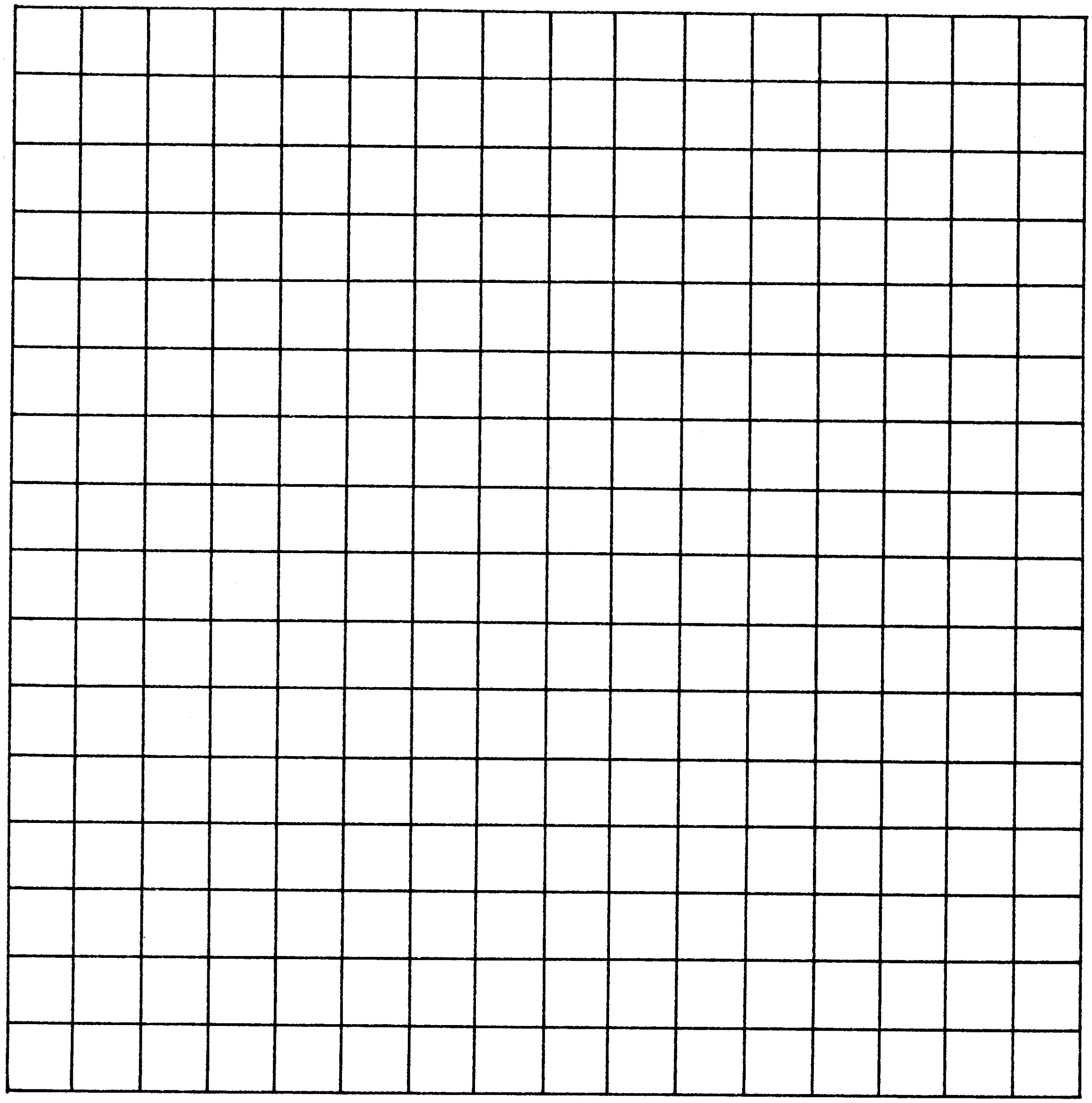
Total population = 122,000 workers.

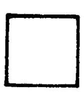
Figure 3. The many-centered city.



Total population = 120,000 workers.

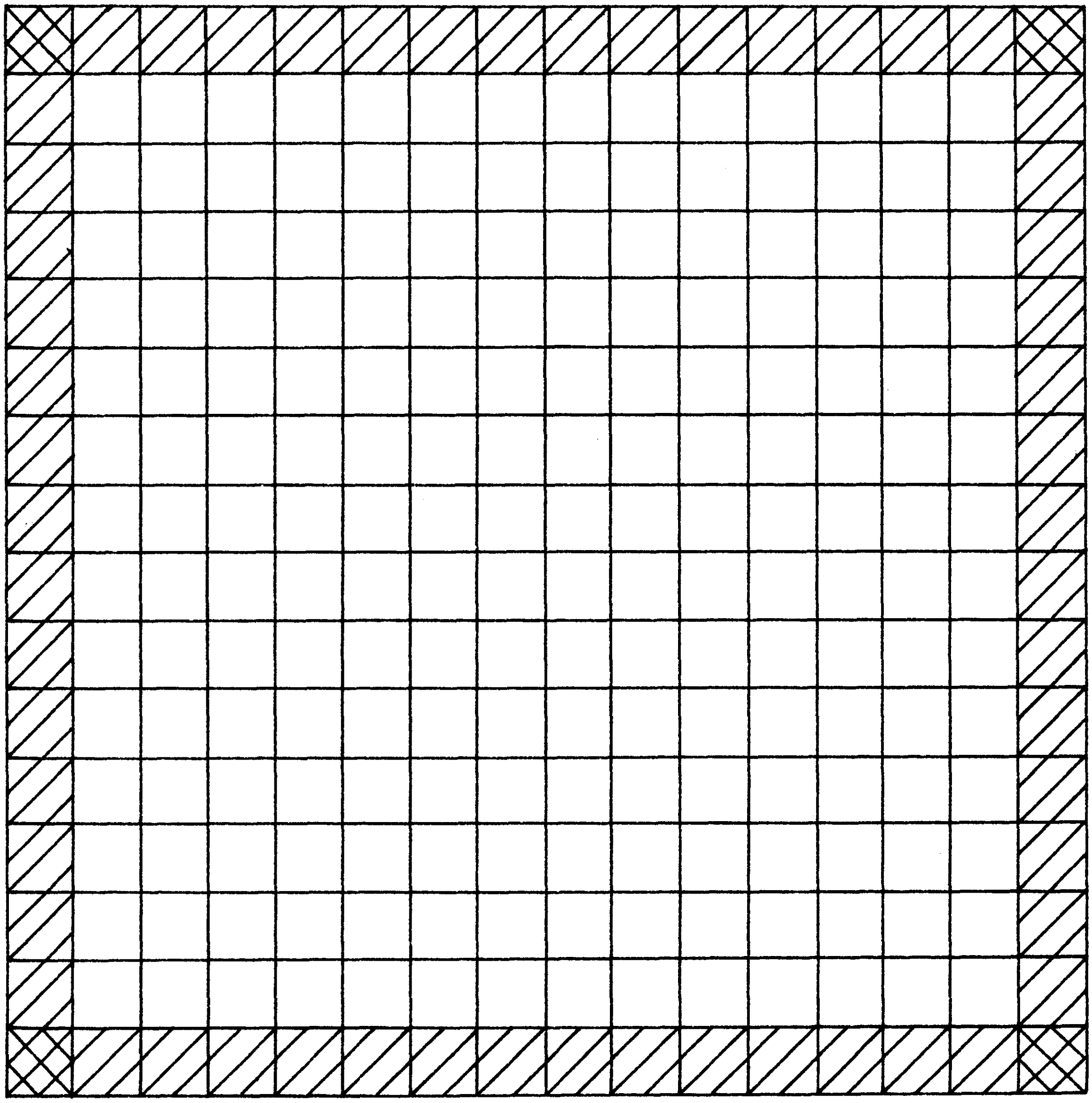
Figure 4. The layered city.



 250 living places and 250 working places

Total population = 64,000 workers.

Figure 5. The homogeneous city.



500 living places

1,633 working places

1,638 working places

Total population = 98,000 workers.

Figure 6. The ring city.

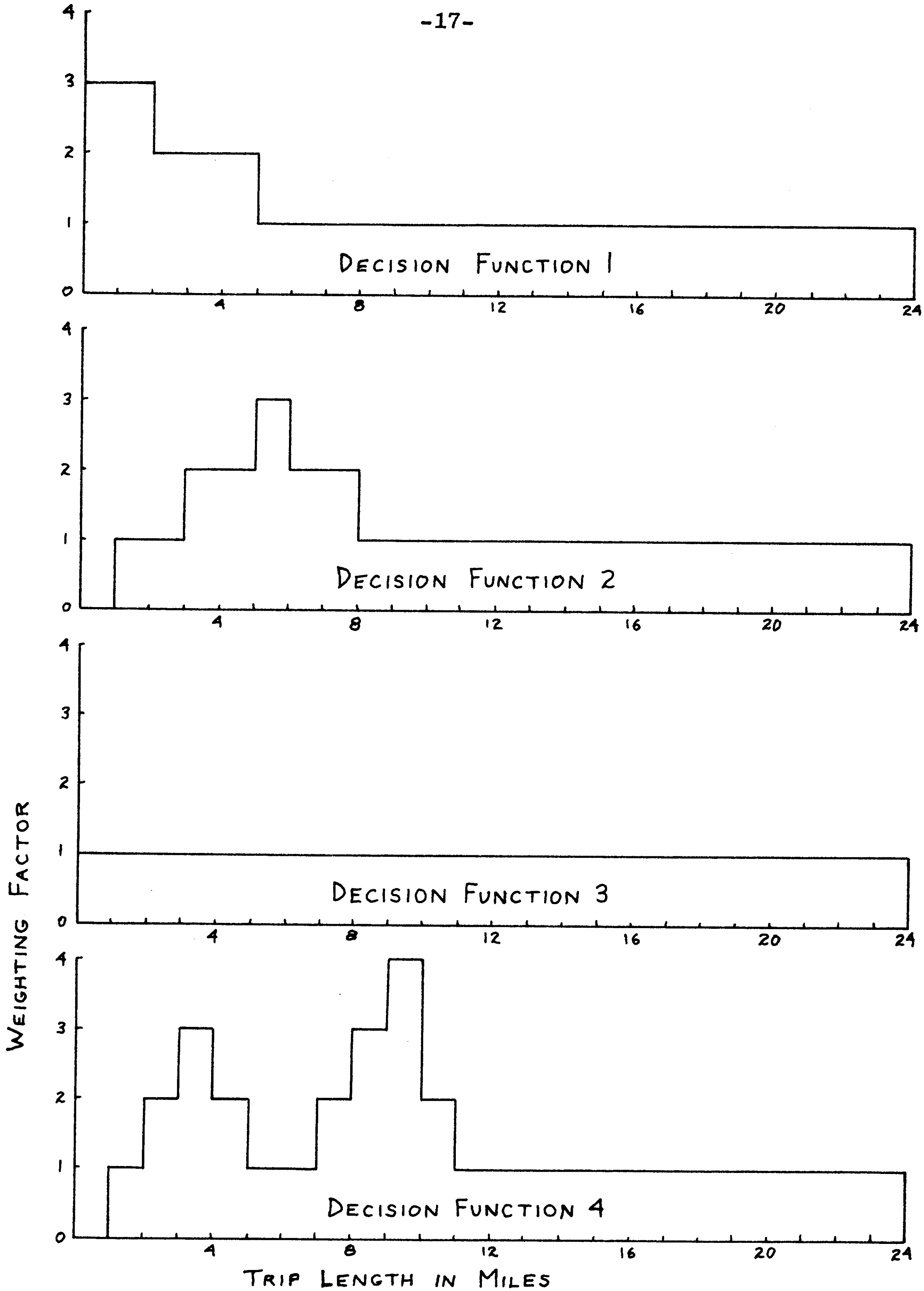


Figure 7. The decision functions.

of the average trip length (measured, in the plan view, in horizontal and vertical directions only) plus its standard deviation. The major observations drawn were: (1)the travel patterns and average trip lengths were dependent more strongly upon city form, and to a lesser degree upon the decision function; and (2)for all decision functions of the six city forms being considered in this thesis, the central city consistently yielded the shortest average trip length, and the ring city, the longest. (It would be well to reiterate that only work trips were being considered here--a simplification which considerably facilitated the computations. The results are still of considerable value, however, for numerous studies have shown that the work trip is the single most common type of trip in the metropolitan area. A recent study, for example, found that 40 percent of all trips during an average day were work trips, and that the percentage was higher, often 60 or 70 percent, during the peak hours which play such a significant role in the design of the transportation system[4]).

The present thesis will be utilizing the flow diagrams produced by Fleisher's work: assigning the flows to prescribed transportation networks, dividing the flows into various splits between private and public transportation (100%-0%, 75%-25%, 50%-50%, 25%-75%, 0%-100%), and then computing costs for the various transportation systems.

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[4]F.B. Curran and J.T. Stegmaier, "Travel Patterns in Fifty Cities," Highway Research Board Bulletin 203, 1958.

With six city forms, four decision functions, and five modal splits, there are 120 city form-decision function-modal split combinations for which to compute costs--an ambitious undertaking with only a desk calculator available for assistance in performing the arithmetic. However, since the travel patterns in the cities do not vary much with the decision functions[5], it is possible to simplify the procedure by reducing the number of different combinations of city with which this thesis will deal (to 30) by selecting only one decision function for each city form.

For this reason, too, the choice of one particular decision function is not a very critical decision. However, in another thesis which also utilized Fleisher's work, Ronald Rice does provide some rationale for doing this.[6] On the maps showing the total number of trip crossings through each one-mile square, contour lines can be drawn which represent isolines of trip density. Considering these now as three-dimensional topographic surfaces, the calculation of the volume beneath these surfaces will yield a measure of total capacity (total number of trip crossings per square x the number of squares). Rice has performed this calculation, and the present thesis has arbitrarily selected for study, for each city form, only that decision function which produces a total capacity requirement which

[5]See the flow diagrams contained in Aaron Fleisher, op. cit.
[6]Ronald G. Rice, "Public Transportation in Urban Areas: Analysis and Expectations," S.M. Thesis, M.I.T., Jan., 1964.

lies closest to the average of the total capacity requirements produced by all four decision functions. The decision functions selected in this manner are decision function 4 for the homogeneous city, decision function 3 for the central city, and decision function 1 for the other four city forms, and all subsequent references to any city form shall assume these particular decision functions.

2. Assignment of traffic flows

The first step was to overlay a transportation network on each of the six cities being studied. This was also the first major problem, for there is no general agreement among authorities as to what is the best transportation pattern for a particular form of city, or as to how to go about designing an optimum configuration. For the experiments in this thesis, several forms of radial pattern were considered, but it was finally decided to use, for all the cities, a simple square grid pattern with a one-mile spacing between routes. The major criterion upon which this decision was based was that the networks ought to be such as to facilitate the assignment of traffic flows to them from Fleisher's basic data. (This calculation could be done far easier on the grid than on any other pattern considered). Other criteria which the networks were asked to meet (and which were met almost as well by some radial patterns as by the grid pattern) were: (1)comparisons among the six cities ought to be facilitated; (2)the networks ought to facilitate the cost computations; and (3)no person should live more than one-half mile from the main transportation network.

Traffic flows (the total flow was assumed to occur during a one-hour time period) were then assigned to the networks in the following manner.[7] The transportation network was placed so as to define or outline the mile-square blocks through which the counts had been made of the numbers of trips going in the various directions. North trips through the middle of a block were assigned half to the route bordering the block on the west and half to the route bordering the block on the east. And similarly for the south, east, and west trips. Of the north-east trips through a block, half were routed north along the block's western boundary and then east along its northern boundary, while the other half were routed east along the southern boundary and then north along the eastern boundary. And similarly for the northwest, southwest, and southeast trips.

In addition, symmetry was utilized to simplify the computations for the 256-square-mile cities. In five of the cities, only the traffic flow figures for the north-by-northeast octant of the city was used, and the rest of the city was assumed symmetrical about that octant, while for the sixth city (the layered city), only the northeast quad-

[7]An illustrative calculation is included in Appendix A.

rant was used.[8] Since the original generation of the trips was done (by an electronic computer) in a random manner (though in accordance with the decision functions), some slight asymmetries were produced in the resultant flow diagrams, and the figures used in the present experiment should more accurately have been the averages for all eight octants (or four quadrants). However, these asymmetries did not seem large enough or significant enough to necessitate or justify this very large additional calculation.[9]

As noted earlier, five modal splits were studied: 100%-0%, 75%-25%, 50%-50%, 25%-75%, and 0%-100%. (The first figure represents the percentage of travel by private or automobile transportation; the second figure, by public or mass transportation). The problem then arose as to how to change the flows by a particular mode of travel along each of the various portions of the network if the total flow by that mode were to be reduced by a certain percentage to achieve a different modal split. It was felt that this might simply, rationally, and consistently be done by reducing travel by this mode by an equal percentage from all segments of the network. But what would be the significance of such a procedure? Would it truly be a reasonable approach?

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[8] Diagrams showing the resultant traffic flows for the six cities are included in Appendix A.

[9] Adjustments were made, however, to correct for the slight geometric asymmetries present in the quasi-central, many-centered, and layered cities, by taking average flows among octants (or quadrants) wherever the asymmetry seemed to have a significant effect.

To determine the effects on the flows along the network of various methods of apportionment of a decrease (or a transfer to the other travel mode), an eight-mile length of route was set up, with the source for all trips at one extremity.[10] A decrease in travel was then allocated by several different methods: uniformly (equally) over the eight miles in one case; entirely to the longest trips in the second case; in proportion to the number of trips ending in each mile in the third case; and entirely and equally among the last four miles in the fourth case. And it was found that the percent decrease along each route segment was equal to the percent decrease in the total flow when the decrease was apportioned in accordance with the number of trip-ends in each mile length. Thus, by applying an equal percent decrease to all segments of the transportation network, the assumption is being made that the transference of different lengths of trips to the other mode of travel is being made in direct proportion to the total number of trips of each length which are being made in the city; if, for example, auto travel is being reduced from 100% to 75%, the number of automobile trips of each length is also being reduced to 75%, the total number of person-miles traveled by auto is being reduced to 75%, and the average trip length by auto does not change.

Although it may be argued that particular modes of

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[10]See Appendix B.

travel may be favored by persons making longer or shorter trips, the above assumption, stating that changes from one mode to another will take place equally (percentage-wise) for all lengths of trips, seems not terribly unreasonable for this study. And it certainly does facilitate procedure.

3. Selection of transportation facilities

Before any costs can be calculated, it is necessary to define the types of transportation systems and facilities being used. Basically, the modal split is being thought of as a split between private transportation (in the form of automobile travel over a hierarchy of roadways) and public transportation (in the form of bus transit or rail transit). Summaries of operating characteristics are included with the summaries of cost characteristics in the next section.[11]

There are, of course, many specific types of travel modes to choose from. And enough types must be included to provide some flexibility in designing the system to meet different capacity requirements. But too many types of travel modes can become cumbersome. Consequently, such facilities as busways (exclusive bus highways) and reserved or preferential bus lanes on highways are not included in this study.

Private transportation (automobile travel) is con-

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[11]See Tables 1,2, and 3.

sidered to take place on a hierarchy of roads comprising 2- and 4-lane major streets, 4- and 6-lane expressways, and 4-, 6-, and 8-lane freeways. Freeways are divided highways with fully controlled access (i.e., no direct access from abutting property, entrances and exits only at specifically designated points) and grade-separated intersections or interchanges, and permit continuous, uninterrupted flow. Expressways--though the terms freeway and expressway are often used interchangeably--technically have only partial control of access, and may have occasional intersections at grade.

Since the configuration of the transportation network has already been decided upon--a square gridiron pattern with a one-mile spacing between routes--the required capacity has in a few instances exceeded even the capability of the 8-lane freeway. In these cases, two roads are provided: an 8-lane freeway operating at full capacity plus another road determined by the remaining capacity requirement. (Automobiles are assumed always to contain 1.7 persons per vehicle).

In general, public transportation is supplied by bus transit. The types of roads on which the buses travel is determined by the combined capacity requirement of buses and automobiles on each road, one bus being considered equivalent to two automobiles for this purpose.[12] However,

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[12]This conversion is translated into terms of person-trips in Appendix C.

minimum and maximum figures were assumed for efficient bus operation. Where the average headway between buses would be greater than fifteen minutes (at 50 persons per bus this would mean less than two hundred persons per hour), no bus service was provided, these persons having to travel instead by automobile. And where the average headway would be less than twenty-five seconds (or where the flow would be greater than 7,200 persons per hour), rail transit would have to be utilized instead of bus transit.

Both bus and rail transit are assumed to operate at full capacity during the peak hour. Also, buses and trains are assumed to make one stop per mile, and the average speeds indicated for these vehicles[13] includes time spent during these stops plus time for acceleration and deceleration.

4. Selection and calculation of costs

Costs of transportation systems are borne by various parties; they are borne by the government and by the user of transportation, as well as by the owner and user of land nearby the transportation facilities. Some of these costs are monetary costs, while others are measured in terms of comfort and convenience. None of these costs are actually entirely separable from the others.

But for the purposes of computation and analysis, costs are broken down in this thesis into three basic cate-

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[13]In Tables 2 and 3.

gories: capital and maintenance costs, operating costs, and time costs. Capital and maintenance costs are computed on an annual basis. (Right-of-way costs, however, are omitted because they are far too variable, far too dependent on specific local real estate values). Because of the great difference in costs between types of rail facilities, two alternative costs are calculated whenever rail transit is necessitated: one cost is applicable in the case where the railroad can be placed on the surface of the land (surface rail); the other, where it must be constructed below the surface (subway).

The distinction between operating costs and maintenance costs is not always clearly defined; road maintenance and yard and shop costs for buses and trains are grouped with constructions costs, but, because it was more convenient (costs were grouped this way by most references), the maintenance costs of buses, trains, and railroad way and structures were grouped with operating costs. Also, for the same reason, the purchase cost of automobiles was included with the operating costs (in terms of depreciation per mile).

It is very important to note, too, that the operating costs are being computed for the one peak hour only--or for the work trips, in essence. (Although it would be possible to assume a typical distribution of trips over the entire day, the total daily operating costs would depend greatly upon the degree and quality of transit service provided in the off-peak hours, and would thus necessitate another major assumption).

Time costs in this experiment are measured simply in units of time; no attempt is made to apply a monetary value to these costs. A measure of time is included as it is one of the most important of the convenience and comfort costs[14], and is a prime consideration in the design of urban transportation systems.

Selecting the actual unit costs, for all three categories of costs being investigated, was not an easy chore. Quick reference to just a few sources will indicate the disparity that exists among the various estimates of the various types of costs. And, to a very great extent, these disparities exist because of the very real, very large range of values which these costs can assume; because of the many variable factors which exert a strong influence on these costs. The final cost figures used in this thesis are composites and averages taken from many sources.[15] A

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[14]For a discussion of the effects of changes in the modal split (all public transit by bus) on certain other variables, such as street capacity and numbers of casualties, see R.J. Smeed and J.G. Wardrop, "An Exploratory Comparison of the Advantages of Cars and Buses for Travel in Urban Areas," Institute of Transport Journal, March, 1964.

[15]Especially: Martin Wohl, "Costs of Urban Transportation Systems of Varying Capacity and Service," (paper presented at the 43rd annual meeting of the Highway Research Board, Jan., 1964); J.R. Meyer, J.F. Kain, and M. Wohl, "Technology and Urban Transportation," Executive Office of the President, Office of Science and Technology, 1962; Wilbur Smith and Associates, "Future Highways and Urban Growth," New Haven, Conn.: 1961; Keith Gilbert, "Economic Balance of Transportation Modes," Traffic Engineering, Oct., 1963; R.L. Creighton, D.I. Gooding, G.C. Hemmens, and J.E. Fid-

compilation of these costs is included in Tables 1, 2, and 3.

For the actual cost computations, diagrams were drawn, for each of the thirty combinations of city form and modal split, showing the traffic flows in the direction of heavier flow along each one-mile segment of route (flows were rounded off to the nearest fifty person-trips), and showing the type of road which would be required by these flows.[16] By using the traffic flows only in the direction of heavier flow, the computations were greatly facilitated. (It was only these flows which determined the type of road or transit facility required along the various portions of the network). However, for the calculation of operating and time costs, as well as the required numbers of buses and railroad cars, total two-directional figures were needed. What was done in these cases was to multiply the one-directional figures (for flows in the heavier directions only) by a factor equal to the quotient of the total two-directional flow (this quantity <u>was</u> measured) divided by the sum of the flows in the peak directions only.

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ler, "Optimum Investment in Two-Mode Transportation Systems," (paper presented at the 43rd annual meeting of the Highway Research Board, Jan., 1964); Arrigo Mongini, "The Physical and Economic Characteristics of Express Bus Urban Transit Systems," S.B. Thesis, M.I.T., June, 1961; Delaware River Port Authority of Pennsylvania and New Jersey, "Southern New Jersey Rapid Transit System, Haddonfield-Kirkwood Line," 1961; Edward H. Holmes, "Highway Transportation," <u>U.S. Transportation, Resources, Performance and Problems</u>, (papers prepared for the Transportation Research Conference convened by the National Academy of Sciences at Woods Hole, Mass.), 1960; Ronald G. Rice, <u>op. cit.</u>

[16] These diagrams are included in Appendix C.

Road	Construction cost/mile, in $millions	Average operating speed, in miles/hour	Average capacity, persons/hour--one direction	Operating cost per person-mile, in ¢
Freeway				
8-lane	3.6	55	9,600	4.7
6-lane	2.7	55	7,200	4.7
4-lane	2.0	55	4,800	4.7
Expressway				
6-lane	1.1	35	3,200	5.3
4-lane	0.8	35	2,400	5.3
Major Street				
4-lane	0.6	25	1,900	5.9
2-lane	0.4	25	900	5.9

Automobile capacity assumed at 1.7 persons per vehicle.

Operating cost includes gas, oil, tires, maintenance, depreciation, insurance, registration, parking and garaging.

Road maintenance = $1,000/lane-mile per year.

Estimated life of all roads = 35 years.

Interest rate assumed at 5½%.

To compute annual costs, use capital recovery factor (CRF), where n = life in years and i = rate of interest:

$$CRF = i/(1 - (1 + i)^{-n})$$

Table 1. Automobile and road costs.

Capital and maintenance costs

Purchase cost per bus = \$30,000 (life of 12 years).

Yard and shop cost per bus = \$4,500 (life of 40 years).

To compute annual costs, use capital recovery factor (CRF), where n = life in years and i = rate of interest (use $5\frac{1}{2}\%$):

$$CRF = i/(1 - (1 + i)^{-n})$$

Operating costs

Operating cost per bus-mile = \$.50.

Operating cost includes maintenance and garage, fuel and oil, administration, insurance, and wages of drivers and other transportation employees.

Speed and capacity

Seating capacity per bus = 50 persons.

In determining roadway capacities, one bus is assumed equivalent to two automobiles.

Average speed (including stops and acceleration and deceleration)
= 30 miles per hour on freeways
= 20 miles per hour on expressways
= 15 miles per hour on major streets.

Waiting time per person = one-half average headway.

Minimum average headway = 25 seconds
= 144 buses per hour
= 7,200 persons per hour (above which, rail transit must be employed).

Maximum average headway = 15 minutes
= 4 buses per hour
= 200 persons per hour (below which, no public transit is provided).

Table 2. Bus costs.

Capital and maintenance costs

Purchase cost per car = \$90,000 (life of 30 years).

Yard and shop cost per car = \$8,000 (life of 50 years).

Construction cost per 2-track mile of surface rail
= \$4,000,000 (life of 50 years).

Construction cost per 2-track mile of subway
= \$17,500,000 (life of 50 years).

Construction cost per surface rail station (one per mile)
= \$500,000 (life of 50 years).

Construction cost per subway station (one per mile)
= \$3,000,000 (life of 50 years).

To compute annual costs, use capital recovery factor (CRF), where n = life in years and i = rate of interest (use $5\frac{1}{2}\%$):

$$CRF = i/(1 - (1 + i)^{-n})$$

Operating costs

Operating cost per car-mile = \$.70.

Operating cost includes way and structures, equipment, power, conducting transportation, traffic, insurance, general and administrative.

Speed and capacity

Seating capacity per car = 80 persons.

Average speed (including stops and acceleration and deceleration) = 35 miles per hour.

Waiting time per person = one-half average headway.

Maximum capacity = 40 trains per hour, with 8 cars per train
= 25,600 persons per track-hour.

Table 3. Rail costs.

The actual processes of the tabulation of the travel characteristics and the calculation of the various costs for the thirty different city form-modal split combinations is far too lengthy to be reproduced in the text; however, the results of the tabulations (totals for entire cities, not just octants or quadrants) plus a detailed sample calculation for a representative city form and modal split are included in appendices.[17]

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[17] See Appendices D and E.

RESULTS AND IMPLICATIONS

1. The results and their interpretation

The results of the cost computations are listed in Tables 4 through 9, each table summarizing the capital and maintenance costs, the operating costs, and the time costs for one of the cities. A protracted verbal description of each of the minor results listed in these tables would be quite unnecessary and quite tiresome; however, the implications of the major results certainly bear some discussion.

In Figures 8, 9, and 10, the three basic costs being investigated--per capita capital and maintenance cost, per capita operating cost for the work trip, and average time spent for the complete door-to-door journey--are graphed against the modal split. (The costs are reduced to a per capita basis so as to enable comparison among the six cities, which happen to have different populations). One of the most significant observations to be made from examining Figure 8 is that the general trend of the physical costs of the transportation systems (capital or construction costs plus maintenance costs) is to decrease as the percentage of public or mass transportation increases. In four of the six cities, the cost curve does actually take a slight upward swing after the percentage of public transportation reaches about seventy-five percent, and in another of the cities, the homogeneous city, this upward swing in fact begins at about the twenty percent mark. It is sug-

	Percent Modal Split:				
	100-0	75-25	50-50	25-75	0-100
I. Capital and Maintenance Costs (in $1,000)					
Annual road construction cost	33,735	27,471	21,572	15,750	12,267
Annual road maintenance cost	1,944	1,768	1,512	1,280	944
Total annual road cost	35,679	29,239	23,084	17,030	13,211
Annual bus purchase cost	--	915	2,078	3,463	4,194
Annual bus yard & shop cost	--	74	167	279	338
Total annual bus cost	--	989	2,245	3,742	4,532
Annual train purchase cost	--	--	93	303	681
Annual train yard & shop cost	--	--	7	23	52
Annual construction cost of surface rail track & stations	--	--	1,063	3,189	6,379
Annual construction cost of subway track and stations	--	--	4,843	14,529	29,058
Tot. an'l surface rail cost	--	--	1,163	3,515	7,112
Total annual subway cost	--	--	4,943	14,855	29,791
Total capital and maintenance costs (with surface rail)	35,679	30,228	26,492	24,287	24,855
Total capital and maintenance costs (with subway)	"	"	30,272	35,627	47,534
Per capita capital & maint. costs (w. surf. rail) (in $)	283.17	239.90	210.25	192.75	197.26
Per capita capital & maint. costs (with subway) (in $)	"	"	240.25	282.75	377.25
II. Operating Costs (in dollars)					
Auto cost on major street	17,766	16,392	17,299	12,583	78
Auto cost on expressway	11,475	12,919	5,790	3,825	--
Auto cost on freeway	32,624	18,895	9,907	928	--
Bus cost	--	2,879	5,590	7,703	9,034
Rail cost	--	--	348	1,192	2,687
Total operating cost	61,865	51,085	38,934	26,231	11,799
Avg. op. cost/person (in ¢)	49.10	40.54	30.90	20.82	9.36
Avg. oper. cost/mile (in ¢)	5.10	4.21	3.21	2.16	0.97
III. Trip Time (in person-hours)					
Total traveling time on main transportation network	30,852	38,769	49,562	63,865	69,051
Average headway for buses (in minutes)	--	3.98	2.48	1.93	1.64
Average headway for 4-car trains (in minutes)	--	--	2.12	1.86	1.65
Total waiting time for public transit	--	993	1,218	1,343	1,387
Total preliminary traveling time to transp'tion network	5,250	8,994	13,031	17,033	20,983
Total time for all journeys	36,102	48,756	63,811	82,241	91,421
Average journey time, door-to-door (in minutes)	17.19	23.22	30.39	39.16	43.53
Average journey speed, door-to-door (in m.p.h.)	33.57	24.85	18.99	14.73	13.26

Table 4. Summary of costs for the central city.

	Percent Modal Split: 100-0	75-25	50-50	25-75	0-100
I. Capital and Maintenance Costs (in $1,000)					
Annual road construction cost	28,433	23,885	19,830	15,152	13,827
Annual road maintenance cost	1,976	1,792	1,528	1,216	1,064
Total annual road cost	30,409	25,677	21,358	16,368	14,891
Annual bus purchase cost	--	1,156	2,562	4,184	5,319
Annual bus yard & shop cost	--	93	206	337	429
Total annual bus cost	--	1,249	2,768	4,521	5,748
Annual train purchase cost	--	--	--	105	328
Annual train yard & shop cost	--	--	--	8	25
Annual construction cost of surface rail track & stations	--	--	--	1,063	3,189
Annual construction cost of subway track and stations	--	--	--	4,843	14,529
Tot. an'l surface rail cost	--	--	--	1,176	3,542
Total annual subway cost	--	--	--	4,956	14,882
Total capital and maintenance cost (with surface rail)	30,409	26,926	24,126	22,065	24,181
Total capital and maintenance cost (with subway)	"	"	"	25,845	35,521
Per capita capital & maint. cost (w. surf. rail) (in $)	249.25	220.70	197.75	180.86	198.20
Per capita capital & maint. cost (with subway) (in $)	"	"	"	211.84	291.16
II. Operating Costs (in dollars)					
Auto cost on major street	29,443	30,700	25,194	17,487	265
Auto cost on expressway	18,474	10,841	5,554	1,932	--
Auto cost on freeway	23,771	12,340	5,860	--	--
Bus cost	--	3,085	6,396	9,163	11,457
Rail cost	--	--	--	412	1,275
Total operating cost	71,688	56,966	43,004	28,994	12,997
Avg. op. cost/person (in ¢)	58.76	46.69	35.25	23.77	10.65
Avg. oper. cost/mile (in ¢)	5.53	4.40	3.32	2.24	1.00
III. Trip Time (in person-hours)					
Total traveling time on main transportation network	38,071	47,930	59,086	74,294	80,725
Average headway for buses (in minutes)	--	5.50	3.15	2.26	1.86
Average headway for 4-car trains (in minutes)	--	--	--	2.28	2.22
Total waiting time for public transit	--	1,332	1,582	1,647	1,740
Total preliminary traveling time to transp'tion network	5,083	8,714	12,609	16,417	20,278
Total time for all journeys	43,154	57,976	73,277	92,358	102,743
Average journey time, door-to-door (in minutes)	21.22	28.51	36.04	45.42	50.53
Average journey speed, door-to-door (in m.p.h.)	30.04	22.36	17.69	14.03	12.62

Table 5. Summary of costs for the quasi-central city.

	Percent Modal Split:				
	100-0	75-25	50-50	25-75	0-100
I. Capital and Maintenance Costs (in $1,000)					
Annual road construction cost	26,536	21,858	18,245	15,230	14,139
Annual road maintenance cost	1,936	1,872	1,608	1,248	1,088
Total annual road cost	28,472	23,730	19,853	16,478	15,227
Annual bus purchase cost	--	1,347	2,966	4,654	6,346
Annual bus yard & shop cost	--	109	239	375	511
Total annual bus cost	--	1,456	3,205	5,029	6,857
Annual train purchase cost	--	--	--	--	--
Annual train yard & shop cost	--	--	--	--	--
Annual construction cost of surface rail track & stations	--	--	--	--	--
Annual construction cost of subway track and stations	--	--	--	--	--
Tot. an'l surface rail cost	--	--	--	--	--
Total annual subway cost	--	--	--	--	--
Total capital and maintenance cost (with surface rail)	28,472	25,186	23,058	21,507	22,084
Total capital and maintenance cost (with subway)	"	"	"	"	"
Per capita capital & maint. cost (w. surf. rail) (in $)	233.38	206.44	189.00	176.29	181.02
Per capita capital & maint. cost (with subway) (in $)	"	"	"	"	"
II. Operating Costs (in dollars)					
Auto cost on major streets	31,780	39,033	35,331	20,039	--
Auto cost on expressways	26,672	16,406	4,165	539	--
Auto cost on freeways	15,262	3,504	971	--	--
Bus cost	--	3,212	6,685	10,174	13,666
Rail cost	--	--	--	--	--
Total operating cost	73,714	62,155	47,152	30,752	13,666
Avg. op. cost/person (in ¢)	60.42	50.95	38.65	25.21	11.20
Avg. oper. cost/mile (in ¢)	5.39	4.55	3.45	2.25	1.00
III. Trip Time (in person-hours)					
Total traveling time on main transportation network	41,829	55,543	69,141	81,187	91,109
Average headway for buses (in minutes)	--	5.58	3.26	2.33	1.84
Average headway for 4-car trains (in minutes)	--	--	--	--	--
Total waiting time for public transit	--	1,335	1,623	1,761	1,868
Total preliminary traveling time to transp'tion network	5,083	8,667	12,544	16,431	20,333
Total time for all journeys	46,912	65,545	83,308	99,379	113,310
Average journey time, door-to-door (in minutes)	23.07	32.24	40.97	48.87	55.73
Average journey speed, door-to-door (in m.p.h.)	29.14	20.86	16.41	13.76	12.06

Table 6. Summary of costs for the many-centered city.

	Percent Modal Split:				
	100-0	75-25	50-50	25-75	0-100
I. Capital and Maintenance Costs (in $1,000)					
Annual road construction cost	33,059	27,043	20,155	15,802	14,139
Annual road maintenance cost	1,968	1,780	1,664	1,332	1,088
Total annual road cost	35,027	28,823	21,819	17,134	15,227
Annual bus purchase cost	--	1,076	2,614	4,487	6,050
Annual bus yard & shop cost	--	87	211	361	487
Total annual bus cost	--	1,163	2,825	4,848	6,537
Annual train purchase cost	--	--	--	--	--
Annual train yard & shop cost	--	--	--	--	--
Annual construction cost of surface rail track & stations	--	--	--	--	--
Annual construction cost of subway track and stations	--	--	--	--	--
Tot. an'l surface rail cost	--	--	--	--	--
Total annual subway cost	--	--	--	--	--
Total capital and maintenance cost (with surface rail)	35,027	29,986	24,644	21,982	21,764
Total capital and maintenance cost (with subway)	"	"	"	"	"
Per capita capital & maint. cost (w. surf. rail) (in $)	291.89	249.88	205.37	183.18	181.37
Per capita capital & maint. cost (with subway) (in $)	"	"	"	"	"
II. Operating Costs (in dollars)					
Auto cost on major streets	22,174	23,719	21,137	18,823	239
Auto cost on expressways	14,482	12,477	14,334	665	--
Auto cost on freeways	30,928	16,861	1,552	--	--
Bus cost	--	3,111	6,460	9,755	13,031
Rail cost	--	--	--	--	--
Total operating cost	67,584	56,168	43,483	29,243	13,270
Avg. op. cost/person (in ¢)	56.32	46.81	36.24	24.37	11.06
Avg. oper. cost/mile (in ¢)	5.17	4.30	3.33	2.24	1.02
III. Trip Time (in person-hours)					
Total traveling time on main transportation network	34,805	44,760	60,962	77,525	87,034
Average headway for buses (in minutes)	--	4.86	2.84	1.99	1.58
Average headway for 4-car trains (in minutes)	--	--	--	--	--
Total waiting time for public transit	--	1,156	1,405	1,488	1,579
Total preliminary traveling time to transp'tion network	5,000	8,570	12,410	16,195	19,954
Total time for all journeys	39,805	54,486	74,777	95,208	108,567
Average journey time, door-to-door (in minutes)	19.90	27.24	37.39	47.60	54.28
Average journey speed, door-to-door (in m.p.h.)	32.84	23.99	17.48	13.73	12.04

Table 7. Summary of costs for the layered city.

	Percent Modal Split:				
	100-0	75-25	50-50	25-75	0-100
I. Capital and Maintenance Costs (in $1,000)					
Annual road construction cost	16,114	14,866	14,139	14,139	14,139
Annual road maintenance cost	1,392	1,200	1,088	1,088	1,088
Total annual road cost	17,506	16,066	15,227	15,227	15,227
Annual bus purchase cost	--	546	1,497	2,266	3,147
Annual bus yard & shop cost	--	44	121	183	254
Total annual bus cost	--	590	1,618	2,449	3,401
Annual train purchase cost	--	--	--	--	--
Annual train yard & shop cost	--	--	--	--	--
Annual construction cost of surface rail track & stations	--	--	--	--	--
Annual construction cost of subway track and stations	--	--	--	--	--
Tot. an'l surface rail cost	--	--	--	--	--
Total annual subway cost	--	--	--	--	--
Total capital and maintenance cost (with surface rail)	17,506	16,656	16,845	17,676	18,628
Total capital and maintenance cost (with subway)	"	"	"	"	"
Per capita capital & maint. cost (w. surf. rail) (in $)	273.53	260.25	263.25	276.19	291.06
Per capita capital & maint. cost (with subway) (in $)	"	"	"	"	"
II. Operating Costs (in dollars)					
Auto cost on major streets	40,738	33,828	21,750	11,967	775
Auto cost on expressways	--	--	--	--	--
Auto cost on freeways	--	--	--	--	--
Bus cost	--	1,174	3,218	4,878	6,773
Rail cost	--	--	--	--	--
Total operating cost	40,738	35,002	24,968	16,845	7,548
Avg. op. cost/person (in ¢)	63.65	54.69	39.01	26.32	11.79
Avg. oper. cost/mile (in ¢)	5.90	5.07	3.62	2.44	1.09
III. Trip Time (in person-hours)					
Total traveling time on main transportation network	27,619	30,759	36,199	40,632	45,681
Average headway for buses (in minutes)	--	12.08	7.37	4.98	4.25
Average headway for 4-car trains (in minutes)	--	--	--	--	--
Total waiting time for public transit	--	1,096	1,833	1,877	2,222
Total preliminary traveling time to transp'tion network	2,667	4,026	6,395	8,317	10,515
Total time for all journeys	30,286	35,881	44,427	50,826	58,418
Average journey time, door-to-door (in minutes)	28.39	33.64	41.65	47.65	54.77
Average journey speed, door-to-door (in m.p.h.)	22.80	19.25	15.54	13.59	11.82

Table 8. Summary of costs for the homogeneous city.

	Percent Modal Split:				
	100-0	75-25	50-50	25-75	0-100
I. Capital and Maintenance Costs (in $1,000)					
Annual road construction cost	22,351	20,376	18,557	14,139	14,139
Annual road maintenance cost	2,048	2,048	1,768	1,088	1,088
Total annual road cost	24,399	22,424	20,325	15,227	15,227
Annual bus purchase cost	--	1,455	3,004	4,508	6,005
Annual bus yard & shop cost	--	117	242	363	484
Total annual bus cost	--	1,572	3,246	4,871	6,489
Annual train purchase cost	--	--	--	--	--
Annual train yard & shop cost	--	--	--	--	--
Annual construction cost of surface rail track & stations	--	--	--	--	--
Annual construction cost of subway track & stations	--	--	--	--	--
Tot. an'l surface rail cost	--	--	--	--	--
Total annual subway cost	--	--	--	--	--
Total capital and maintenance cost (with surface rail)	24,399	23,996	23,571	20,098	21,716
Total capital and maintenance cost (with subway)	"	"	"	"	"
Per capita capital & maint. cost (w. surf. rail) (in $)	248.97	244.86	240.52	205.08	221.59
II. Operating Costs (in dollars)					
Auto cost on major streets	49,647	57,809	38,148	19,026	--
Auto cost on expressways	23,941	--	--	--	--
Auto cost on freeways	--	--	--	--	--
Bus cost	--	3,128	6,479	9,708	12,959
Rail cost	--	--	--	--	--
Total operating cost	73,588	60,937	44,627	28,734	12,959
Avg. op. cost/person (in ¢)	75.09	62.18	45.54	29.32	13.22
Avg. oper. cost/mile (in ¢)	5.69	4.71	3.45	2.22	1.00
III. Trip Time (in person-hours)					
Total traveling time on main transportation network	46,565	60,048	68,968	77,621	86,212
Average headway for buses (in minutes)	--	6.72	3.62	2.42	1.81
Average headway for 4-car trains (in minutes)	--	--	--	--	--
Total waiting time for public transit	--	1,327	1,478	1,482	1,478
Total preliminary traveling time to transp'tion network	4,083	7,048	10,208	13,522	16,333
Total time for all journeys	50,648	68,423	80,654	92,625	104,023
Average journey time, door-to-door (in minutes)	31.01	41.89	49.38	56.71	63.69
Average journey speed, door-to-door (in m.p.h.)	25.53	18.90	16.03	13.96	12.43

Table 9. Summary of costs for the ring city.

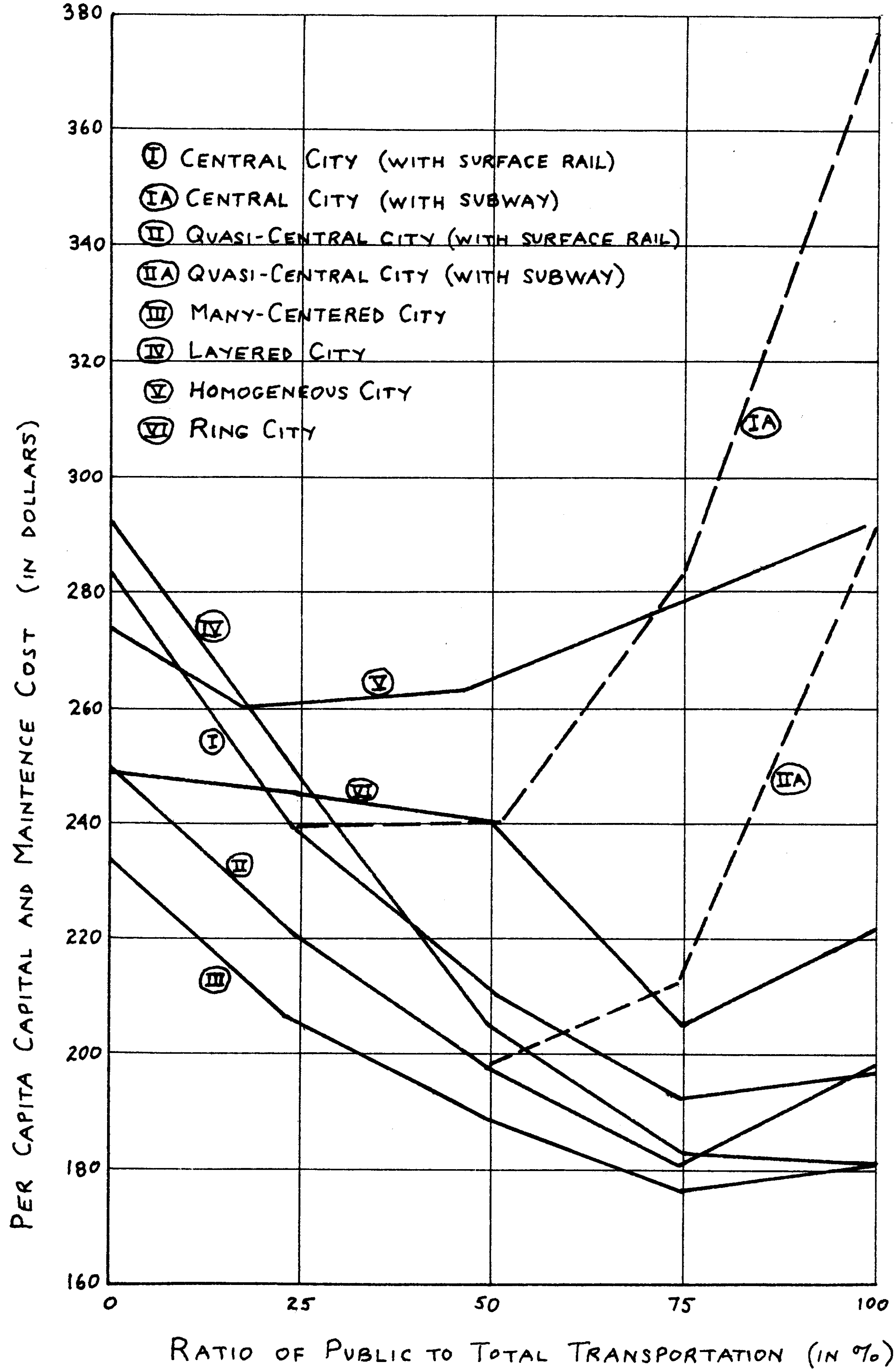

Figure 8. Graph of per capita capital and maintenance costs vs. modal split.

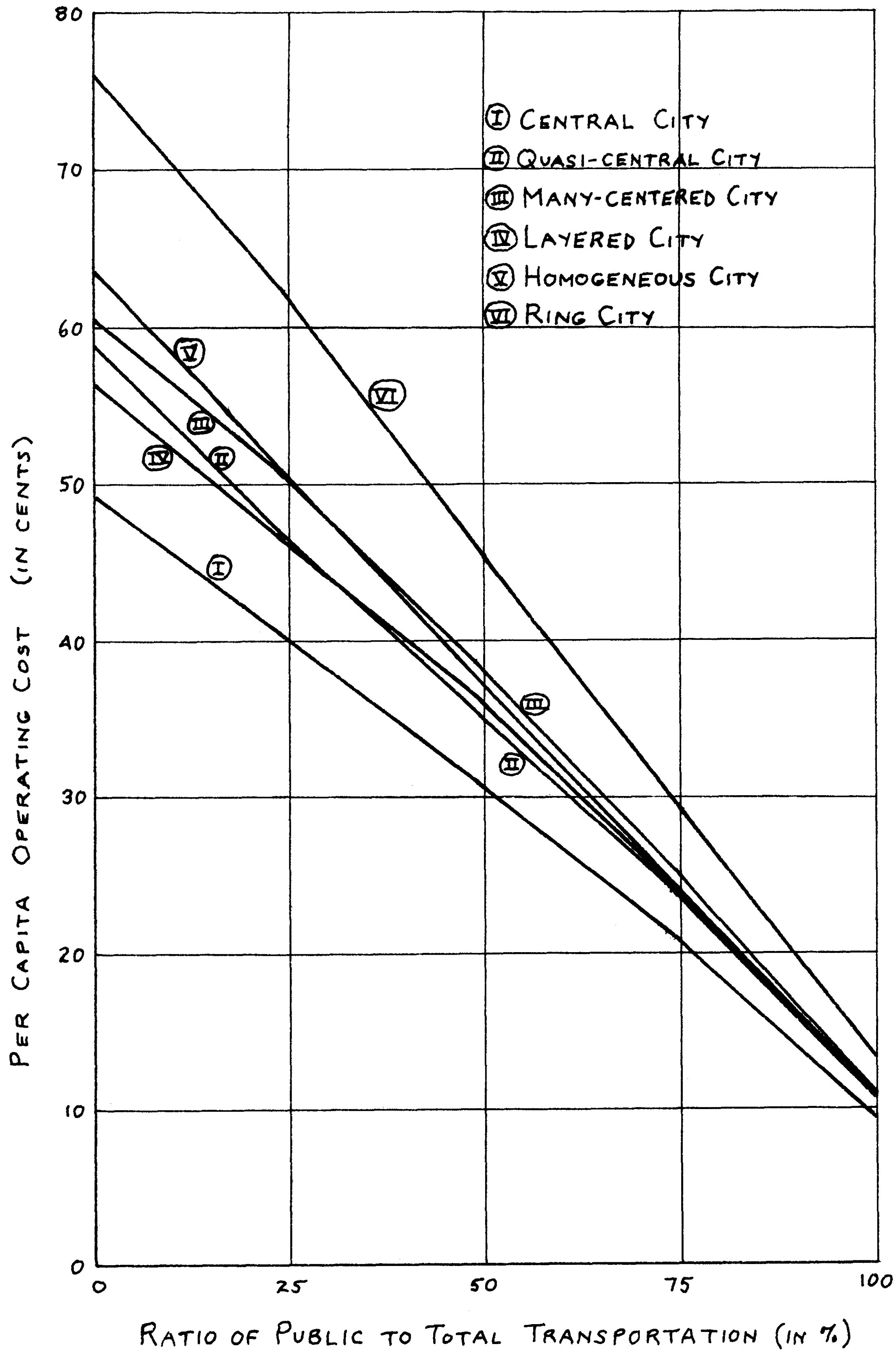

Figure 9. Graph of per capita operating costs vs. modal split.

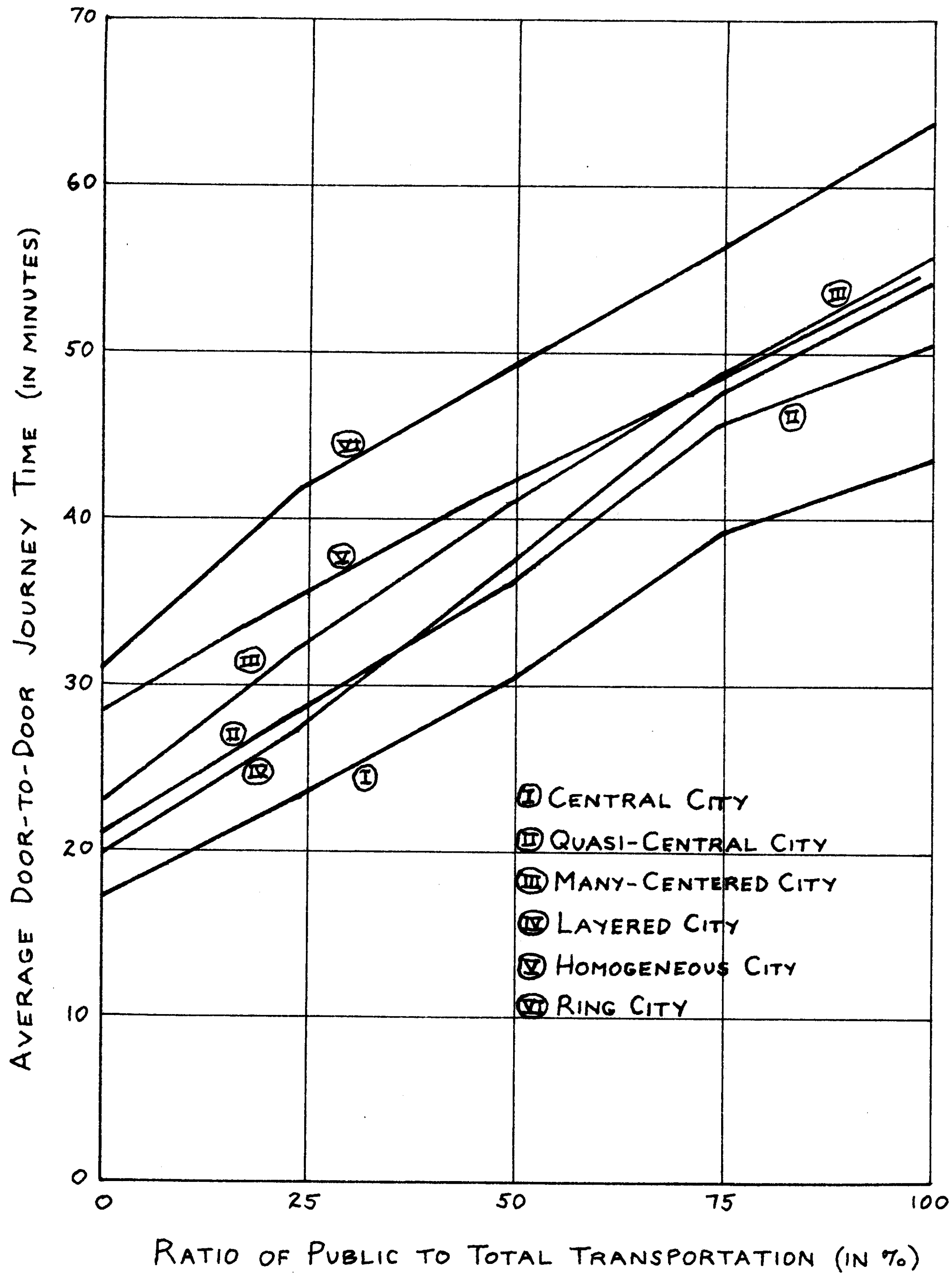

Figure 10. Graph of average door-to-door journey time vs. modal split.

gested here that one of the limitations under which the experiment has operated--the predetermination and fixity of the densities of the cities--has played a significant role in fashioning these idiosyncrasies of the cost curves; density, which was held constant in this experiment[1], is actually a significant variable. Thus, in four of the cities, operating under the defined unit costs and operating characteristics, the densities may have been such that after the percentage of public transportation reached seventy-five percent, further increase in mass transit was uneconomical; additional buses had to be bought while the roads (the least expensive and the lowest capacity carrying used in this experiment) had yet sufficient surplus capacity to have carried many of these additional transit riders by automobile. And in the case of the homogeneous city, which had a much lower residential density and a much smaller total population than any of the other cities, this point where additional mass transit becomes uneconomical may have been reached much earlier on the scale of percentages of public transportation. For this experiment, then, it is suggested that the density of the homogeneous city was too low for an efficient transportation system at all points on the curve; or conversely, the one-mile spacing of the transportation routes on the grid network was too close for the given density.

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[1]See Figures 1 through 6.

In general, however, increasing public transportation *has* increased economy in this study; the savings in roadway requirements resulting from replacing private transportation with public transportation has generally outstripped the cost of the additional transit facilities. But this statement does require some qualification. Especially, in the case where rail transit was required, the general trend was significantly altered. While surface rail, in the cases of the two cities which required some rail transit, did not significantly affect the general downward direction of the cost curves, such factors as noise and right-of-way costs may well prohibit the construction of such facilities in areas of high enough density to require rail transit. And this would necessitate underground or subway facilities, which, as can readily be seen in Figure 8, caused steep rises in the physical costs of the systems.[2] (In fact, the right-of-way costs in such dense areas may just as easily prove exceedingly expensive for freeways, and in dense areas a system utilizing a combination of automobiles and buses on expressways and major streets may well turn out to be the superior transportation in terms of physical cost).

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[2]Although not considered in this study, elevated rail facilities or elevated all-bus highways are other possibilities for the densely populated areas; however, these would still have significantly higher construction costs than the corresponding surface facilities. And any savings in right-of-way costs, or increases in costs for easements for light, air, etc., would be hard to gauge except in specific situations.

Comparing the physical costs of the various cities, it is noted that, with public transportation greater than about twenty-five percent, these costs were lower for the central, quasi-central, many-centered, and layered cities than for the ring city, and lower for the ring city than for the homogeneous city. This was not unexpected, as the first group of cities contains the greatest concentrations of trips[3], which would seem to be a requisite for efficient mass transportation. Carrying the breakdown a little further, the cost for the many-centered city was the lowest on the graph for all values of modal split. At first glance this seemed a bit surprising, for the central and quasi-central cities do have even greater concentrations of trips than does the many-centered city. However, for that range of modal splits where there is a considerable amount of private transportation, these greater trip concentrations required more freeways. And, while the freeways are superior in terms of capacities and travel speeds, they also have higher cost to capacity ratios than the expressways. As for those modal splits where public transportation is dominant, the greater trip concentrations required more rail transit, which, apparently, still was not competing economically with bus transit at these densities.

The low-density homogeneous city had very definitely

[3]See the flow diagrams in Aaron Fleisher, "Experiments on the Form of the City and the Qualities of Travel" (unpublished draft), M.I.T.-Harvard Joint Center for Urban Studies, 1963.

the greatest physical transportation costs for almost the entire range of modal splits (except where public transportation is less than approximately twenty percent). It appears that the reasons for this were that this city, lacking sufficient concentrations of trips, was least suited for public transit, and that, at its low density, it had to use a predominance of two-lane major streets, which have the lowest ratio of capacity to cost of all the roads used in this experiment.

With respect to the operating costs in the various cities, it can be seen from Figure 9 that these costs exhibit an approximately linear relationship with the modal split for all six cities; operating costs vary inversely with the percentage of public transportation. The central city, which utilizes the most rail transit and the most freeways (which have the lowest operating costs among the various forms of public and private transportation, respectively, used in this study), did indeed have a significantly lower per capita operating cost than all the other cities for the entire range of modal splits. Four of the other five cities were grouped rather closely together, but the sixth, the ring city, consistently exhibited a significantly higher level of per capita operating costs. On the surface, this seemed somewhat surprising, for it is not so obvious that greater operating costs were being encountered here than in, say, the homogeneous city. However, this was probably accounted for by the fact that the average trip length was significantly greater in the ring city than in any of the other cities[4], so that, all else being about equal, this city would then yield the highest per capita operating cost for the total journey.

The graph of the average journey times (Figure 10) is similar to that of the per capita operating costs. In this case, the average door-to-door journey times seem approximately to vary directly with the percentage of public transportation. And again, the central city exhibited a consistently lower average journey time than all the other cities, while the average journey time for the ring city was the highest for the entire range of modal splits. (Of course, these figures, too, reflect the fact that the average trip length was longest in the ring city and shortest in the central city. It will be seen from Tables 4-9 that while the central city--having the highest proportion of high-speed roads and transit facilities--did also yield the fastest average travel speeds over the entire range of modal splits, the homogeneous city--having generally the lowest proportion of high speed transportation facilities--produced slower average travel speeds than the ring city).

When analyzing the average journey times and speeds, however, a very basic assumption made in this experiment

[4]From Tables 10-15 (in Appendix D), the average trip lengths are 9.62 miles for the central city, 10.62 miles for the quasi-central city, 11.20 miles for the many-centered city, 10.89 miles for the layered city, 10.79 miles for the homogeneous city, and 13.19 miles for the ring city.

must be borne in mind. This is, that speeds of travel were taken to be independent of congestion; all routes were designed so that their capacities were never exceded, and all vehicles were assumed to travel at the design speeds of these routes. In reality, of course, increased traffic flow on a road (even at levels below the capacity of the road) does often decrease the average speed of travel on that road. However, this error, particularly with proper law enforcement on the road system, is probably not a large one as long as roadway capacities are not being exceeded; certainly not large enough to necessitate the complicated and lengthy adjustment in the calculations which would be required to correct for it.

Another important limitation on the experiment is the omission of the time required for parking. Parking may not be a significant factor in low density areas, but in high density areas it will almost certainly require large expenditures both in terms of time and money. In this experiment, however, neither parking time nor capital expenditures for parking facilities have been included; these are not difficult calculations, but they do require significant additional assumptions. Furthermore, unlike all other time and operating costs measured in this experiment, these parking costs will not be the same for the home-to-work journey as for the work-to-home journey. Consequently, they have been omitted here, and their inclusion is left to any interested subsequent researchers.

In summary, then, the following general observations have been gleaned from the results of the computations. Increasing the percentage of public transportation decreased the per capita physical cost of the total systems. Public transportation was more economical in areas of higher density. Subway construction (excluding right-of-way costs) was uneconomical at even the maximum densities used in this experiment. Increasing the percentage of public transportation decreased per capita operating costs but increased the average door-to-door journey time.

And, concerning the differences among the various cities, the many-centered city was the most efficient in terms of physical cost of the transportation system, but ranked only about average with respect to operating cost and journey time. The central city was the most efficient in these latter two categories, but required about an average expenditure for the physical costs of the system. The ring city yielded the highest operating costs and journey times and one of the highest physical costs, and seemed in general to be about the most inefficient city form. The homogeneous city did exhibit a higher physical cost, but this may well have been due to a density that was too low and inefficient for the experiment, and, furthermore, it still ranked considerably better than the ring city in terms of operating costs and average journey time.

These observations, of course, must be taken in light of the nature of the experiments and its limitations. This study represents just one more bit of knowledge to be added to the results of the many other studies which have been undertaken in the transportation field, and any inferences drawn from the observations herein should be very carefully reconciled with the validity and scope of the results.

2. Comparison with the results of other studies

If there is a single lesson to be learned from previous transportation studies, it is probably that group (mass) and individual (automobile) modes of transportation do not function completely independently; each has its own advantages and disadvantages, and, consequently, its own set of functions which it can efficiently serve. Indiscriminate replacement or substitution of one mode by the other will likely lead to considerable waste and inefficiency. Typical statements to this effect can be found in a study conducted by Wilbur Smith and Associates:

> ...(W)hile transit does not serve the majority of trips in any urban area, it is valuable for those particular movements or trip linkages that are concentrated in space and time, especially in high-density urban complexes. Thus, transit is a valuable adjunct to freeways in serving peak-hour movements along heavy travel corridors leading to and from the central business district, particularly in big cities.
>
> ...Urban transportation needs will usually require that highways be augmented by public transit and that transit be fostered even though, at best, it will but hold its present levels.
>
> ...Rapid transit, with its high peak-hour passenger capacities, is a desirable element in the total urban transportation system wherever there are sufficient concentrations of people to warrant such facilities.
>
> ...Just as freeways do not obviate the need for transit, neither can rapid transit be regarded as a

substitute for needed new freeways.[5]

And even the Automobile Manufacturers Association has stated:

> Metropolitan freeway systems will contribute to the economic vigor of downtown areas by sharply reducing downtown traffic congestion. These systems are designed to allow two-thirds of peak-hour downtown traffic, which now is forced to pass through downtown to other locations, to by-pass the central area entirely.
>
> At the same time, some portions of our metropolitan areas, and particularly their downtown centers, must continue to depend on existing or improved public transit facilities. These transit facilities meet basically different transportation needs than automobiles...[6]

A good comprehensive transportation plan, then, should utilize and coordinate the advantages of both the public and private forms of transportation.

The claim that group and individual modes of transportation are not interchangeable has also been reaffirmed in a study performed for a specific city. A mathematical model, based on such factors as the numbers of persons living and working in various zones and the travel times between zones, was used to estimate origins and destinations of travel, and, consequently, existing and future traffic patterns in the Baltimore metropolitan region.[7] The model was used to predict the future traffic volumes that would occur on a proposed highway system and, also,

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[5]Wilbur Smith and Associates, "Future Highways and Urban Growth," New Haven, Conn.: 1961.

[6]Highway Economics Research Committee of the Automobile Manufacturers Association, Inc., "Urban Transportation, Issues and Trends," 1963.

[7]J. Booth and R. Morris, "Transit vs. Auto Travel in the Future," Journal of the American Institute of Planners, May, 1959.

the volumes that could be expected if specific mass transit improvements were made. Tests of the model were said to have indicated its reliability and versatility. The results indicated that Baltimore transit services, no matter how extensive, cannot be considered a substitute for highway improvements; nor will they drastically reduce highway building requirements.

This is all in agreement with the results of the experiment performed in this thesis, which indicated that the mass transit facilities, and especially rail transit, were not efficiently serving the low-density areas, and that the freeways and expressways, with no mass transit, were not economically meeting the needs of the high-density areas.

In another study, conducted by the Maryland-National Capital Park and Planning Commission, urban form was considered as one of the prime variables in the transportation problem.[8] Four alternative patterns of urban development were proposed for the region: a sprawl pattern (development according to the largely unrestricted forces of private enterprise, as is common today); an average density pattern (similar to the sprawl pattern but with more public control--contains both high and low density residential areas); a satellite pattern (urban development in the central core and in small cities some distance away, with no development in between); and a corridor pattern (similar

[8]Maryland-National Capital Park and Planning Commission, "On Wedges and Corridors," 1962.

to the satellite pattern, but with development permitted along the main transportation routes from the central city to the outer or satellite city).

Preliminary cost studies indicated that the cost for rapid transit was significantly lower in the sprawl and average density cities than in the corridor city, which in turn required a slightly lower expenditure than did the satellite city. While the city forms explored here are not precisely comparable to those investigated in the main body of this thesis, the results obtained by the Maryland-National Capital study are, on the surface, nevertheless somewhat surprising. For it seems as though the corridor and satellite cities would have the greater concentrations of trips, and would, consequently, be the more efficient forms for mass transit. Unfortunately, the dilemma is not easily resolved, as the study does not fully describe its criteria and methods of procedure for the cost analyses.

Many studies, such as the Maryland-National Capital study, have been primarily concerned with either mass transit <u>or</u> highways. But there has been, too, at least one attempt to develop a general method for determining costs of total transportation systems.[9] (Although, little emphasis is placed in this study on the varying types of urban form). Specifically, the authors, trying to define

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[9]R.L. Creighton, D.I. Gooding, G.C. Hemmens, and J.E. Fidler, "Optimum Investment in Two-Mode Transportation Systems," (paper presented at the 43rd annual meeting of the Highway Research Board, Jan., 1964).

a means of optimizing investment in a two-mode transportation system, have developed a method of constructing "cost surfaces" for various modal splits and trip densities. And based on the results of their computations, they have come to two major conclusions. (Although they strongly emphasize that because of the limited number of examples studied, as well as some other limitations on their procedure, the inferences must be treated with caution).

The first conclusion states that some gain will almost always be produced by initial investment in rail facilities, expressways, or any combination of these facilities. The reasoning behind this lies in the fact that investment cost is a small proportion of travel or operating cost (10 to 20 percent when placed on an equivalent basis, such as daily cost), yet it will cause substantial reductions in the travel costs. The present thesis seems to be in agreement with this conclusion. For example, taking a typical figure of sixty cents per person for the peak hour operating cost for an all-private transportation system (the equivalent cost for an all-public transportation system would be considerably lower, but great inefficiencies of operation would be encountered during the off-peak hours which would be difficult to figure quantitatively), the total per capita daily cost would be about six dollars (assuming peak-hour flow at about ten percent of total daily flow). The total yearly operating cost, then, even excluding week-ends, would be $6 x (5 days/week) x (52 weeks/year) = $1,560 or six time the average per capita yearly physical cost of about $260. The implication would seem fairly clear. The operating costs should generally be weighted more heavily than physical costs in planning new investment in high-speed transportation facilities.

The second major conclusion declares that greater gains appear to be produced by exclusive investment in expressways <u>or</u> rail rapid transit than by investment in a combination of these two types of facilities. The reason for this is stated to be that capital requirements for combination investments are high, and full utilization of each type of facility cannot be expected. But this is not in agreement with the results of this thesis, which indicated that investment solely in either roads or transit facilities for the two cities where rail transportation was necessitated, was more expensive than for a combination of roads and transit facilities. However, this thesis did not assume any inherent loss in efficiency of utilization of the facilities for a combined public-private transportation system; nor was any such inherent inefficiency discovered in the process of carrying out the experiment.

Furthermore, it has earlier been noted that a system of transportation combining both group and individual modes of travel is generally thought to be the most effective and most desirable type of system. If a combined system of highways and rail transit is uneconomical, the implication would appear to be that the most desirable type of transportation system, both financially and in terms of quality of service, would be a system of highways serving both automobile and bus transportation.

And this is what the results of this thesis, within the validity of the experiment, seem to suggest: a compromise between the lower costs of bus transit and the superior operating characteristics (such as time, comfort, and convenience) of the automobile.[10] This policy suggestion is well summed up in the following statement.

> Comparisons of the economic feasibility of alternate transit proposals usually indicate that new rapid transit routes should be carefully integrated with freeway construction, and that motor buses should be used. Rail rapid transit will be limited primarily to areas where it now exists or where it can be readily adapted to existing railroad lines.[11]

3. Recommendations for future study

The subject of study in this thesis has by no means undergone a completely thorough analysis. Many assumptions had to be made and many criteria and standards had to be chosen. For example, while the unit costs selected do represent the author's best attempt at defining a set of "average" or "typical" costs, the resultant set of costs is hardly definitive. Furthermore, the standard deviation

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[10]Keith Gilbert, in "Economic Balance of Transportation Modes," Traffic Engineering, October, 1963, states, "It appears that an overall average population density of at least 10,000 persons per square mile would be necessary for economical rail operation." The results of this thesis would put this figure at an even higher density, but this is without the inclusion of right-of-way costs.

[11]Wilbur Smith and Associates, op. cit.

which should be attached to any "average" cost would, due to so many significant variables, be so large as to render the use of such a cost, in any specific situation, exceedingly dangerous without thoroughly investigating the actual cost. And the results obtained are, of course, extremely dependent upon the cost figures used.

Consequently, it is suggested that the experiment performed in this thesis could profitably be re-done to investigate the effects of other variables on the problem; many more sets of curves could be obtained for other city forms, for other unit costs, for other population densities, for other transportation networks, for other performance standards, etc. Of course this could be a very ambitious undertaking, depending on the scope and thoroughness of the investigation, requiring a great deal in the way of time and facilities. But even with limited resources, particular variables could be selected for study. Especially, it is suggested that a significant variation in the results would be obtained by varying the densities of the cities used in this experiment, and that this investigation could be readily carried out. Altering unit costs or transportation networks would also probably effect great changes in the results obtained, but the investigation of these variables would likely prove to be much less systematic and much more time consuming.

Finally, it should be noted that the computations performed in this experiment (on a desk calculator) would probably be readily adaptable for solution by an electronic computer. Such a tool could considerably expedite the mechanics of any investigation, and could, consequently, greatly reduce the number of man-hours required for a study and/or greatly increase the possible scope of such a study.

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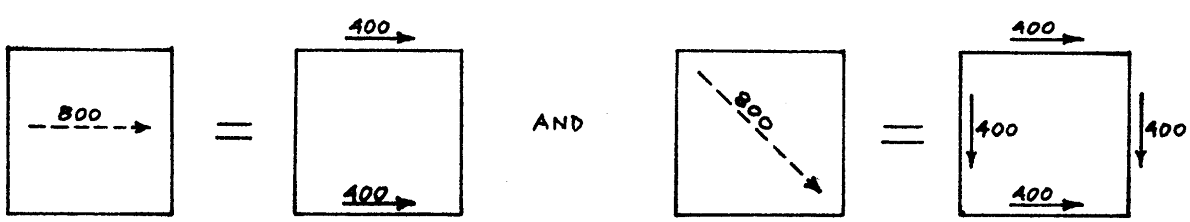
APPENDIX A--TOTAL TRAFFIC FLOWS

The diagrams in this appendix show the total traffic flows in both directions for the six cities. The symbols in the lower right-hand portion of the diagrams indicate (1)the directions of the flows on each route mile, and (2)the octant or quadrant from which the traffic flows were derived. The cities are assumed to be symmetrical about this octant or quadrant, and the figures shown are, in all cases, the actual flows along the indicated route segments.

An illustrative example of the assignment of traffic flow to the transportation network is provided below. The original traffic count was taken on a free surface, through the middle of the one-mile squares formed by the grid, in the north, northeast, east, southeast, south, southwest, west, and northwest directions. These are indicated by dashed arrows, while the final flows (along the transportation network) are indicated by solid arrows.



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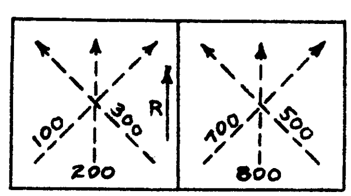
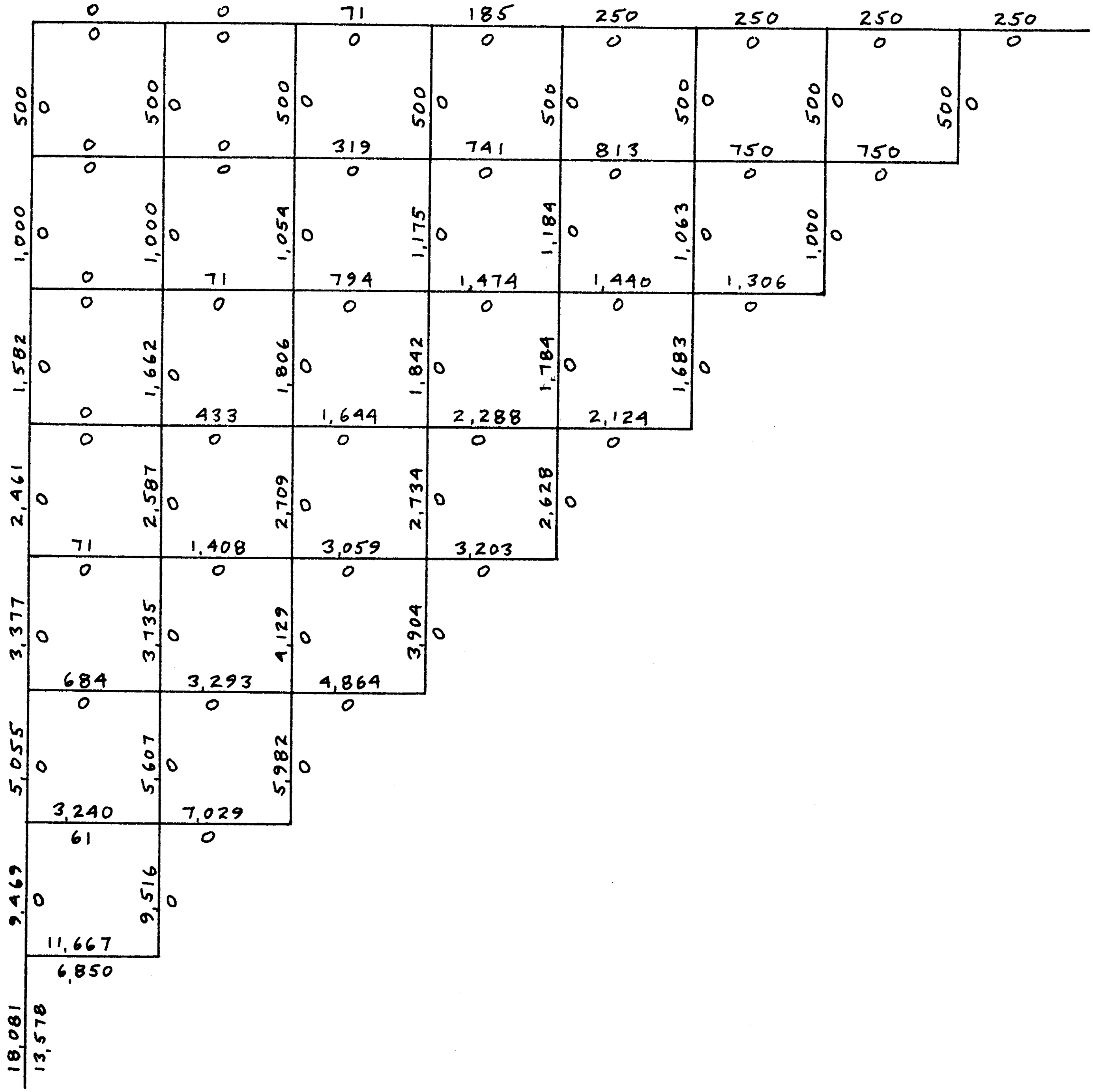


$$R = \frac{1}{2}(100 + 200 + 300 + 700 + 800 + 500)$$
$$= \frac{1}{2}(2{,}600) = 1{,}300 \text{ PERSONS}$$



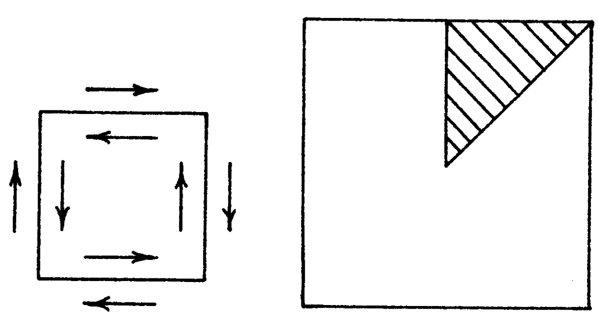


Figure 11. Traffic flow in the central city.

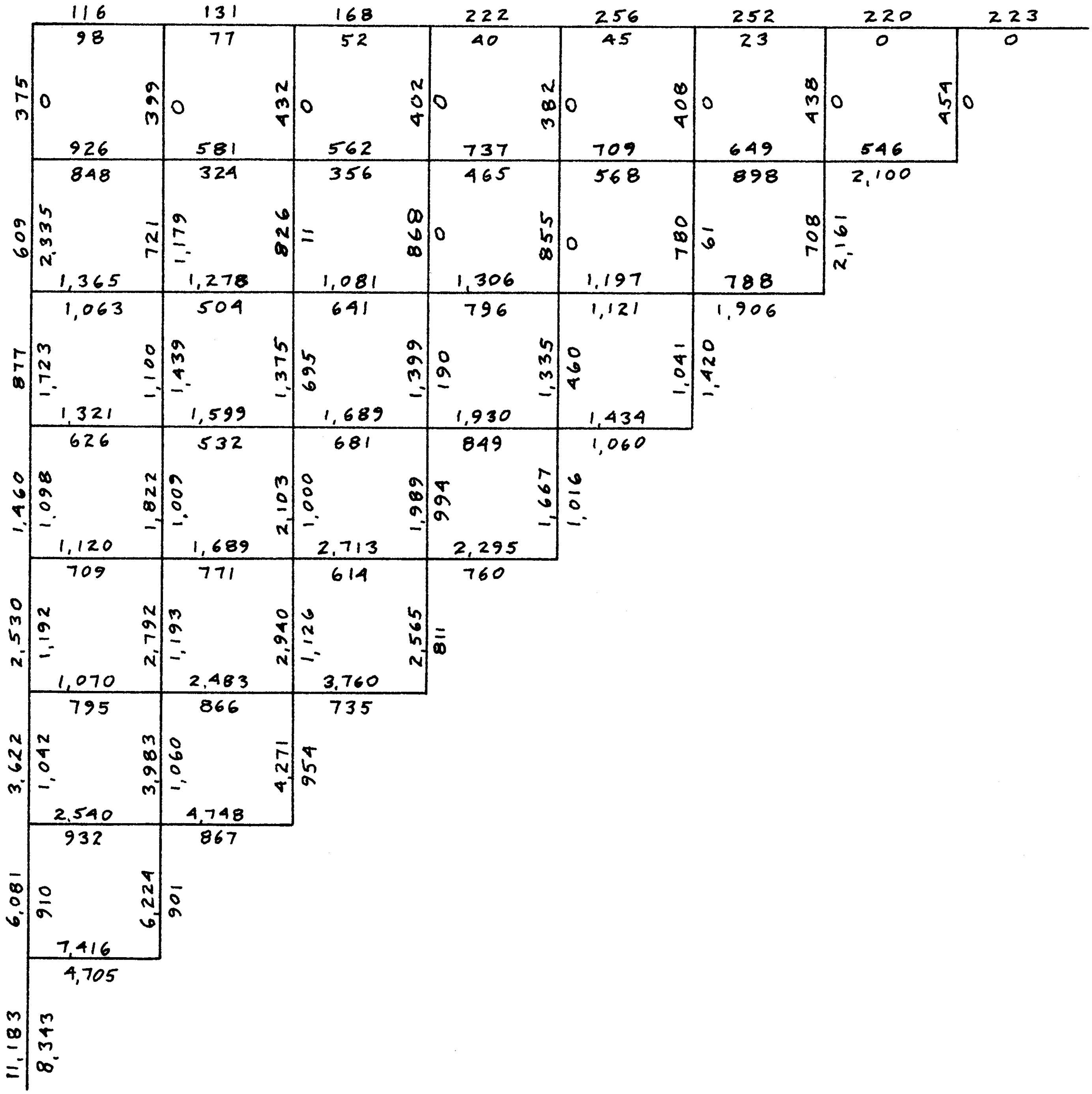
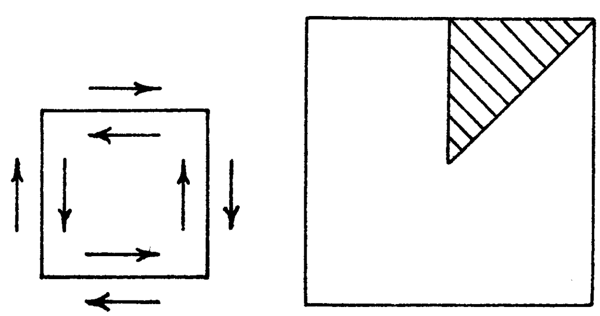
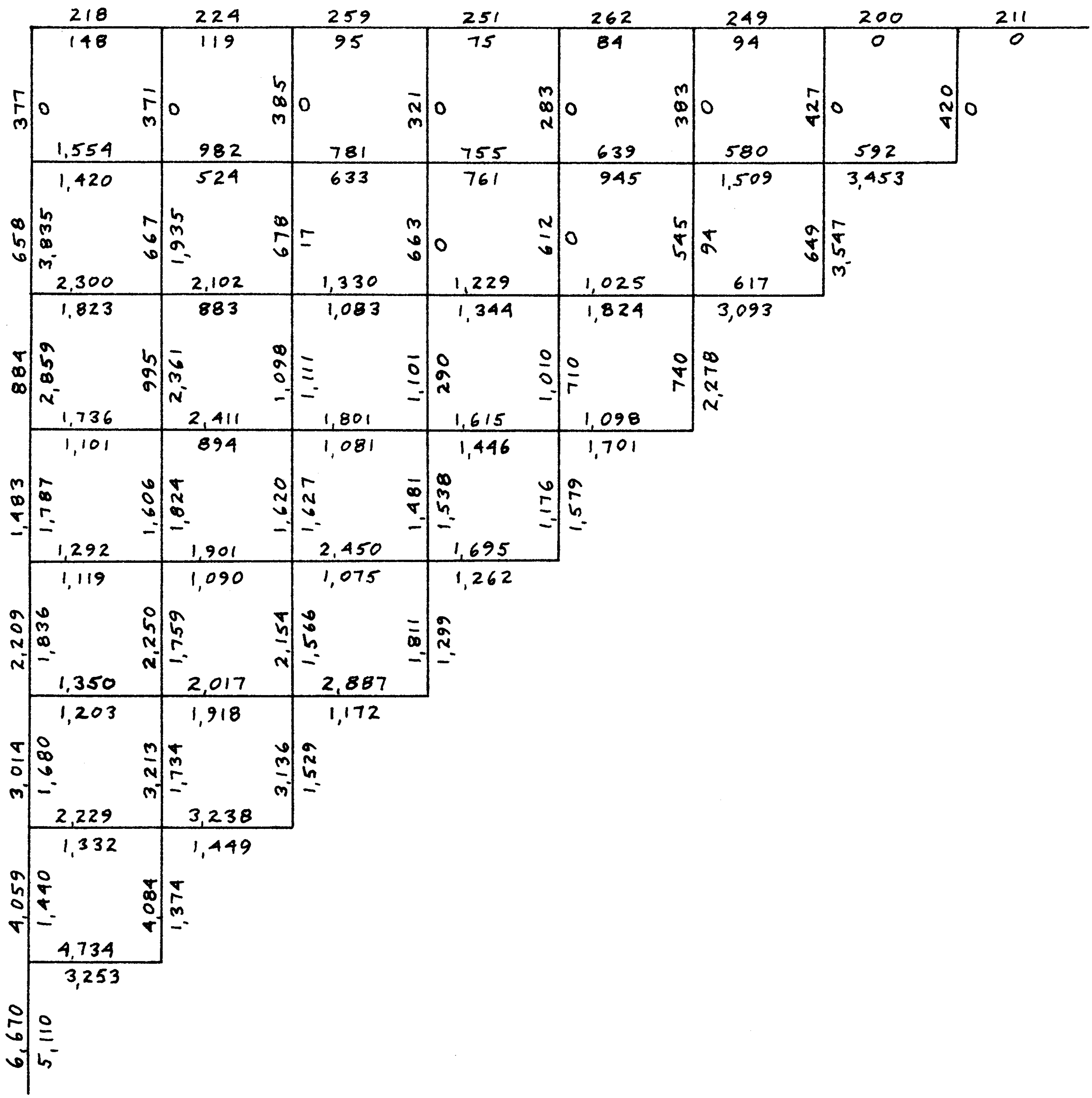


Figure 12. Traffic flow in the quasi-central city.





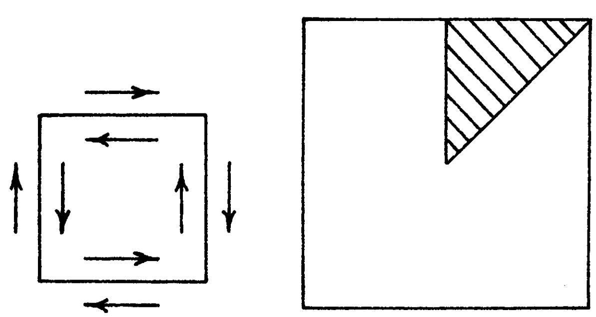
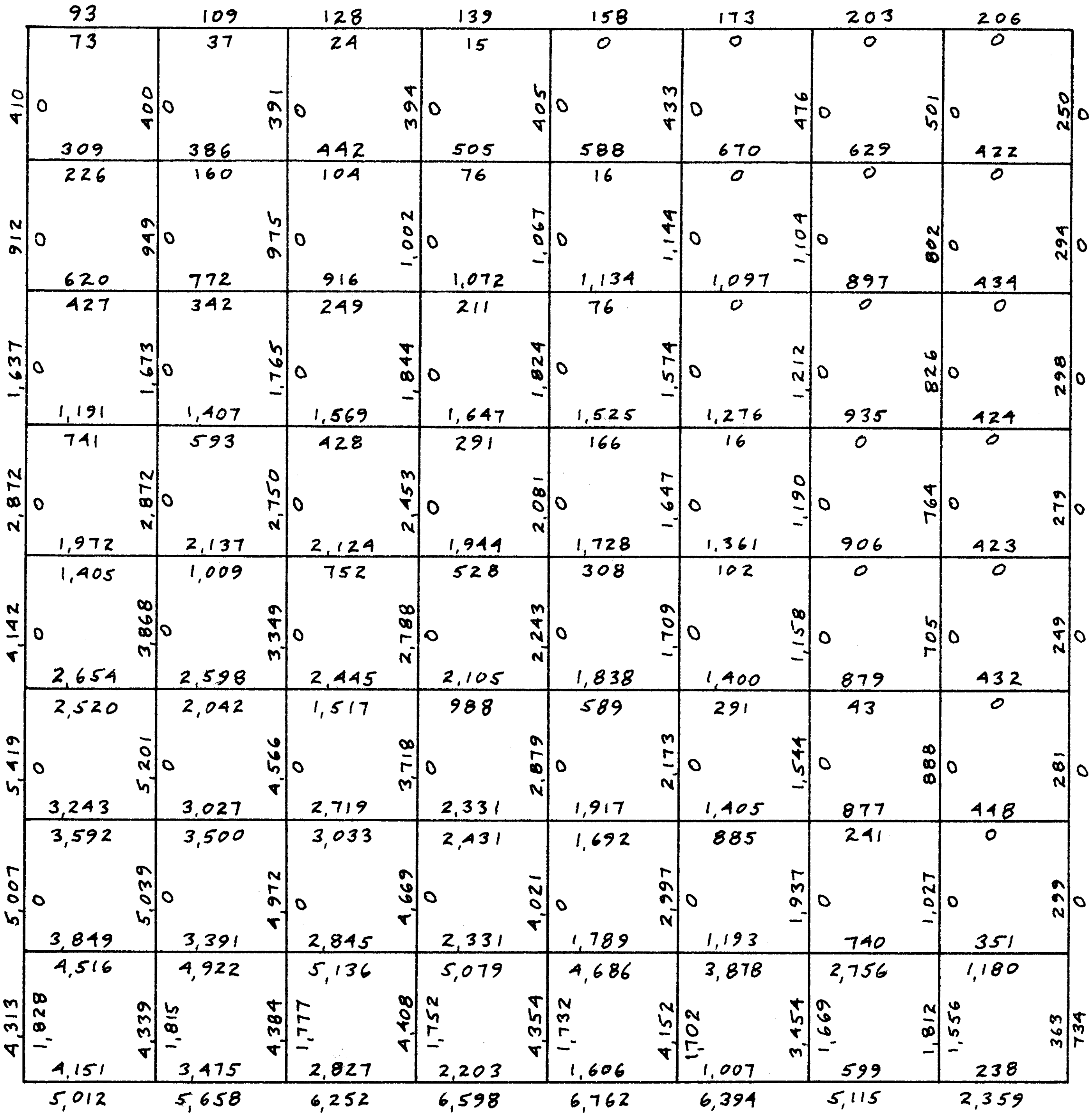


Figure 13. Traffic flow in the many-centered city.



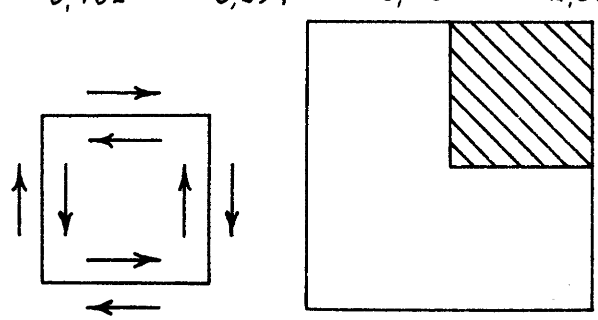


Figure 14. Traffic flow in the layered city.

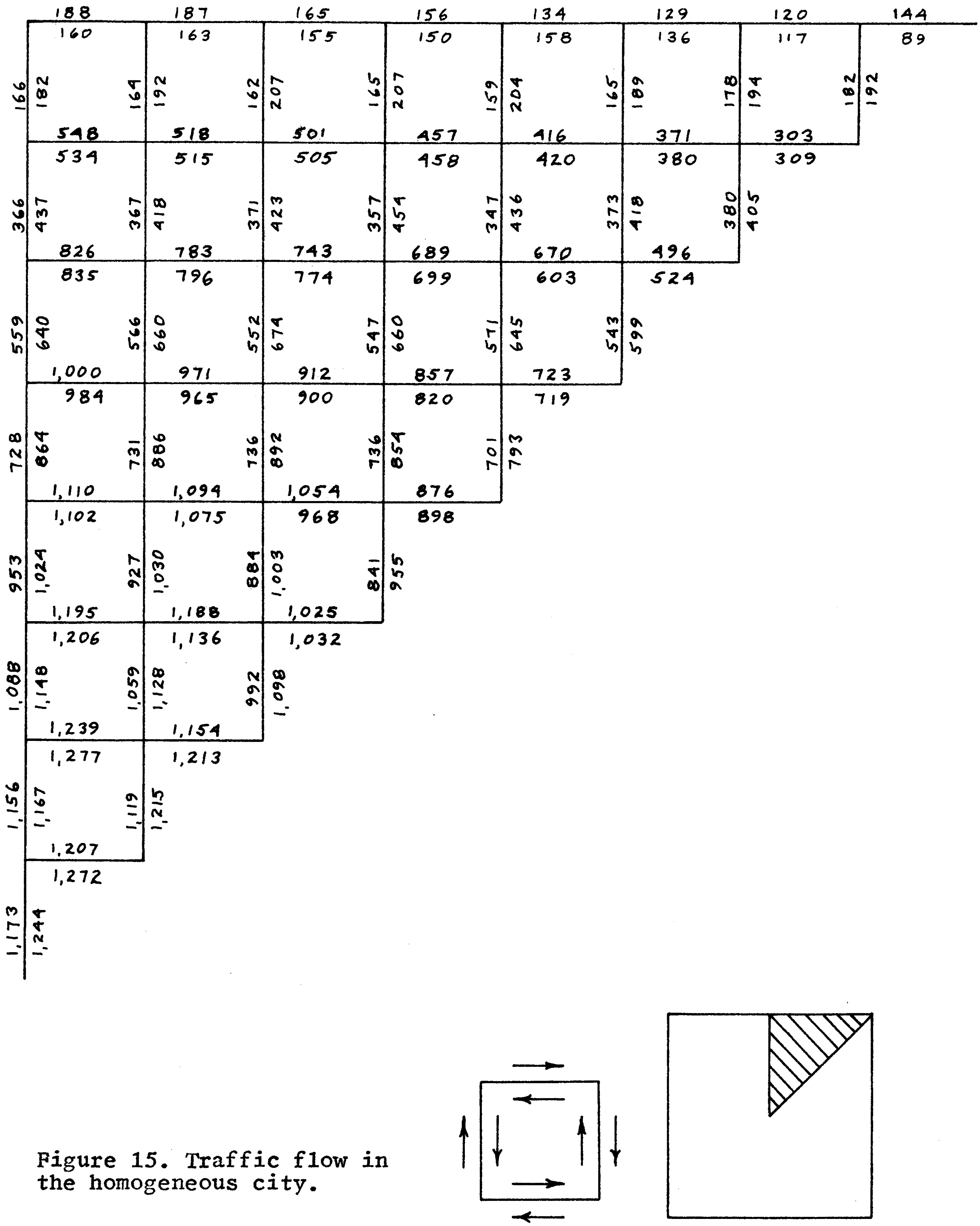


Figure 15. Traffic flow in the homogeneous city.

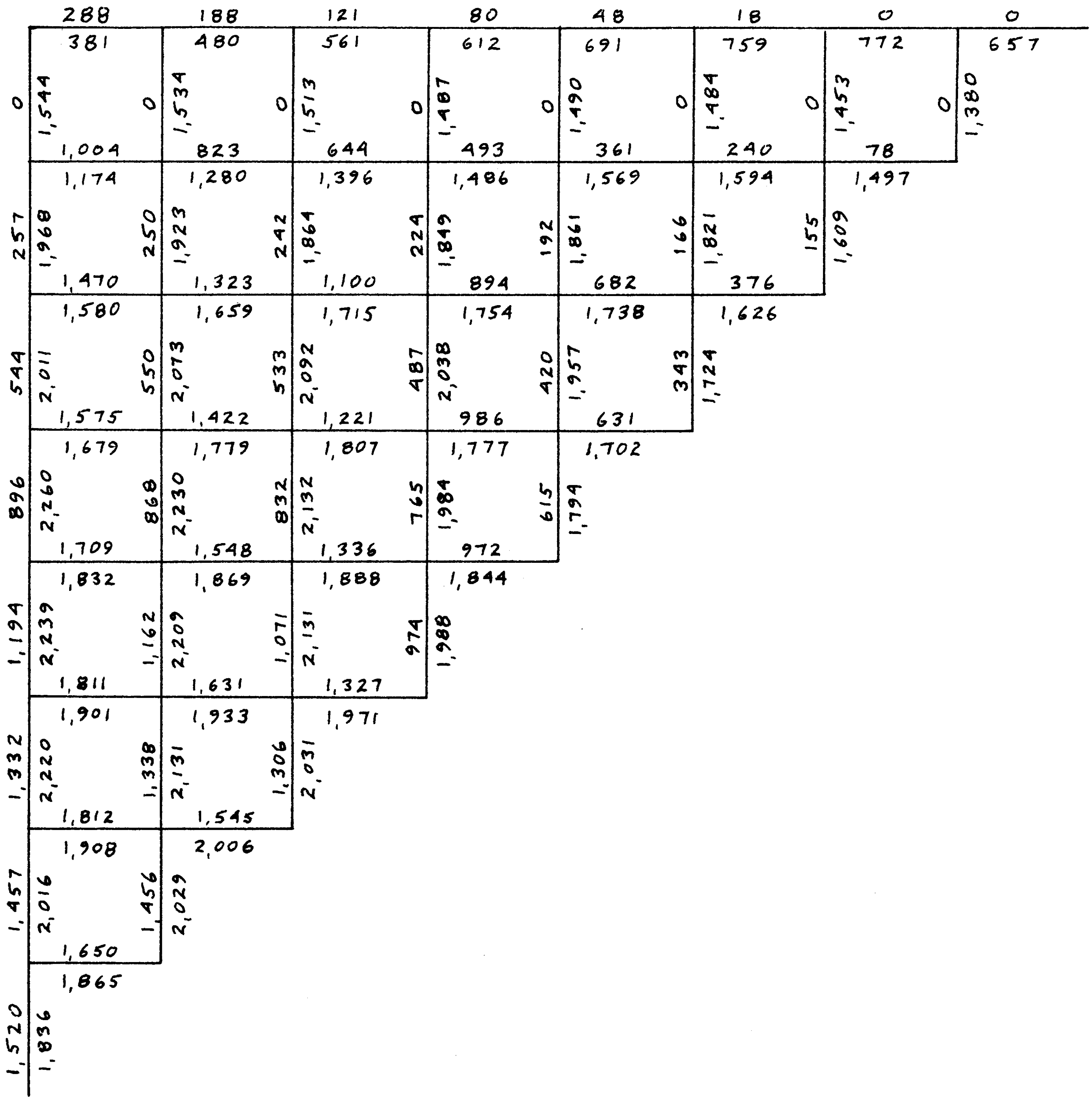
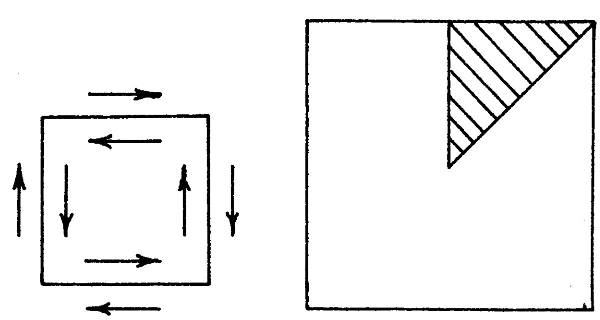


Figure 16. Traffic flow in the ring city.

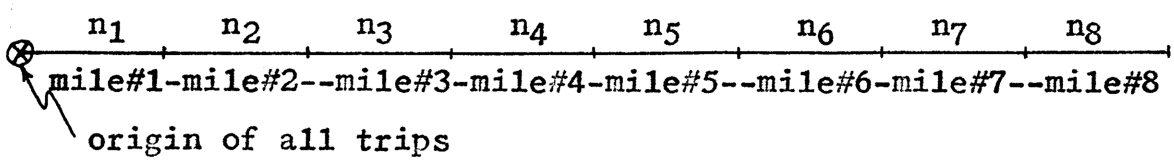


APPENDIX B--AN INVESTIGATION OF VARIOUS METHODS OF VARYING THE MODAL SPLIT

This section studies the effects of various methods of varying the modal split. When the total travel, or total number of person-miles traveled by one transportation mode, is reduced, this total reduction can be achieved by numerous devices: by allocating the decrease in person-miles traveled entirely to the longest trips, or primarily to the longest trips, or equally to all lengths of trips, etc.

Four different types or methods of decreasing travel by a particular mode are studied here to determine the effects on the flows along the various segments of the transportation network. In addition, as it has been suggested in the text that a simple, consistent means of reduction would be to reduce all lengths of trip by the same proportion, the conditions are determined in each of the four cases under which this means of reduction would be applicable.

In each case, the original travel is decreased by 25 percent; the analysis would be the same, however, no matter what percent decrease was used. A particular percent was chosen rather than a general percent (such as "x" percent) because the resultant expressions would be simpler.



n_i = total number of trips through mile i = $\sum_{j=i}^{8} \Delta j$

Δi = trips ending in mile i = $n_i - n_{i+1}$

n_i' = number of trips through mile i after decrease = $n_i + \Delta n_i$

$\Delta n_i = \sum_{j=i}^{8} \Delta(\Delta j)$

Therefore, $n_i' = n_i + \sum_{j=i}^{8} \Delta(\Delta j)$

n_1 = the total number of trips originated

Let $n_1' = 3n_1/4$ (That is, the total number of trips is being decreased by one-quarter).

1. The decrease is distributed uniformly.

$$\Delta(\Delta 1) = \Delta(\Delta 2) = \ldots = \Delta(\Delta 8) = (1/8)(-n_1/4) = -n_1/32$$

$n_1' = n_1 + 8(-n_1/32) = 3n_1/4$ $\quad$ $n_5' = n_5 - 4n_1/32$

$n_2' = n_2 - 7n_1/32$ $\quad$ $n_6' = n_6 - 3n_1/32$

$n_3' = n_3 - 6n_1/32$ $\quad$ $n_7' = n_7 - 2n_1/32$

$n_4' = n_4 - 5n_1/32$ $\quad$ $n_8' = n_8 - n_1/32$

Under what conditions would $n_i' = 3n_i/4$?

$n_2' = 3n_2/4 = n_2 - 7n_1/32$ $\quad$ $7n_1/32 = n_2/4$ $\quad$ $n_2 = 7n_1/8$

$n_3' = 3n_3/4 = n_3 - 6n_1/32$ $\quad$ $6n_1/32 = n_3/4$ $\quad$ $n_3 = 6n_1/8$

etc. Therefore, $n_i = (9-i)n_1/8$

(That is, every mile must contain the same number of trip-ends).

2. The decrease is allocated to the longest trips, assuming $n_1/4 \leq n_8$

$\Delta(\Delta 1) = \Delta(\Delta 2) = \ldots = \Delta(\Delta 7) = 0 \qquad \Delta(\Delta 8) = -n_1/4$

$n_1' = n_1 - n_1/4 = 3n_1/4$

$n_2' = n_2 - n_1/4$

$n_3' = n_3 - n_1/4$

$n_4' = n_4 - n_1/4$

$n_5' = n_5 - n_1/4$

$n_6' = n_6 - n_1/4$

$n_7' = n_7 - n_1/4$

$n_8' = n_8 - n_1/4$

Under what conditions would $n_i' = 3n_i/4$?

$n_2' = 3n_2/4 = n_2 - n_1/4 \qquad n_2 = n_1$

$n_3' = 3n_3/4 = n_3 - n_1/4 \qquad n_3 = n_1$

etc. Therefore, $n_i = n_1$

(That is, all trips must end in mile#8).

3. <u>The decrease is allocated in proportion to the number of trips ending in each mile.</u>

$\Delta(\Delta 1)/(\Delta 1) = \Delta(\Delta 2)/(\Delta 2) = \ldots = \Delta(\Delta 8)/(\Delta 8)$

$\sum_{i=1}^{8} \Delta(\Delta i) = -n_1/4 = \Delta(\Delta 1) + \Delta(\Delta 2) + \ldots + \Delta(\Delta 8)$

Substituting:

$-n_1/4 = \Delta(\Delta 1) + (\Delta 2/\Delta 1)\Delta(\Delta 1) + \ldots + (\Delta 8/\Delta 1)\Delta(\Delta 1)$

$= (\Delta(\Delta 1)/\Delta 1)(\Delta 1 + \Delta 2 + \ldots + \Delta 8) = (\Delta(\Delta 1)/\Delta 1)n_1$

$\Delta(\Delta 1) = -(\Delta 1)/4$

$-n_1/4 = (\Delta 1/\Delta 2)\Delta(\Delta 2) + (\Delta 2/\Delta 2)\Delta(\Delta 2) + \ldots + (\Delta 8/\Delta 2)\Delta(\Delta 2)$

$= (\Delta(\Delta 2)/\Delta 2)(\Delta 1 + \Delta 2 + \ldots + \Delta 8) = (\Delta(\Delta 2)/\Delta 2)n_1$

$\Delta(\Delta 2) = -(\Delta 2)/4$

etc. Therefore, $\Delta(\Delta i) = -(\Delta i)/4$

$n_1' = n_1 + (-\Delta 1/4 - \Delta 2/4 - \ldots - \Delta 8/4)$

$= n_1 - (1/4)(\Delta 1 + \Delta 2 + \ldots + \Delta 8) = n_1 - n_1/4 = 3n_1/4$

$n_2' = n_2 + (-\Delta 2/4 - \Delta 3/4 - \ldots - \Delta 8/4)$

$= n_2 - (1/4)(\Delta 2 + \Delta 3 + \ldots + \Delta 8) = n_2 - n_2/4 = 3n_2/4$

And similarly:

$n_3' = 3n_3/4$ $n_4' = 3n_4/4$ $n_5' = 3n_5/4$

$n_6' = 3n_6/4$ $n_7' = 3n_7/4$ $n_8' = 3n_8/4$

4. <u>The decrease is divided equally and entirely among the last four miles.</u>

$$\Delta(\Delta 1) = \Delta(\Delta 2) = \Delta(\Delta 3) = \Delta(\Delta 4) = 0$$

$$\Delta(\Delta 5) = \Delta(\Delta 6) = \Delta(\Delta 7) = \Delta(\Delta 8) = (-n_1/4)/4 = -n_1/16$$

$n_1' = n_1+4(-n_1/16) = 3n_1/4$ $n_5' = n_5+4(-n_1/16) = n_5-4n_1/16$

$n_2' = n_2-n_1/4$ $n_6' = n_6-3n_1/16$

$n_3' = n_3-n_1/4$ $n_7' = n_7-2n_1/16$

$n_4' = n_4-n_1/4$ $n_8' = n_8-n_1/16$

Under what conditions would $n_i' = 3n_i/4$?

$n_2' = 3n_2/4 = n_2 - n_1/4$ $n_2 = n_1$

And similarly, $n_3 = n_4 = n_5 = n_1$

$n_6' = 3n_6/4 = n_6 - 3n_1/16$ $-n_6/4 = -3n_1/16$ $n_6 = 3n_1/4$

$n_7' = 3n_7/4 = n_7 - 2n_1/16$ $-n_7/4 = -2n_1/16$ $n_7 = n_1/2$

$n_8' = 3n_8/4 = n_8 - n_1/16$ $-n_8/4 = -n_1/16$ $n_8 = n_1/4$

(That is, one-quarter of all the trips must end in each of the last four miles).

APPENDIX C--

PEAK DIRECTIONAL FLOWS FOR THE VARIOUS MODAL SPLITS

The following diagrams give the traffic flows during the peak hour, in numbers of persons, in the direction of heavier flow for each one-mile link in the transportation network. The figures are rounded off to the nearest fifty persons, and are broken down into the numbers of persons traveling by (1)private and (2)public transportation for modal splits of 100%-0%, 75%-25%, 50%-50%, 25%-75%, and 0%-100% for each of the six cities.

The symbols in the lower right-hand portion of the diagrams indicate the octant or quadrant for which the traffic flows are given. The cities are assumed to be symmetrical about these octants or quadrants, and the figures shown are, in all cases, the actual flows along the indicated route segments.

The following notation is used:

M2--no. of persons travelling by auto on 2-lane major road

M4--no. of persons travelling by auto on 4-lane major road

E4--no. of persons travelling by auto on 4-lane expressway

E6--no. of persons travelling by auto on 6-lane expressway

F4--no. of persons travelling by auto on 4-lane freeway

F6--no. of persons travelling by auto on 6-lane freeway

F8--no. of persons travelling by auto on 8-lane freeway

B--persons traveling by bus (on the type of roadway indicated for the auto travel; for all-transit systems, buses travel on 2-lane major roads

R--persons traveling by rail transit (either subway or surface rail)

When buses were run on the roads with automobiles, the automobile-carrying capacities of the roads were decreased in the following manner: a decrease of 50 automobile travelers, assuming 1.7 passengers per automobile, means a decrease of 29.4 automobiles. Since, in terms of roadway capacity, one bus is considered the equivalent of two automobiles, this decrease can be compensated for by an increase of 29.4/2 = 14.7 buses @ 50 passengers per bus = 735 persons. In other words, 735 bus riders must be compensated for by a decrease in automobile capacity of 50 riders; 2 x 735 = 1,470 bus riders would necessitate a decreased capacity of 100 auto riders; 3 x 735 = 2,205 bus riders would necessitate decreasing automobile capacity by 150 riders; etc.

All transit facilities are assumed to operate at full capacity during the peak hour.

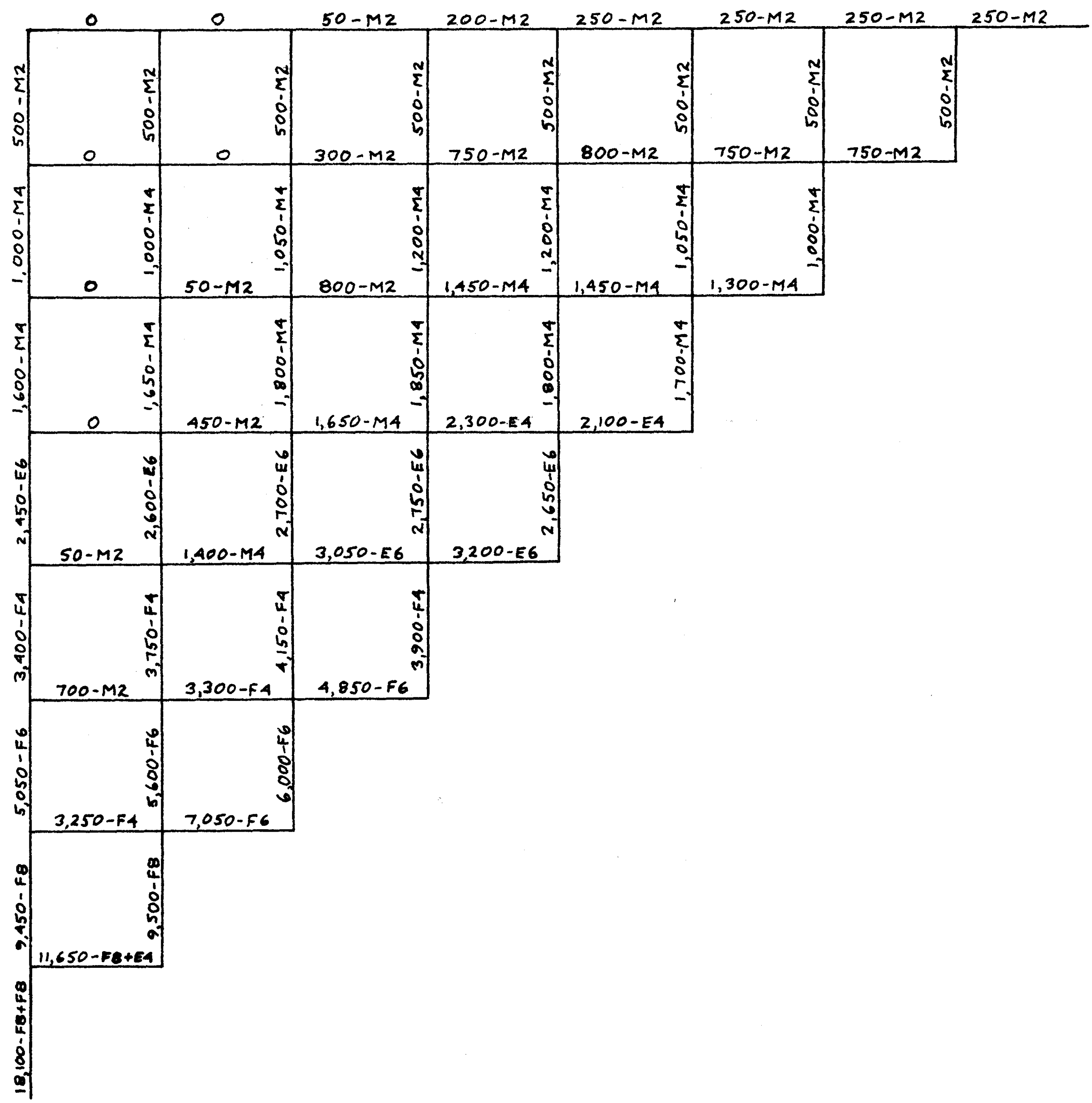
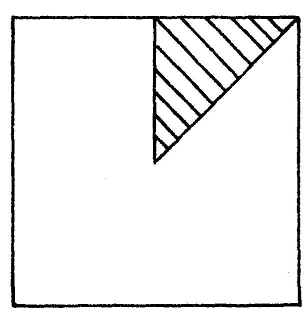


Figure 17.

Peak one-directional flow for central city.

Ratio of private-public transportation: 100%-0%.



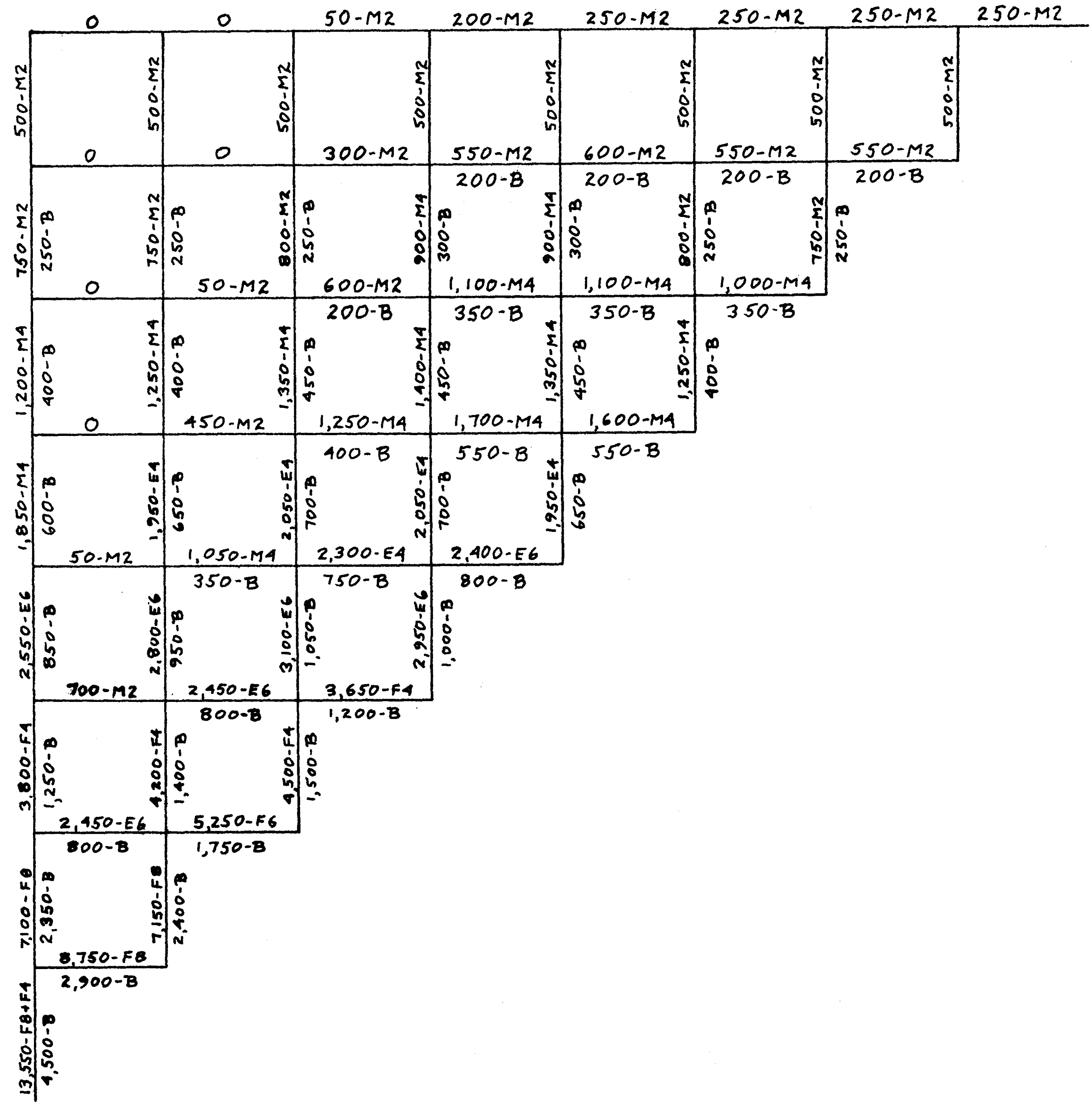
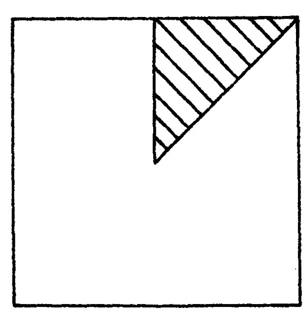


Figure 18.

Peak one-directional flow for central city.

Ratio of private-public transportation: 75%-25%.



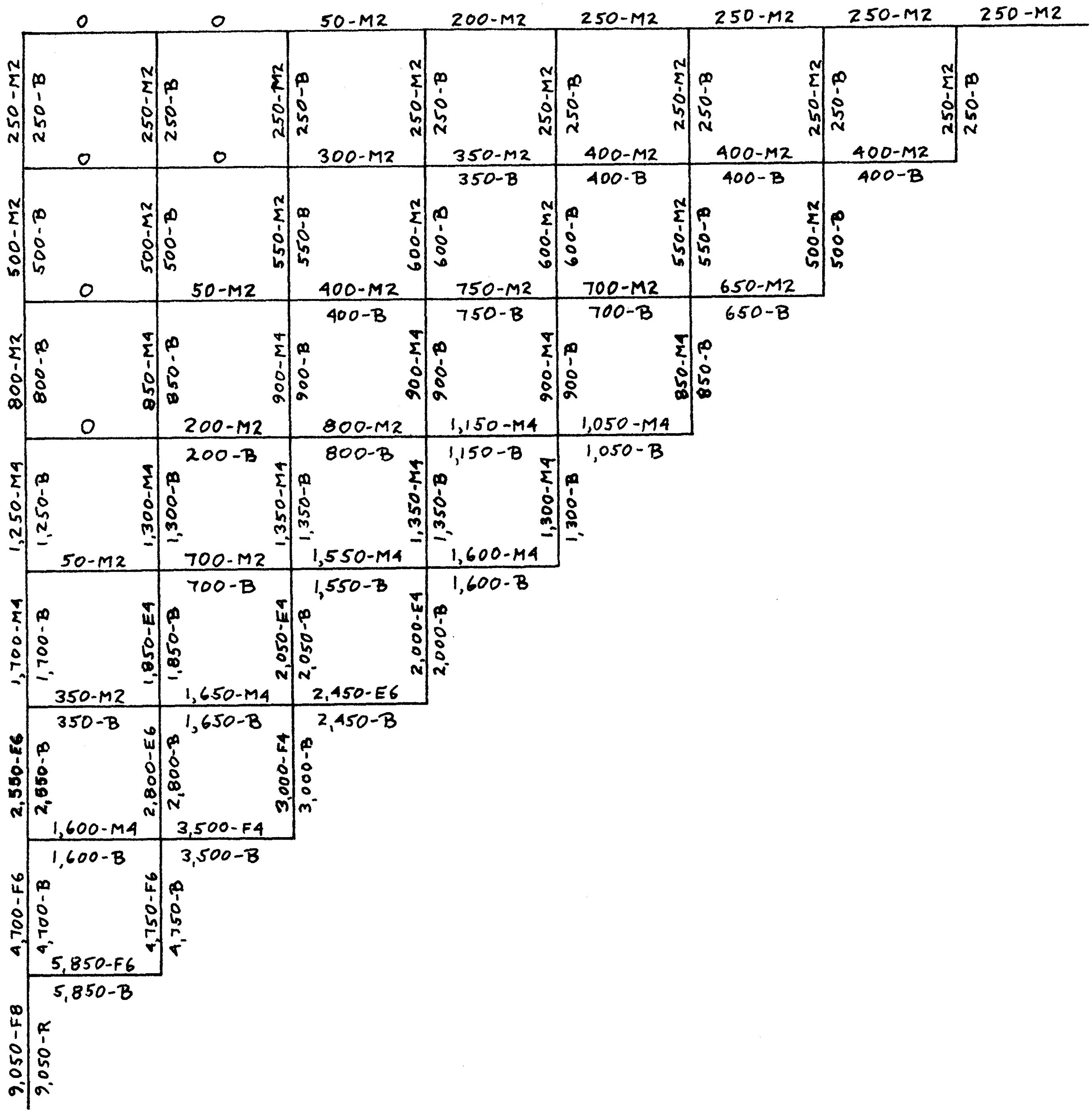
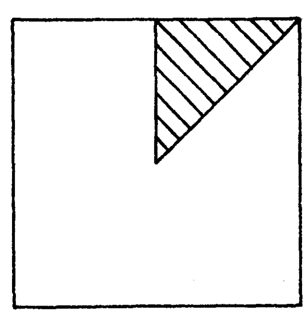
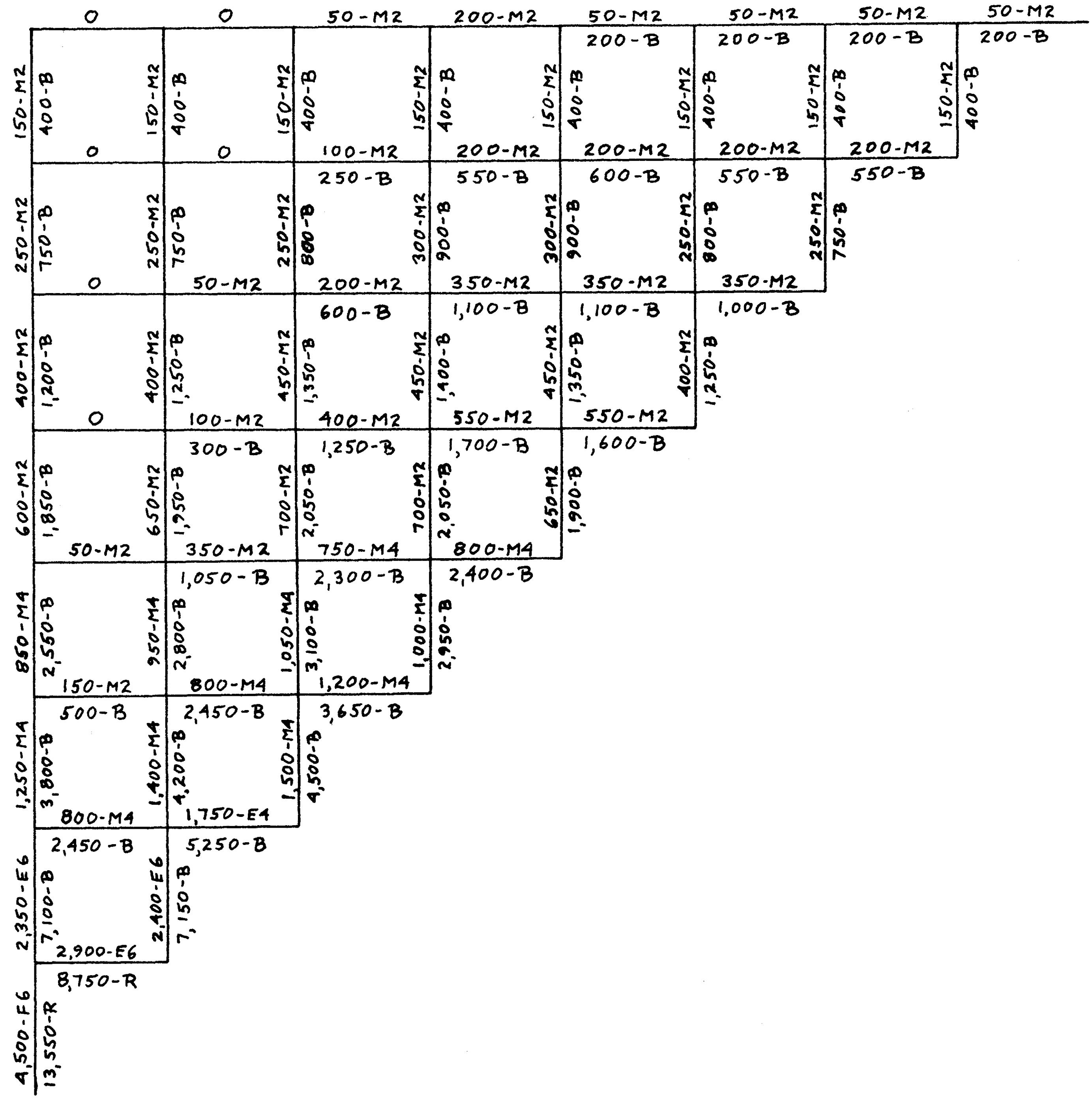


Figure 19.

Peak one-directional flow for central city.

Ratio of private-public transportation: 50%-50%.





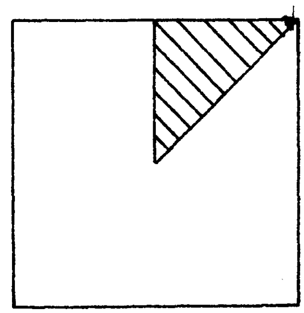


Figure 20.

Peak one-directional flow for central city.

Ratio of private-public transportation: 25%-75%.

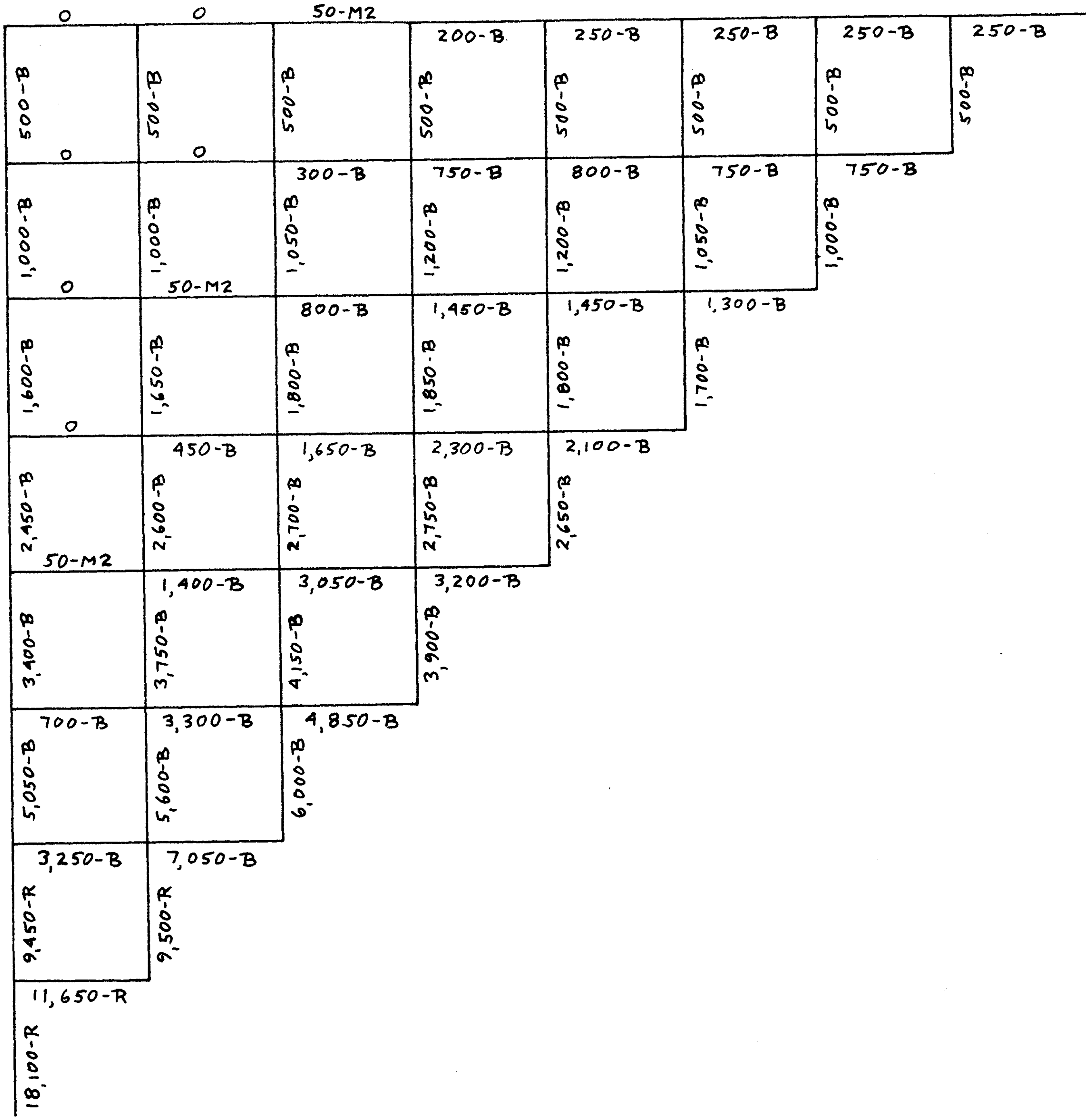
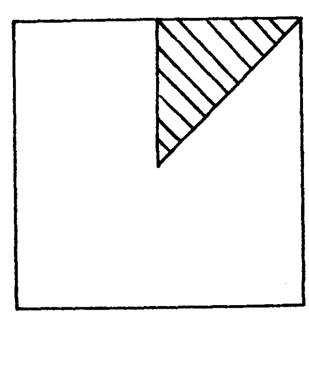


Figure 21.

Peak one-directional flow for central city.

Ratio of private-public transportation: 0%-100%.



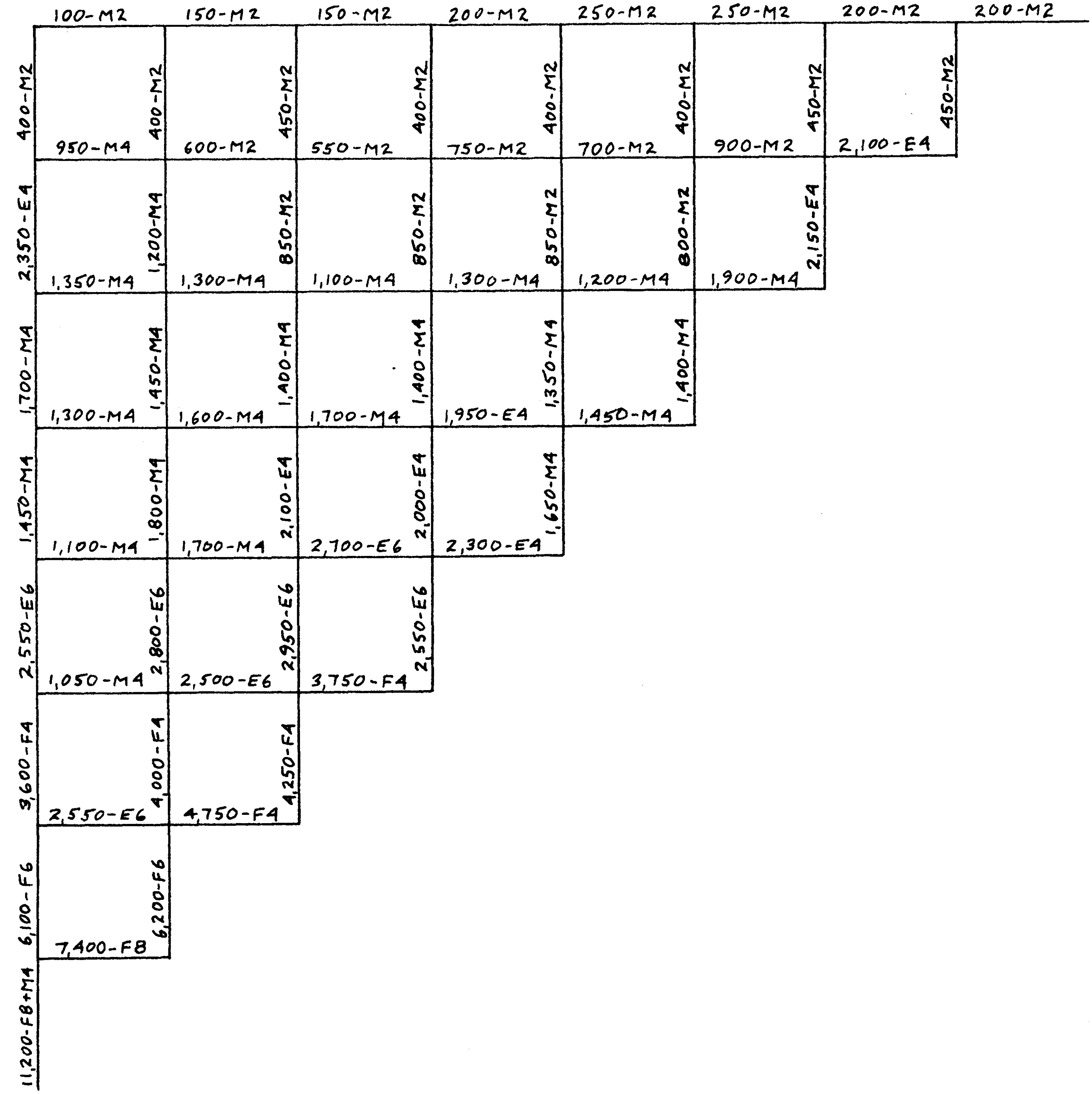
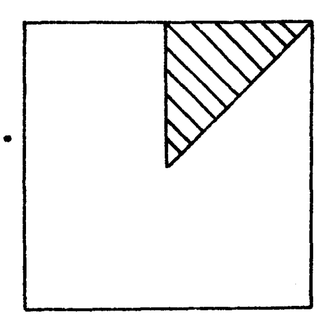


Figure 22.

Peak one-directional flow for quasi-central city.

Ratio of private-public transportation: 100%-0%.



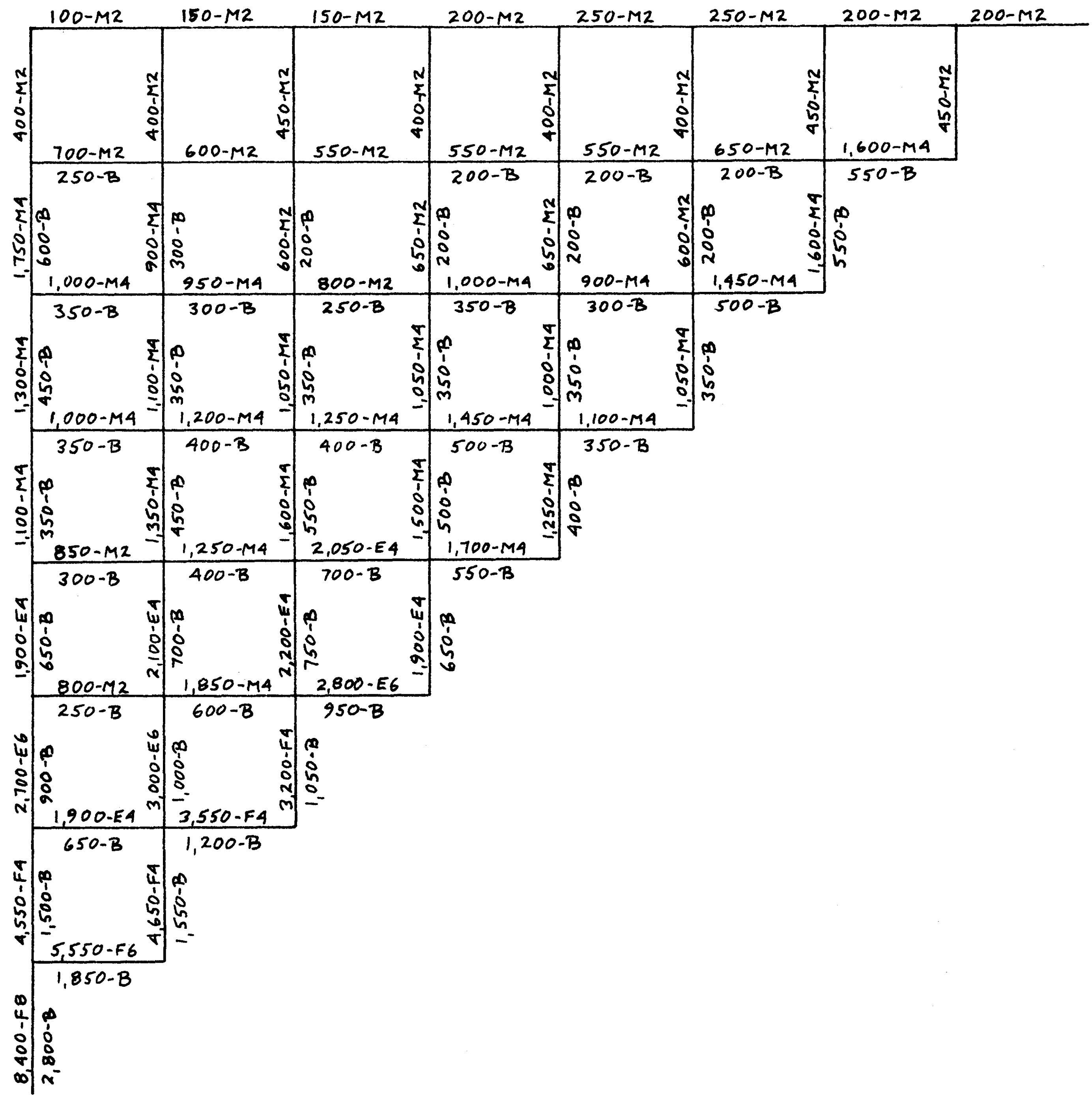
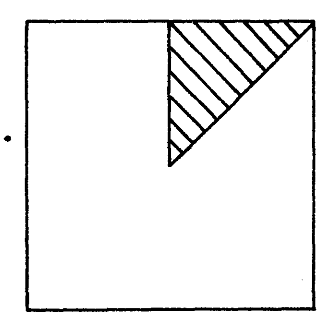


Figure 23.

Peak one-directional flow for quasi-central city.

Ratio of private-public transportation: 75%-25%.



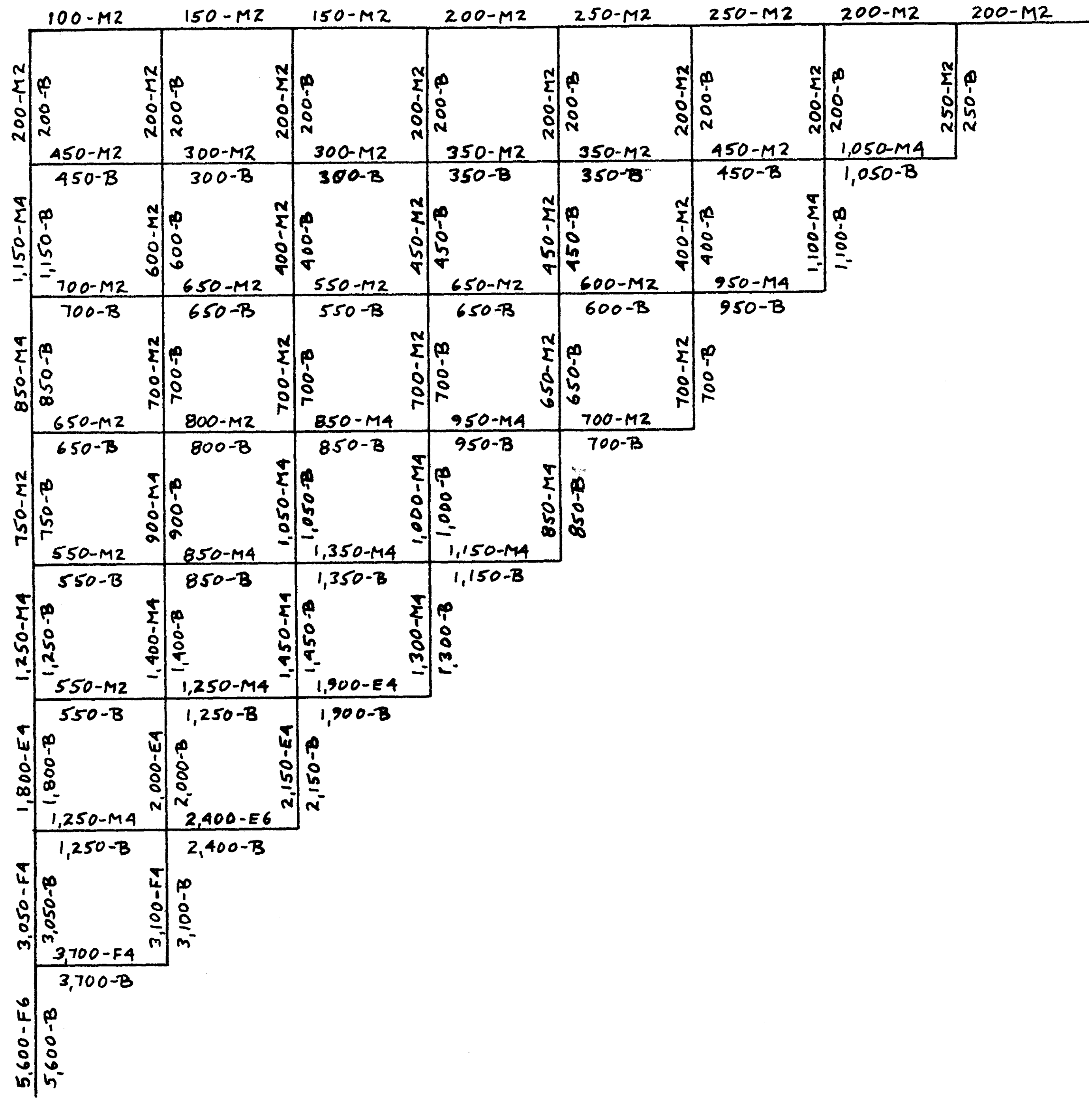
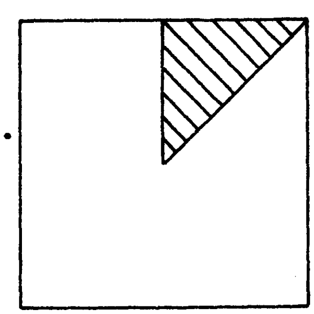


Figure 24.

Peak one-directional flow for quasi-central city.

Ratio of private-public transportation: 50%-50%.



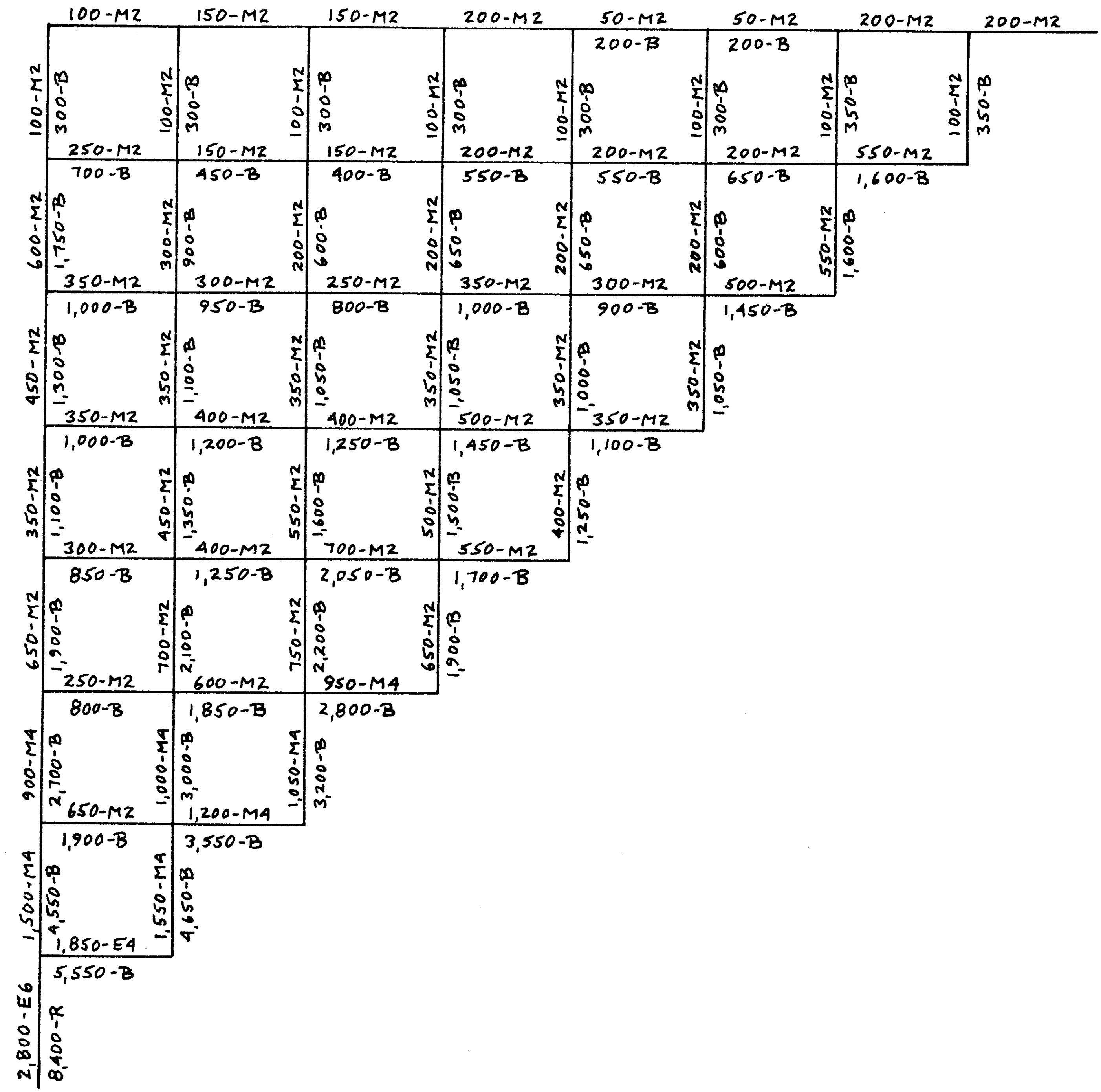
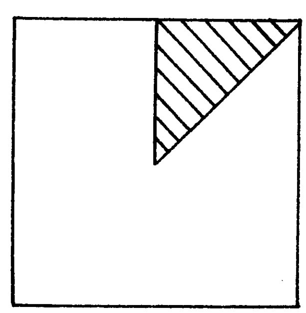


Figure 25.

Peak one-directional flow for quasi-central city.

Ratio of private-public transportation: 25%-75%.



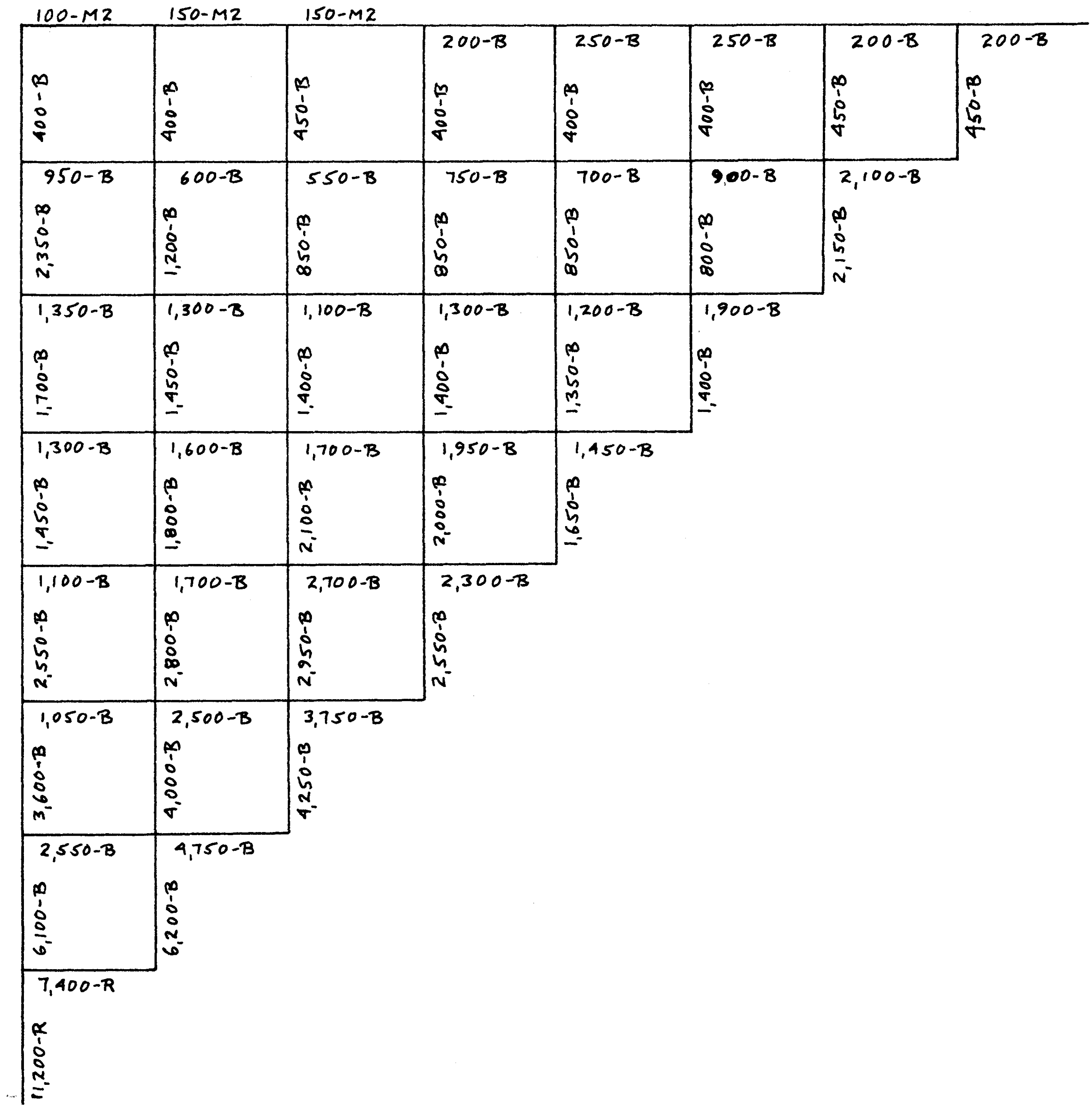
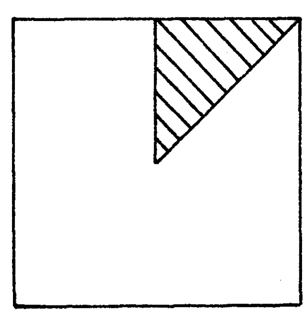
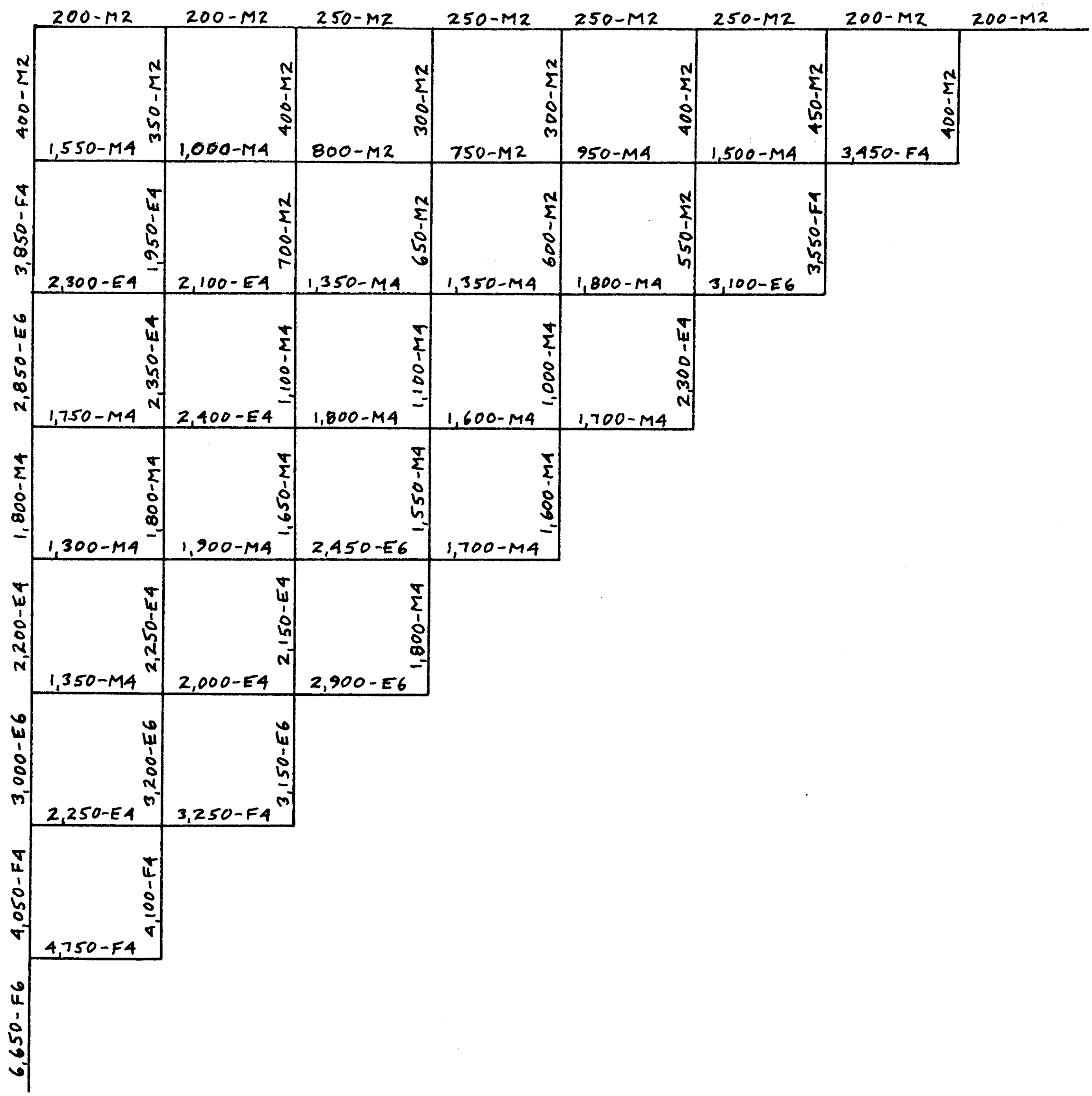


Figure 26.

Peak one-directional flow for quasi-central city.

Ratio of private-public transportation: 0%-100%.





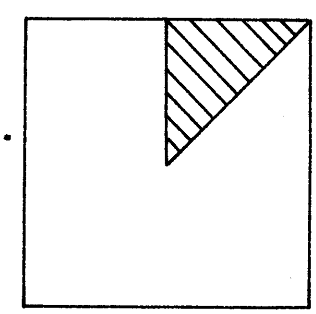
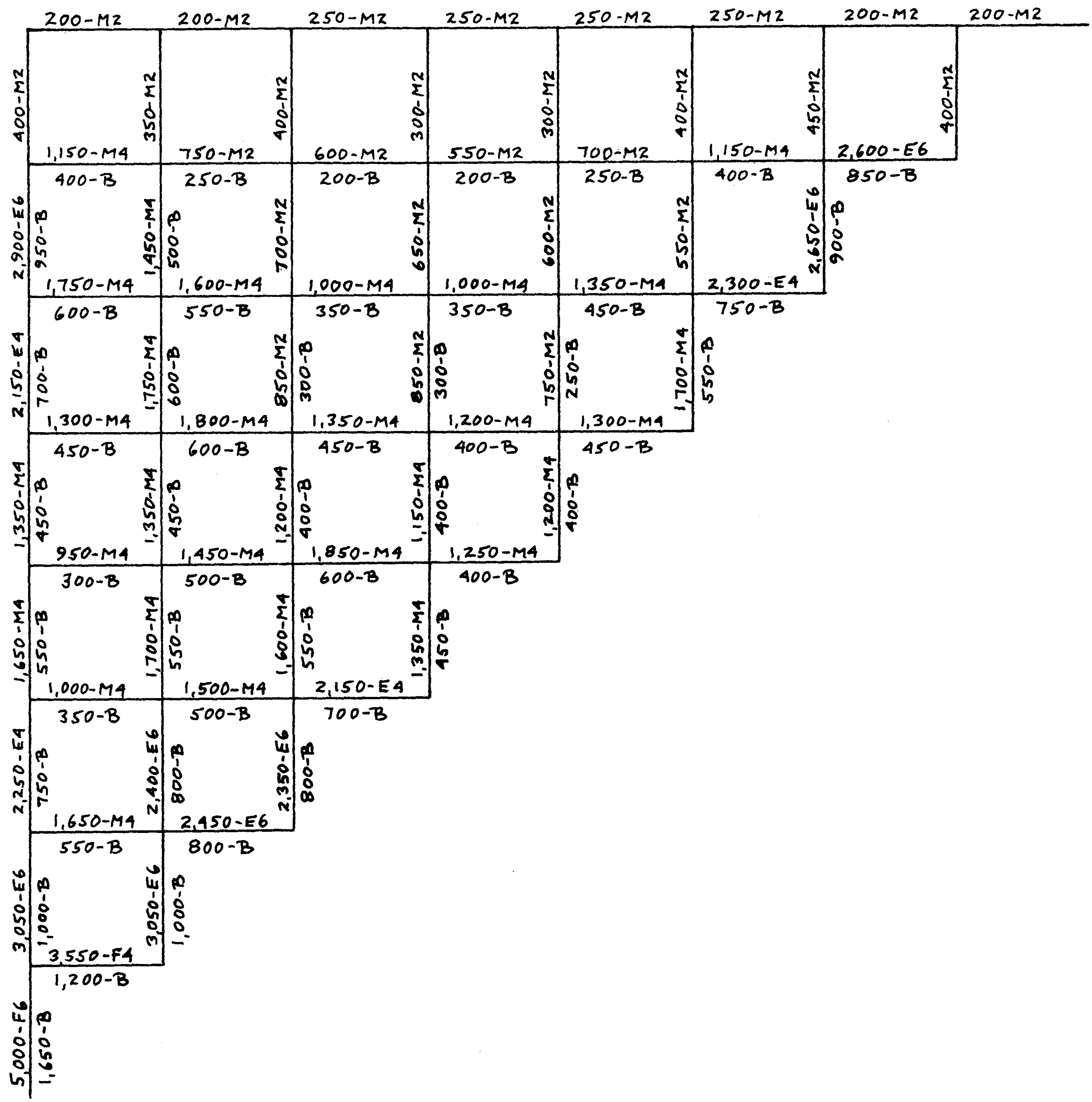


Figure 27.

Peak one-directional flow for many-centered city.

Ratio of private-public transportation: 100%-0%.



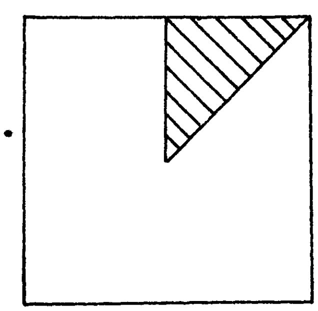


Figure 28.

Peak one-directional flow for many-centered city.

Ratio of private-public transportation: 75%-25%.

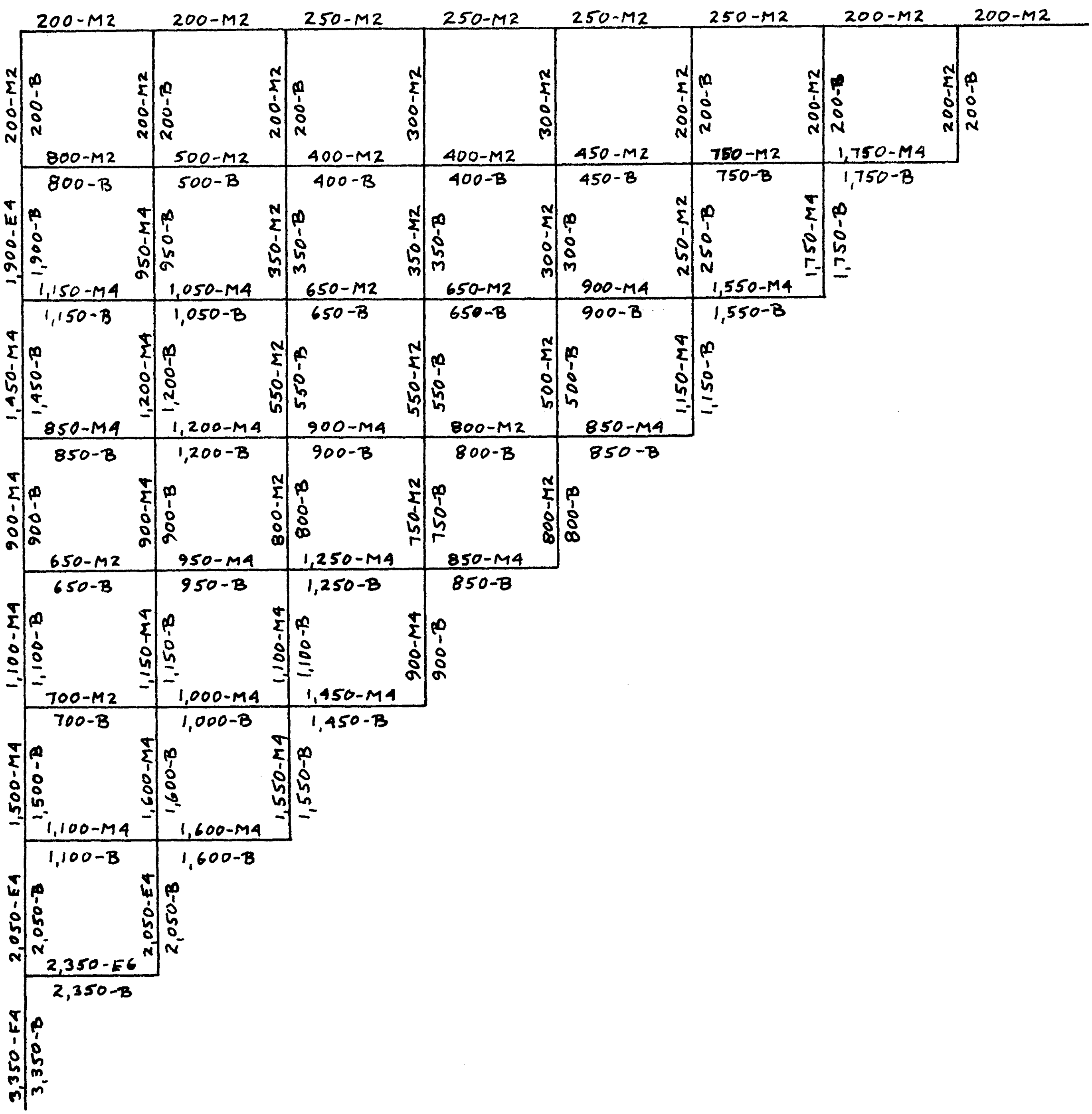
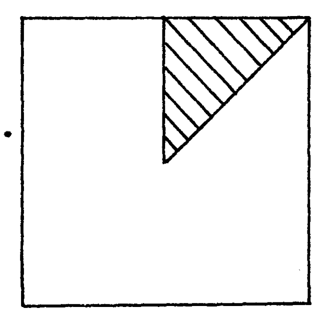


Figure 29.

Peak one-directional flow for many-centered city.

Ratio of private-public transportation: 50%-50%.



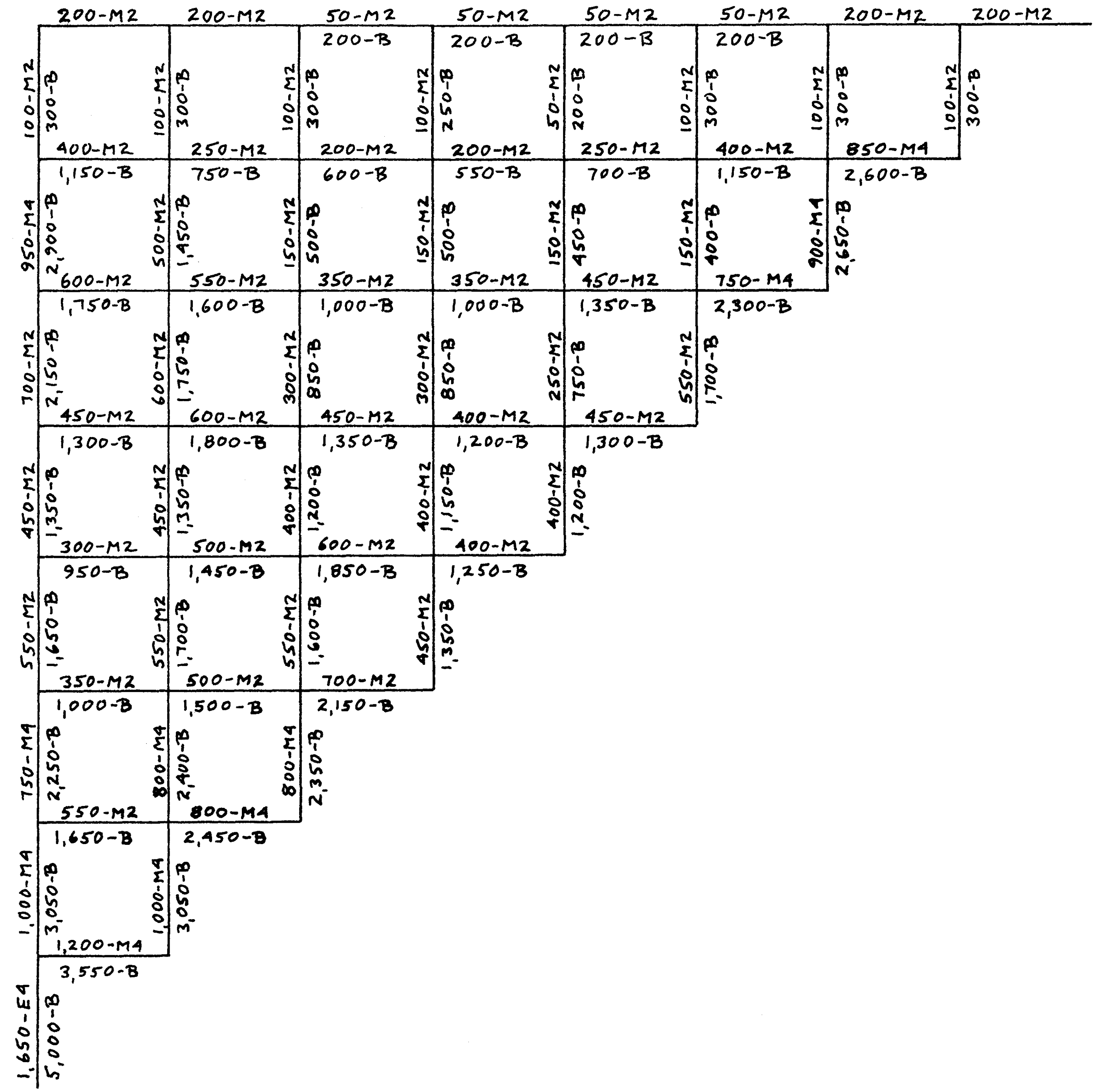
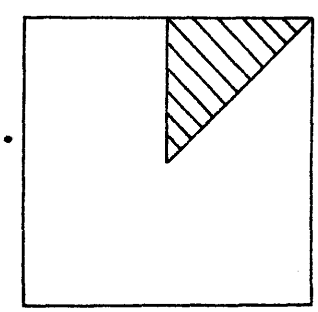


Figure 30.

Peak one-directional flow for many-centered city.

Ratio of private-public transportation: 25%-75%.



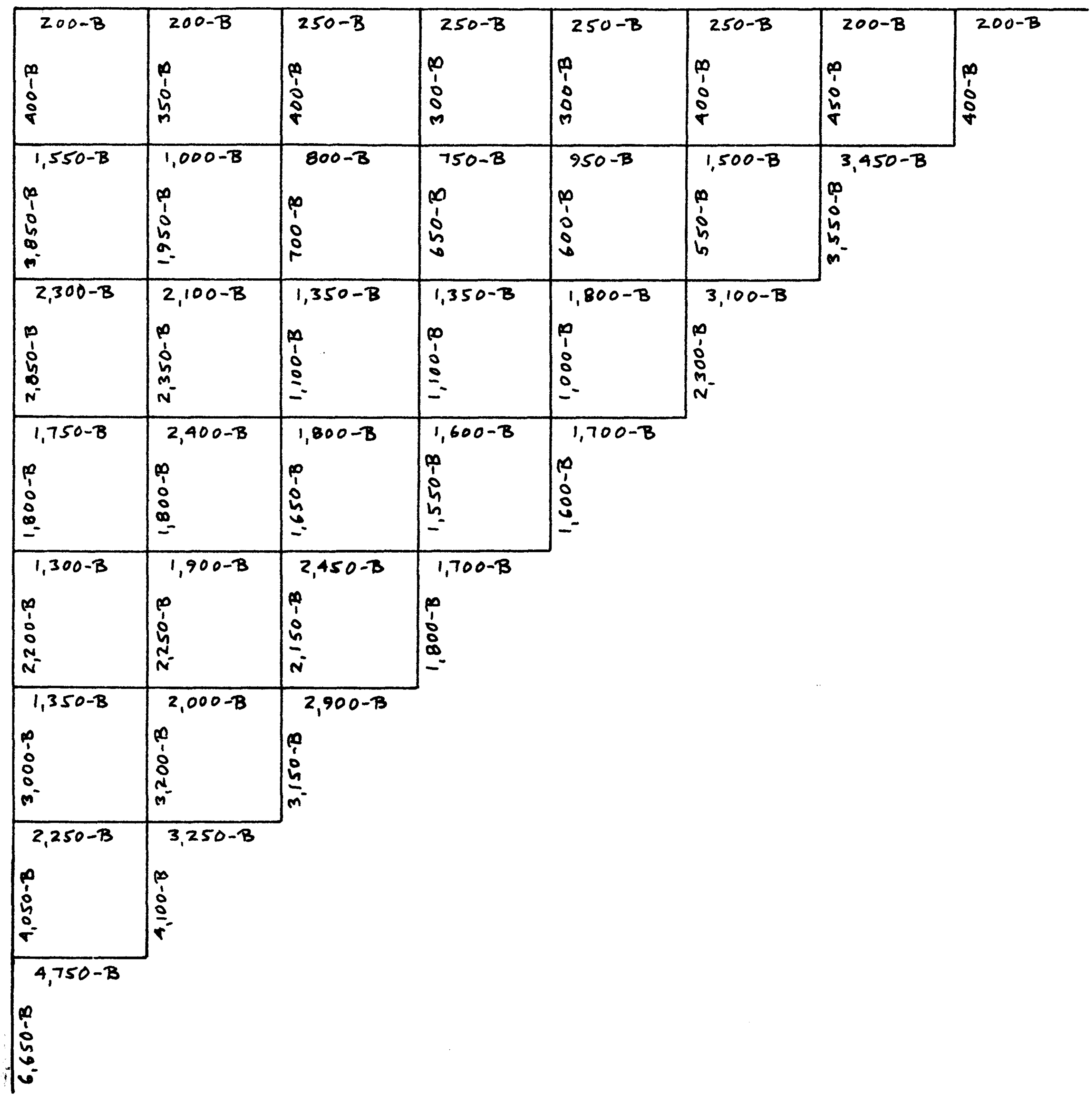
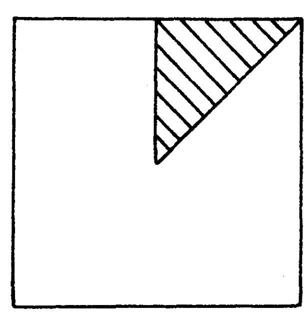


Figure 31.

Peak one-directional flow for many-centered city.

Ratio of private-public transportation: 0%-100%.



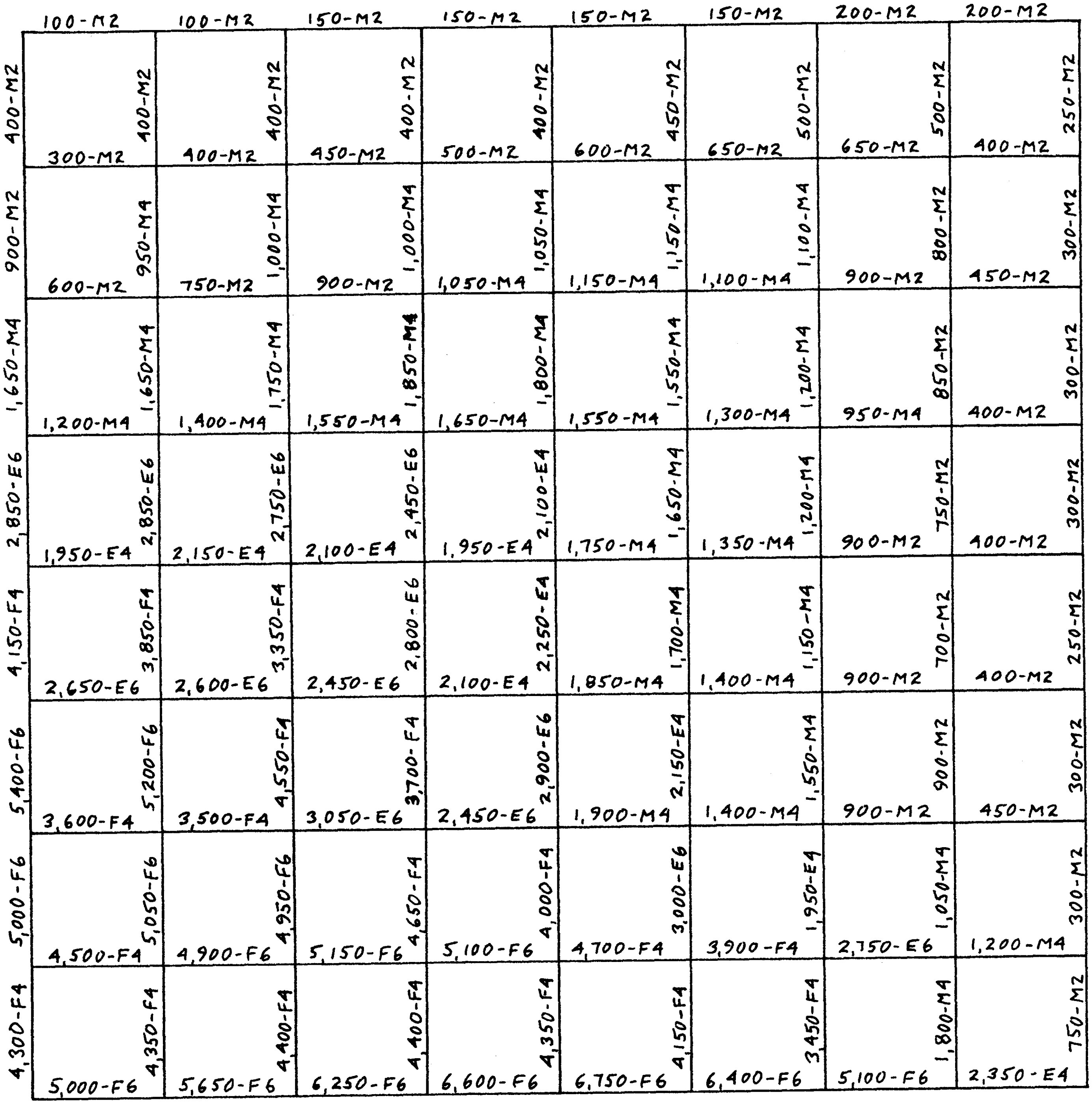
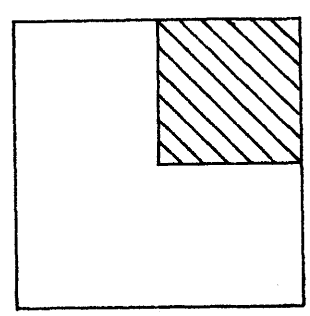
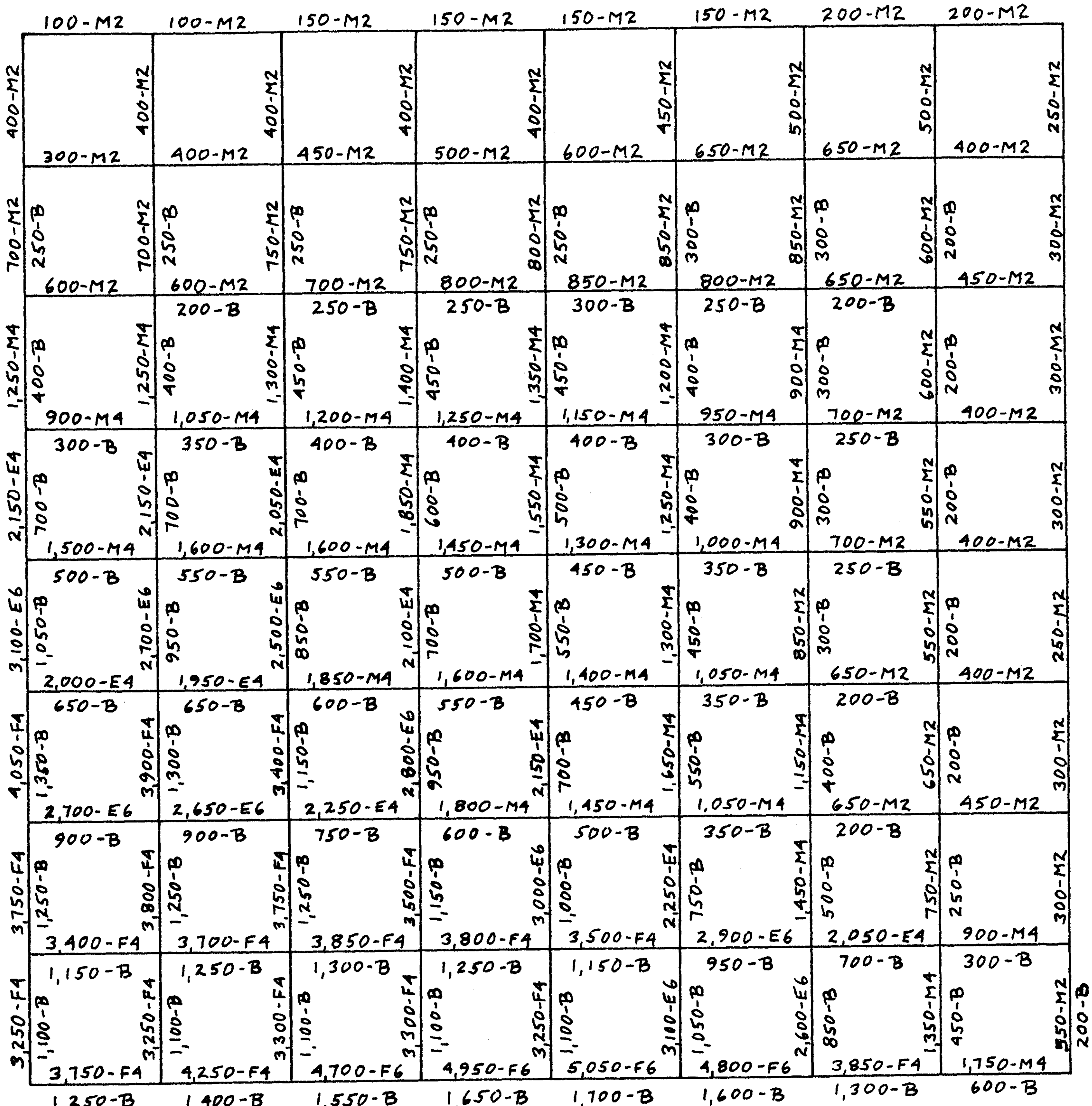


Figure 32.

Peak one-directional flow for layered city.

Ratio of private-public transportation: 100%-0%.





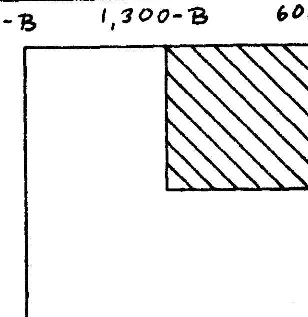
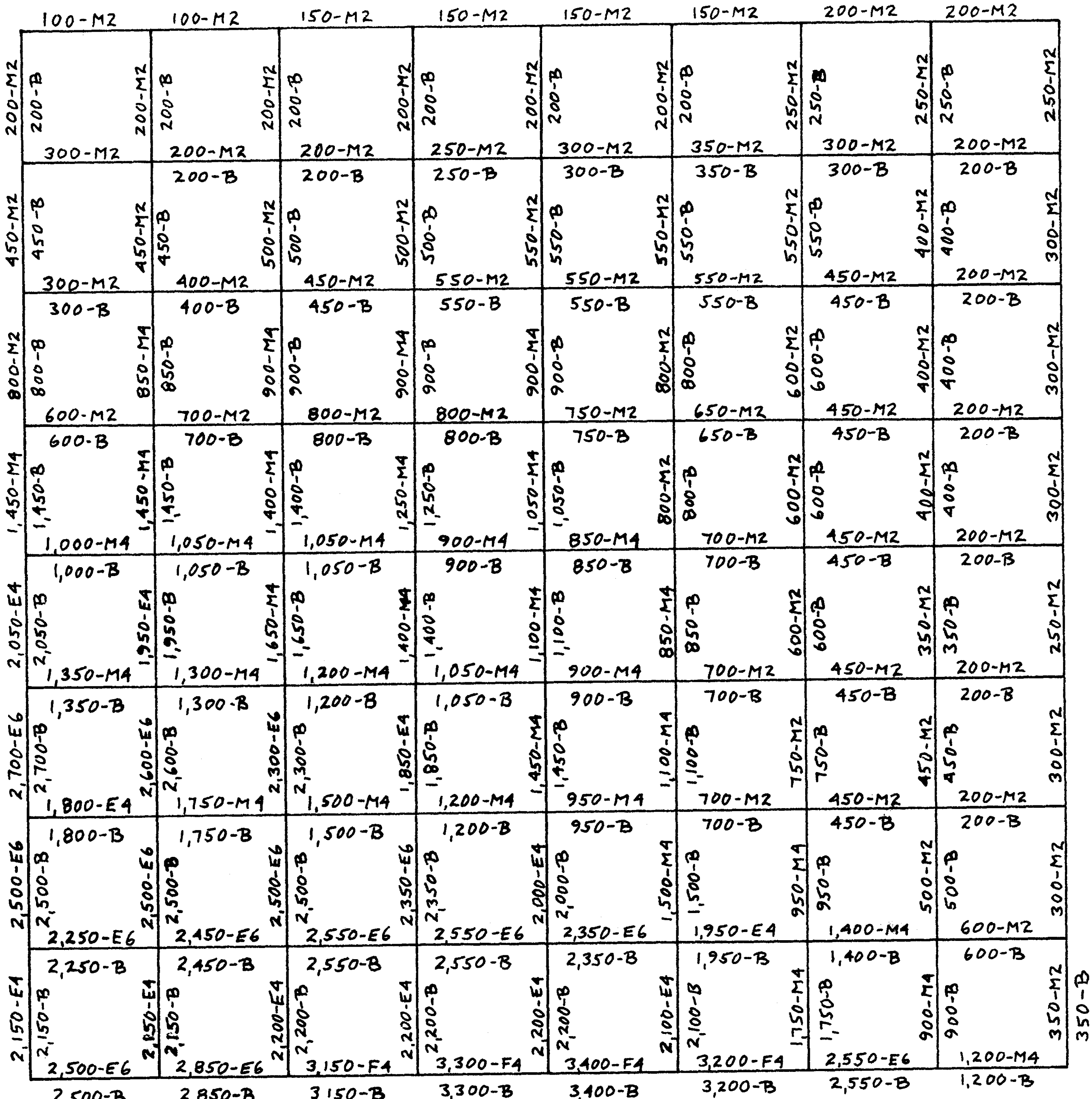


Figure 33.

Peak one-directional flow for layered city.

Ratio of private-public transportation: 75%-25%.



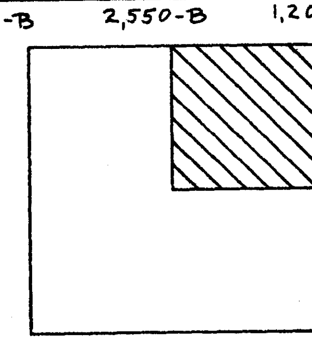
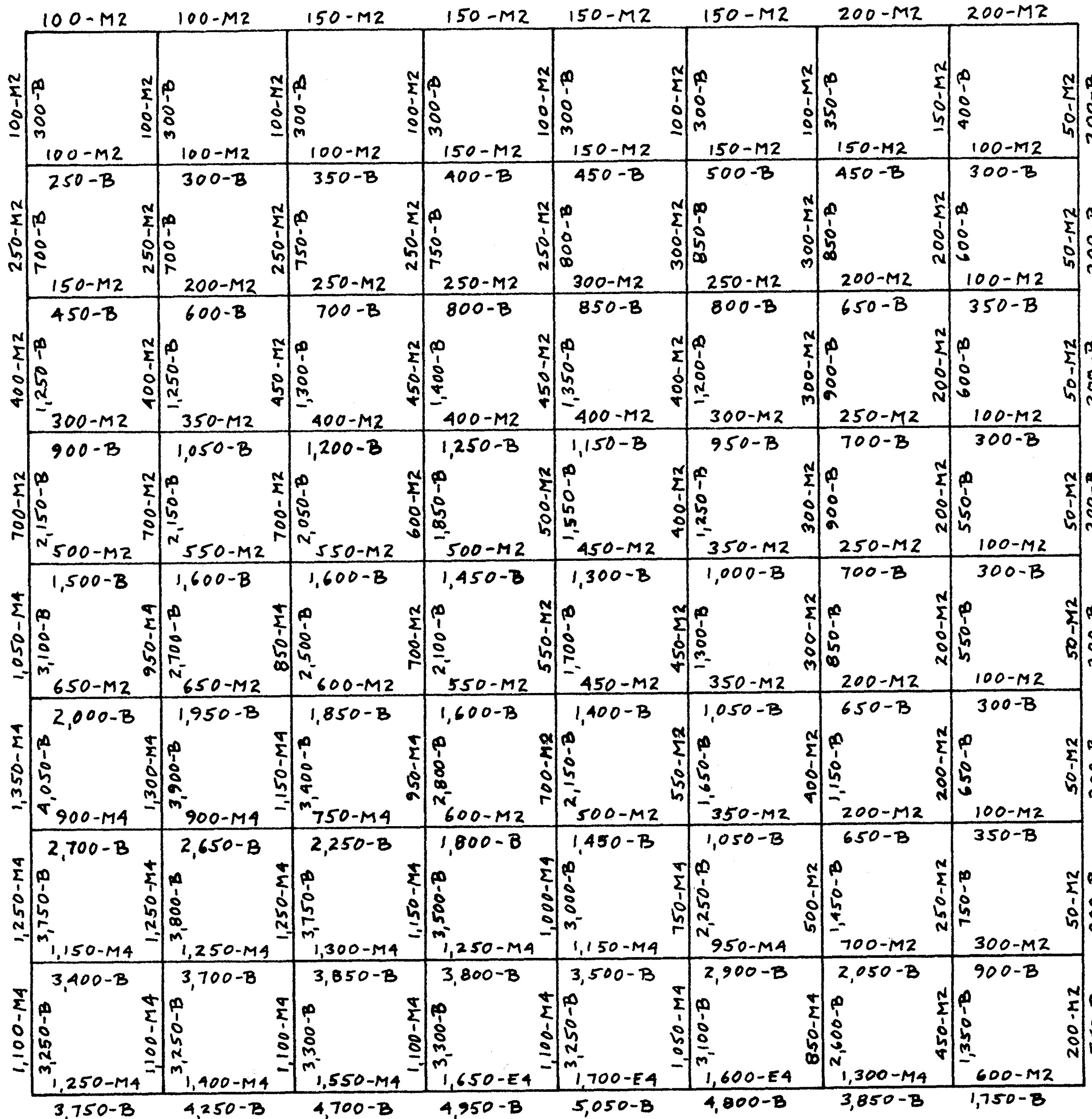


Figure 34.

Peak one-directional flow for layered city.

Ratio of private-public transportation: 50%-50%.



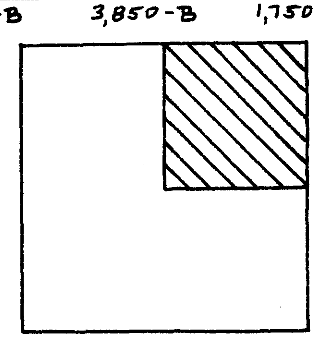
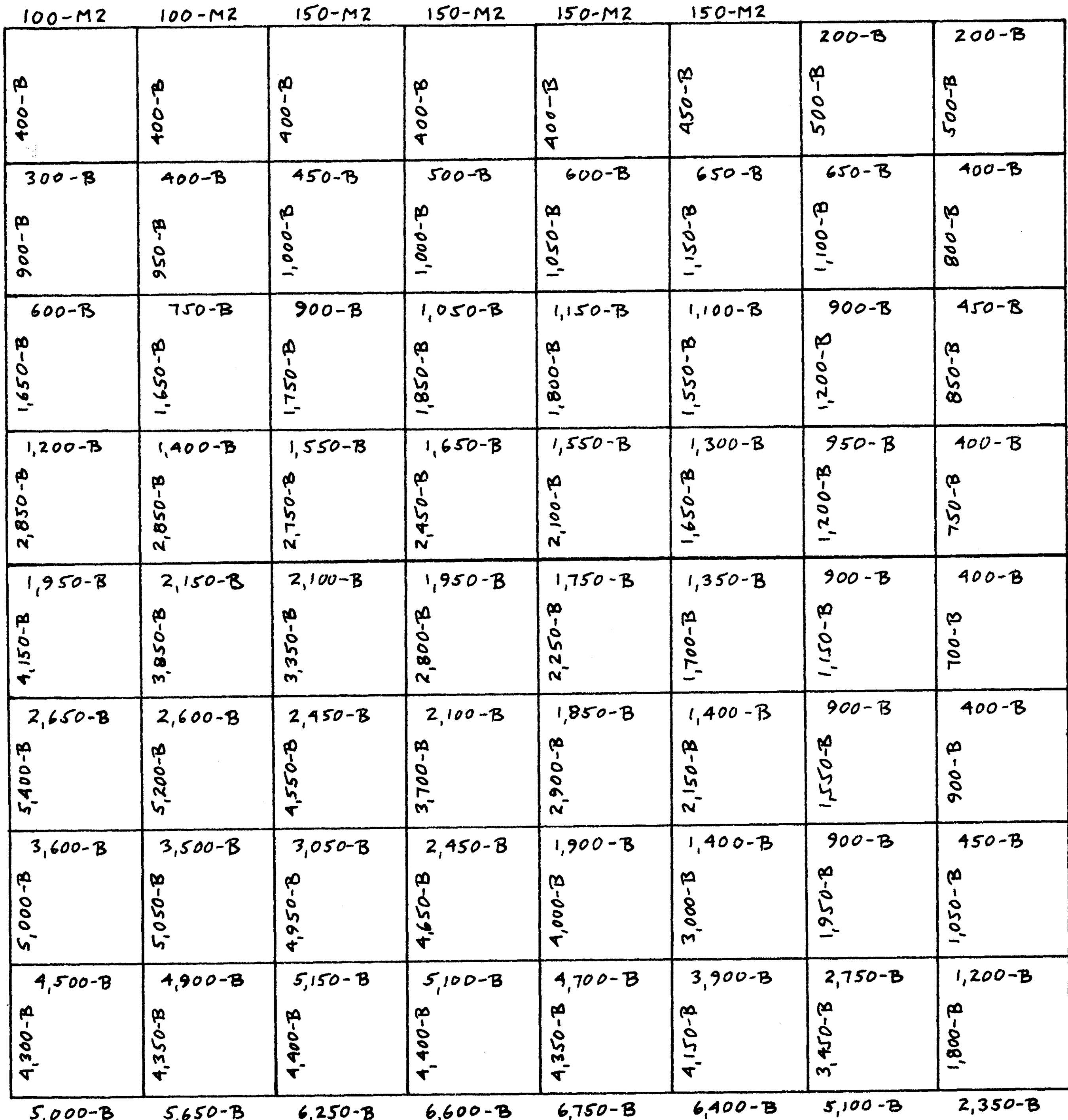


Figure 35.

Peak one-directional flow for layered city.

Ratio of private-public transportation: 25%-75%.



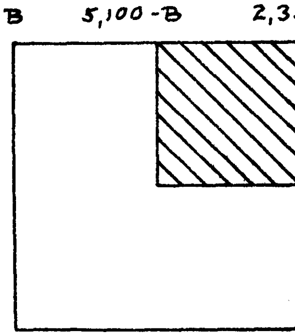


Figure 36.

Peak one-directional flow for layered city.

Ratio of private-public transportation: 0%-100%.

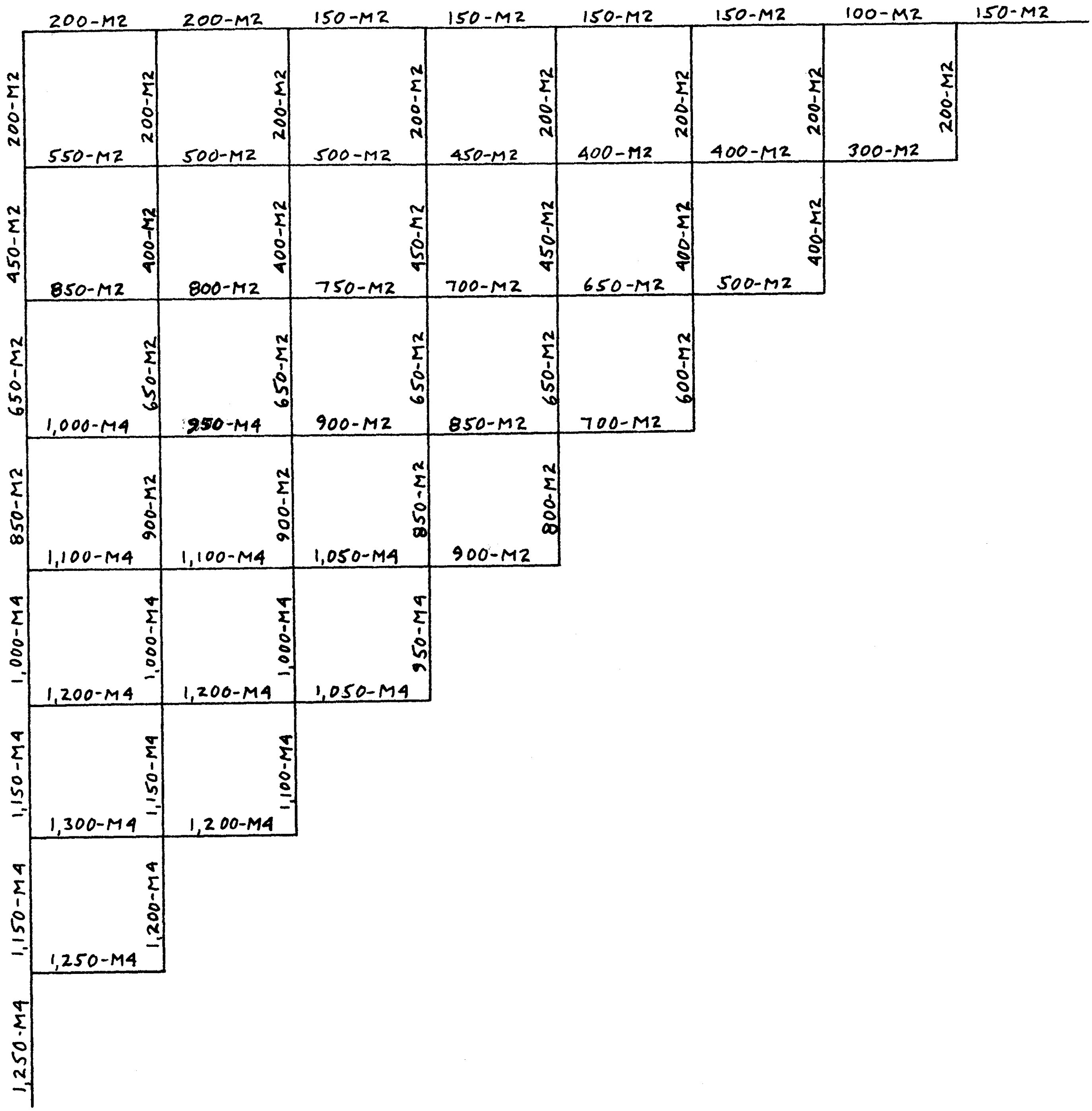
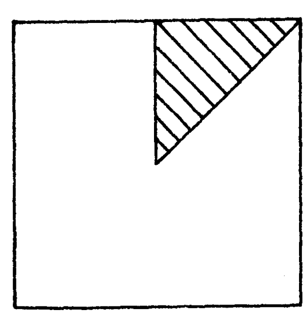


Figure 37.

Peak one-directional flow for homogeneous city.

Ratio of private-public transportation: 100%-0%.



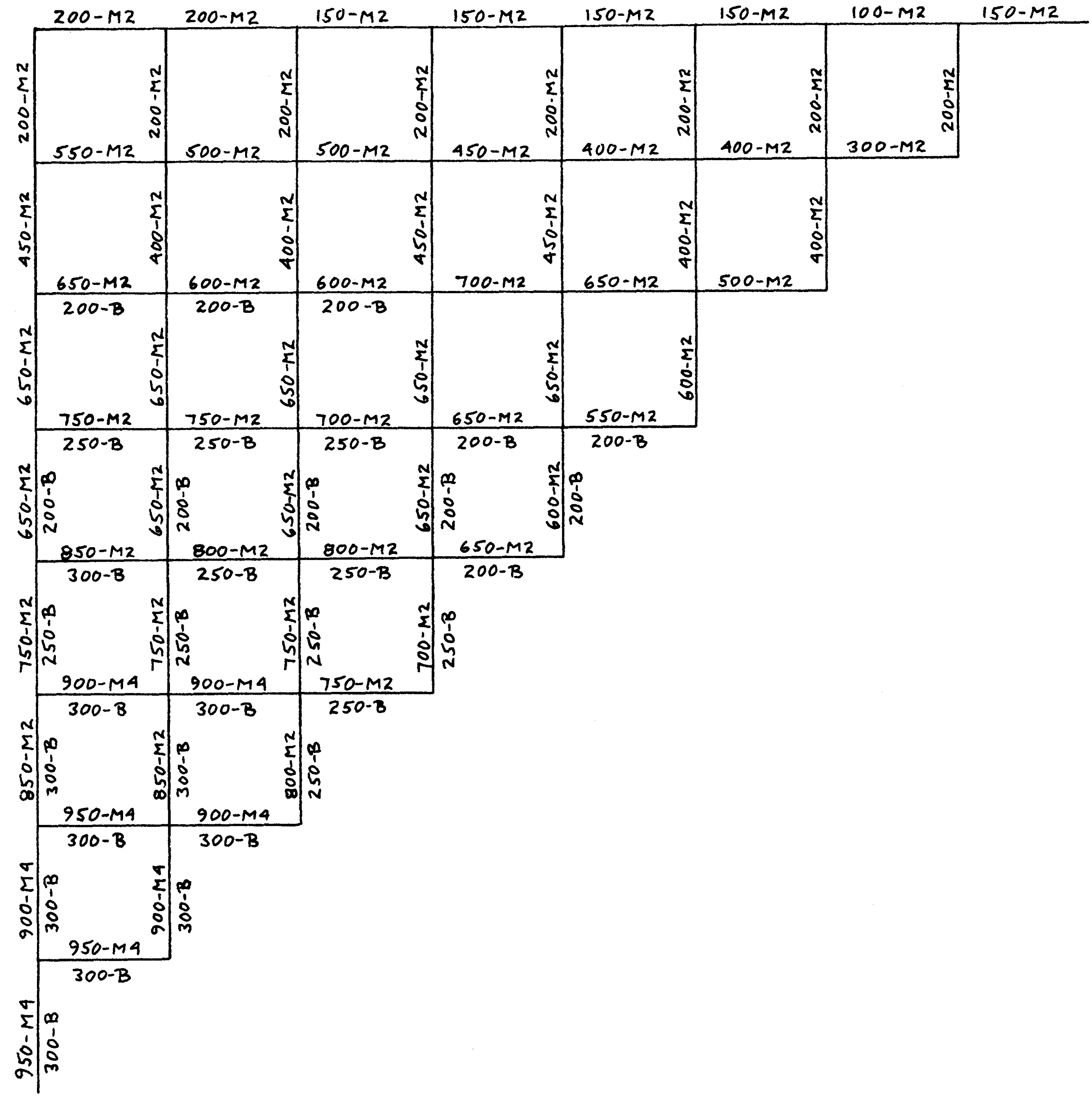
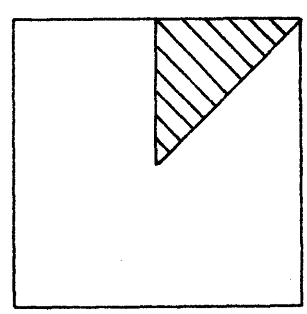


Figure 38.

Peak one-directional flow for homogeneous city.

Ratio of private-public transportation: 75%-25%.



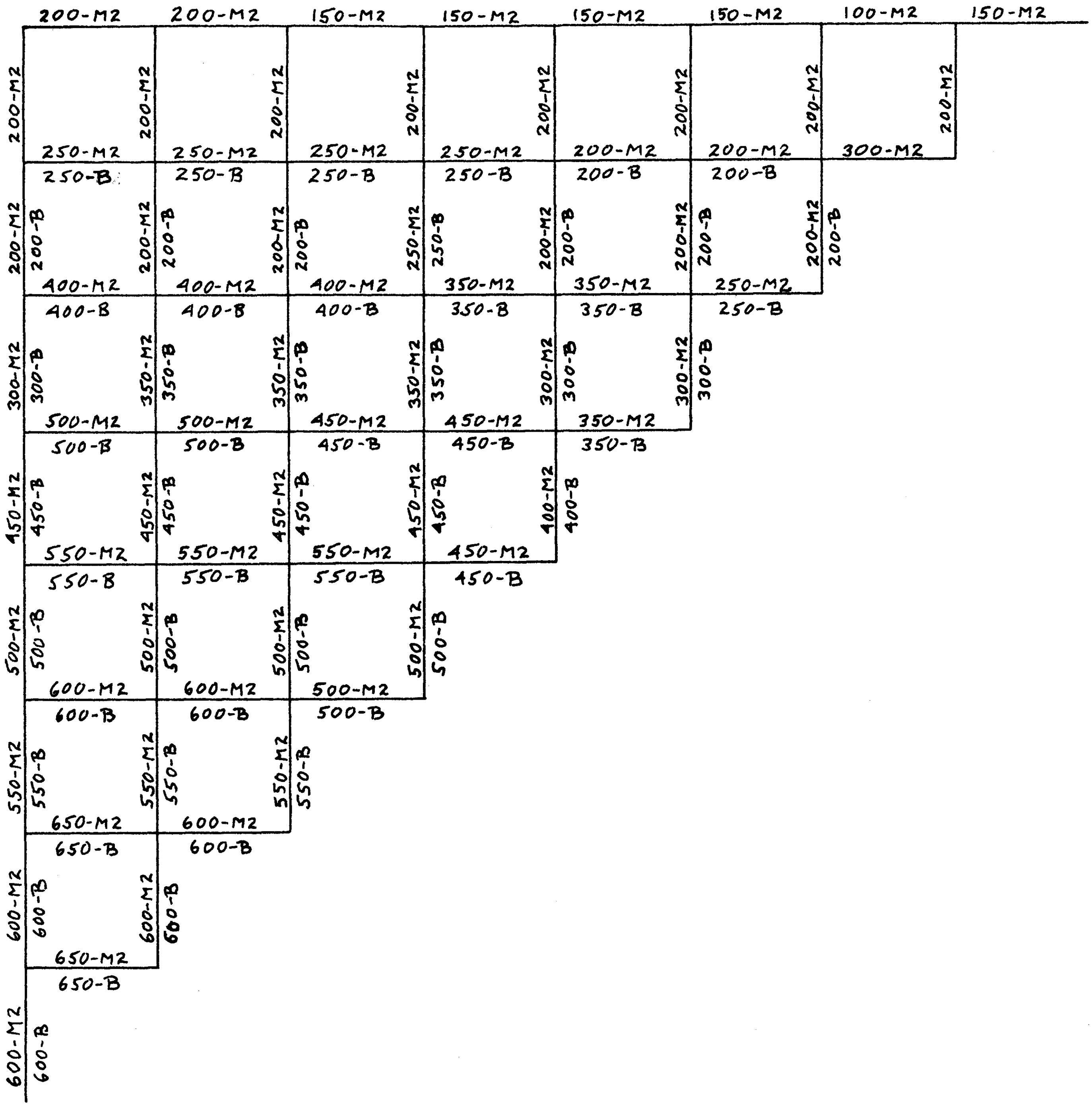
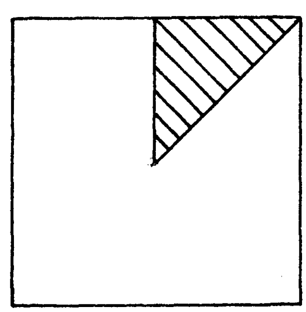


Figure 39.

Peak one-directional flow for homogeneous city.

Ratio of private-public transportation: 50%-50%.



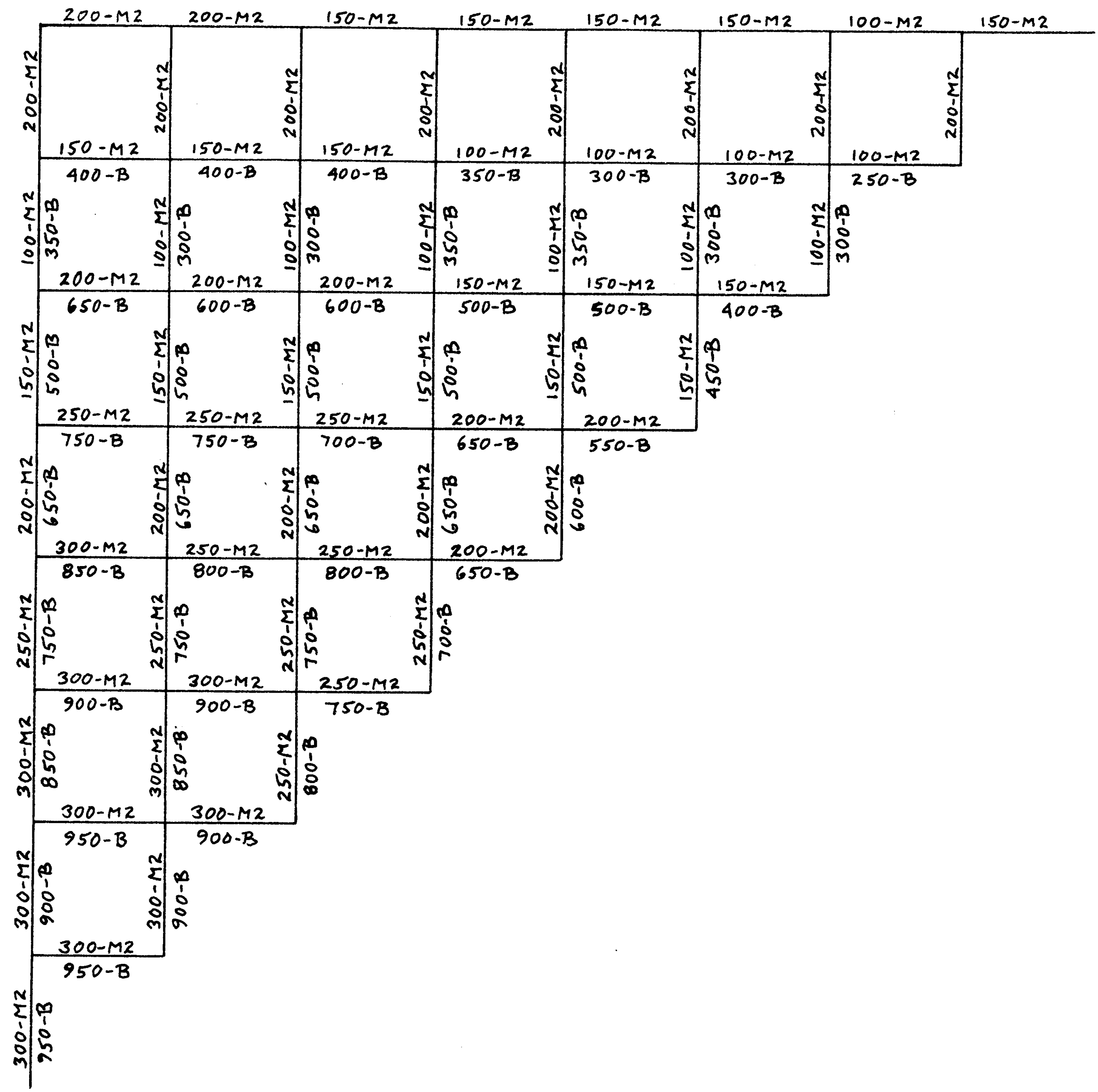
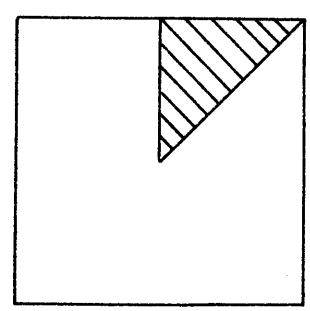


Figure 40.

Peak one-directional flow for homogeneous city.

Ratio of private-public transportation: 25%-75%.



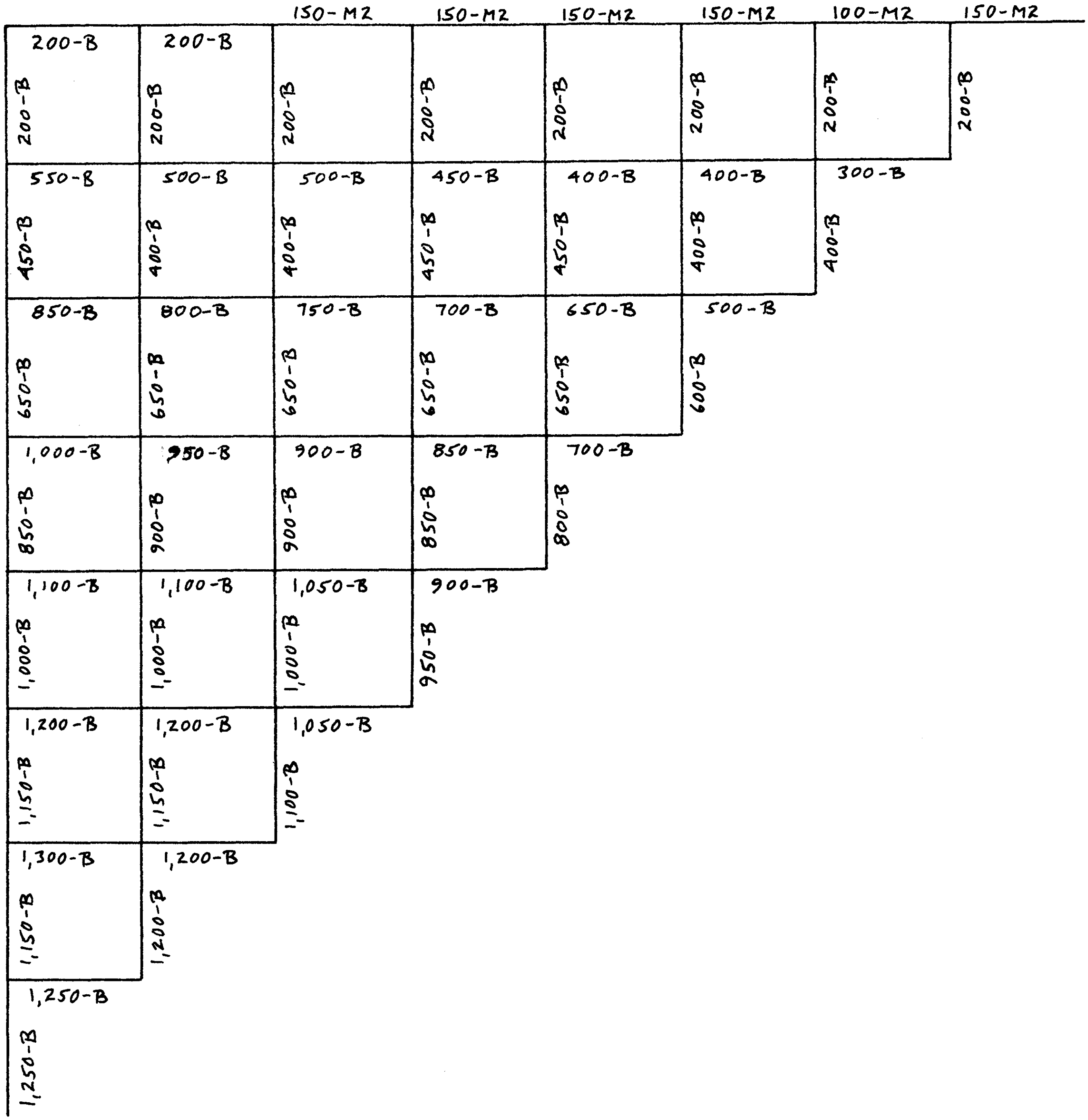
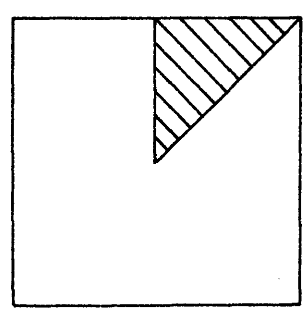


Figure 41.

Peak one-directional flow for homogeneous city.

Ratio of private-public transportation: 0%-100%.



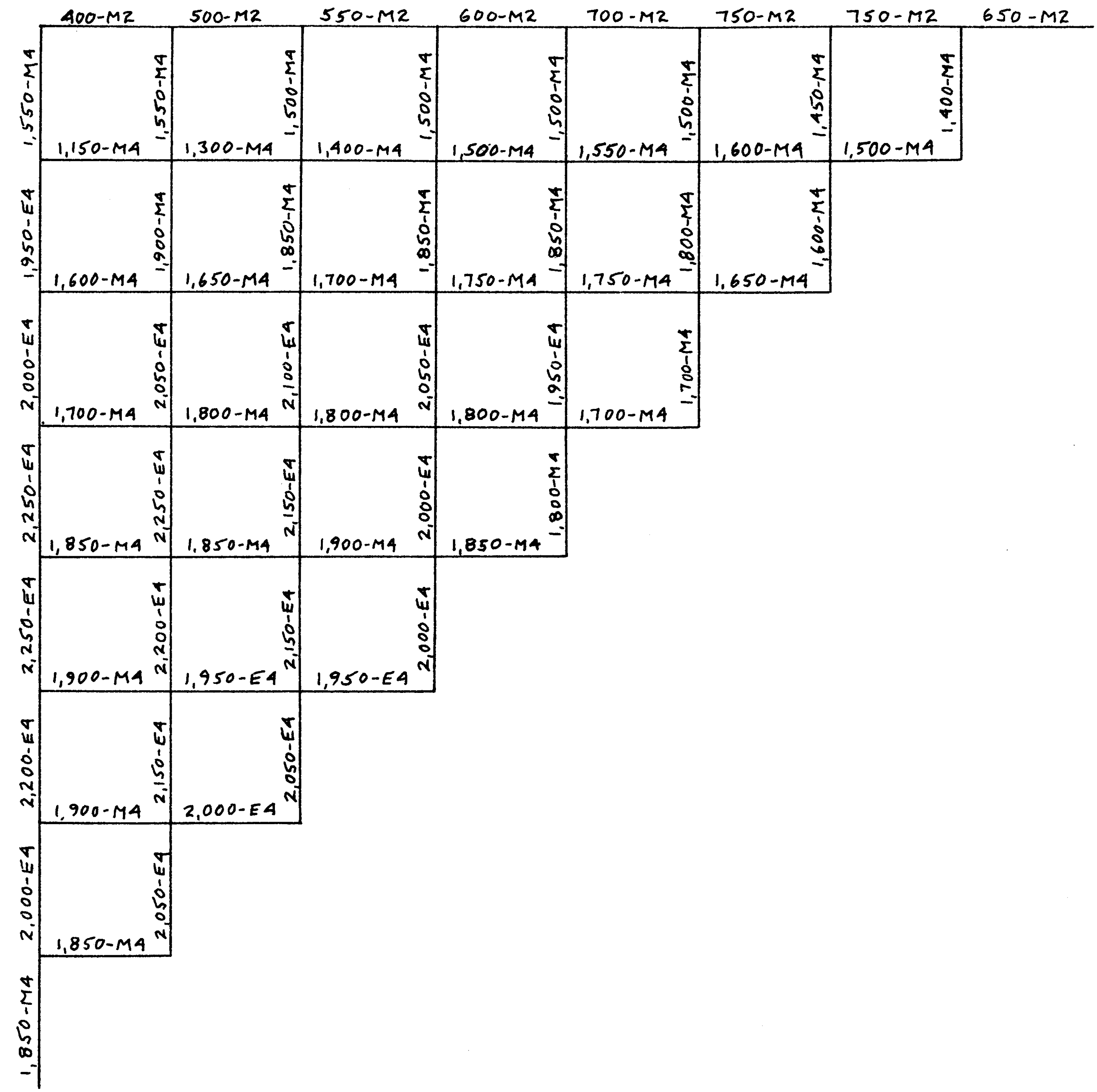
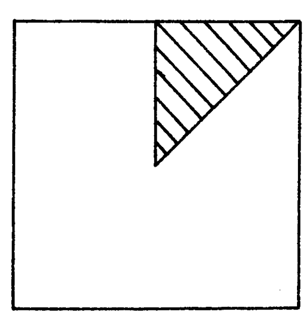


Figure 42.

Peak one-directional flow for ring city.

Ratio of private-public transportation: 100%-0%.



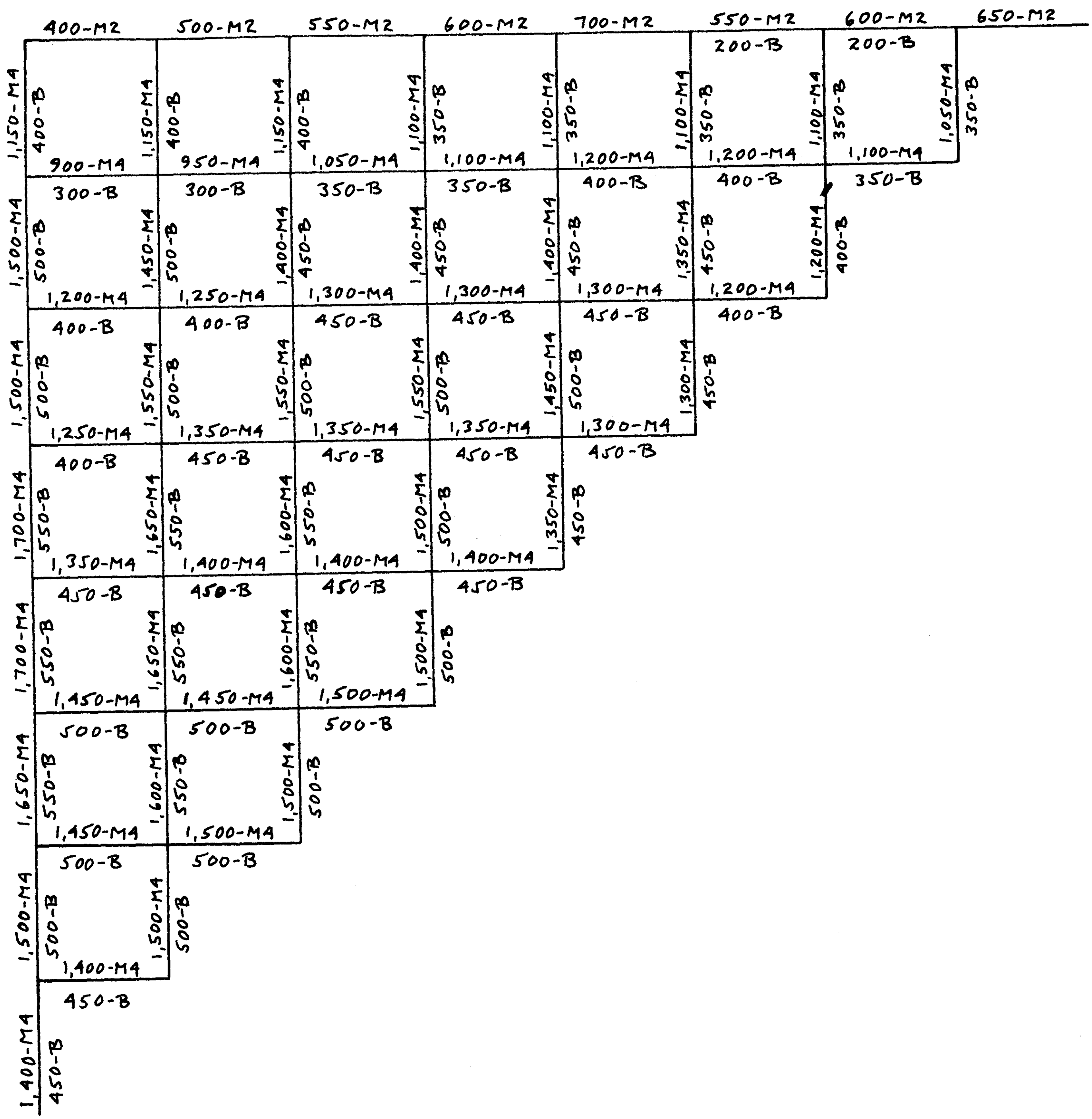
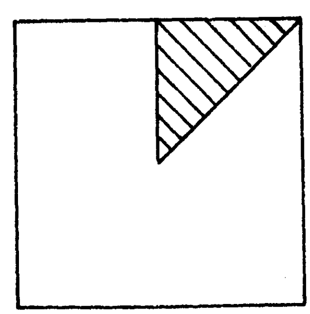


Figure 43.

Peak one-directional flow for ring city.

Ratio of private-public transportation: 75%-25%.



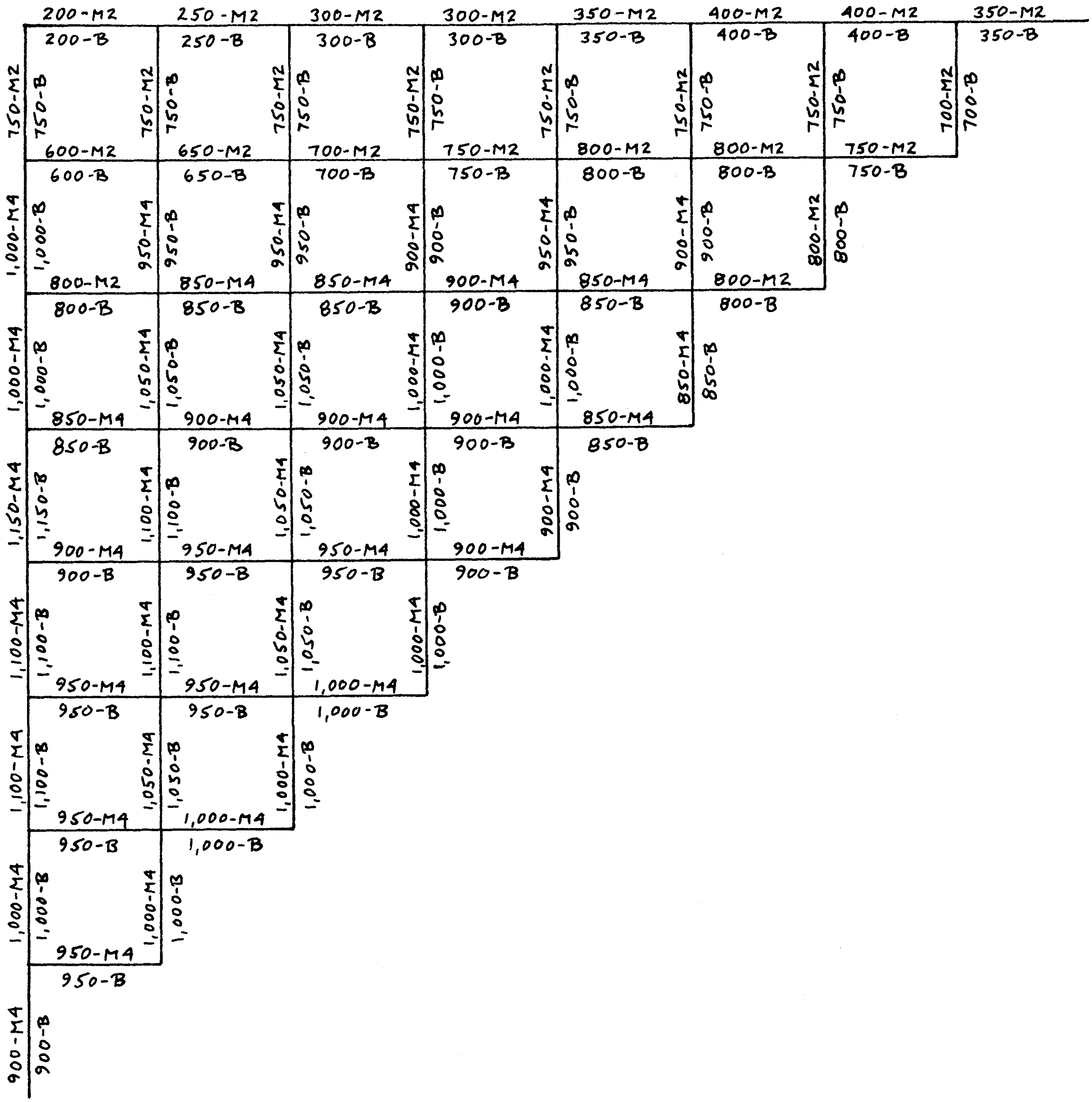
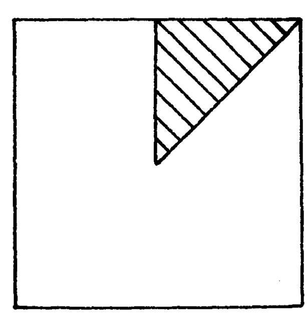


Figure 44.

Peak one-directional flow for ring city.

Ratio of private-public transportation: 50%-50%.



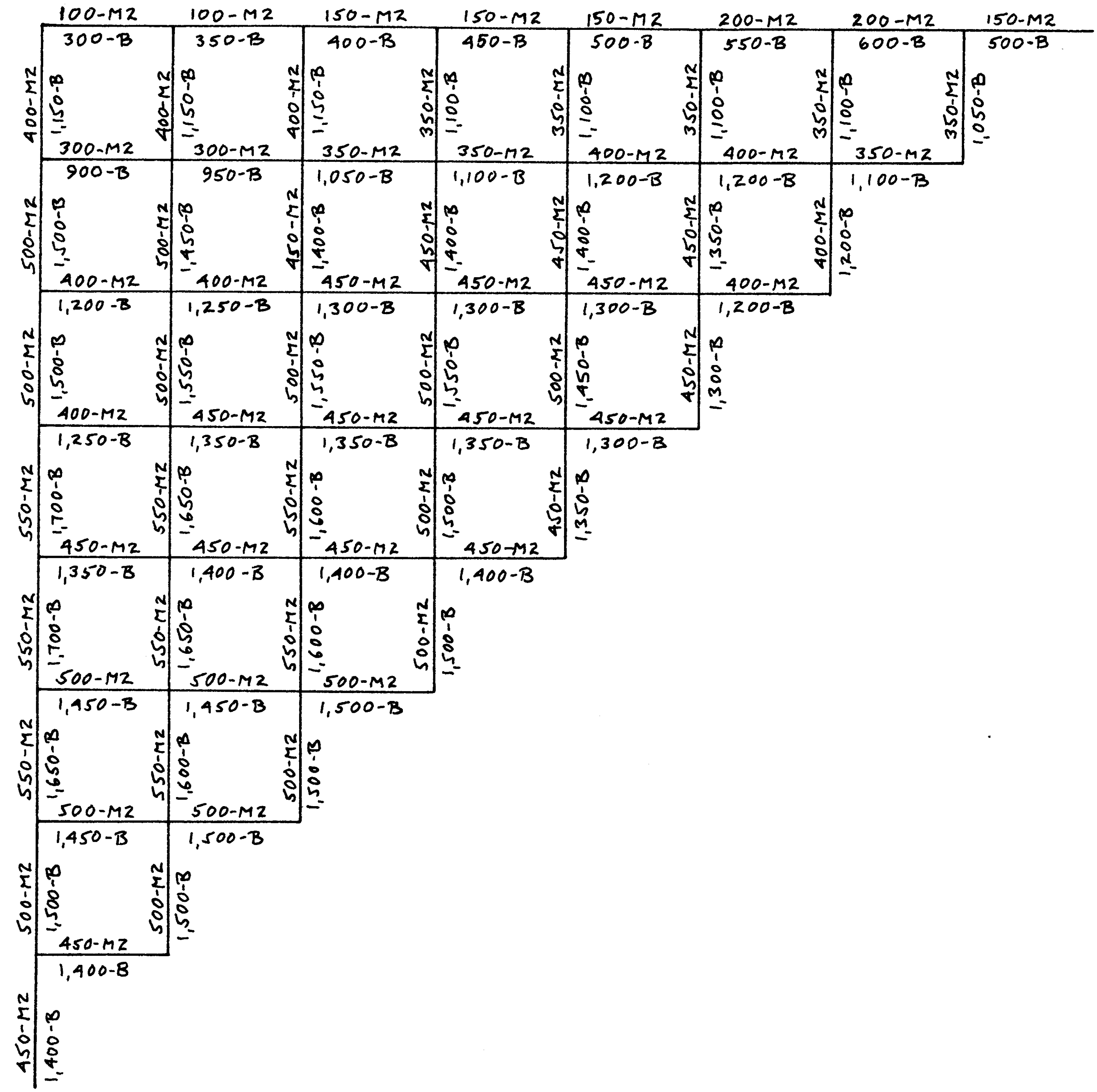
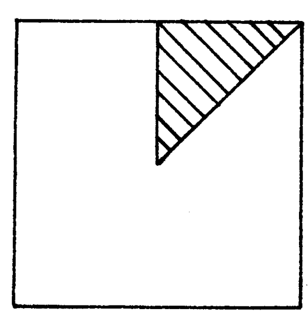


Figure 45.

Peak one-directional flow for ring city.

Ratio of private-public transportation: 25%-75%.



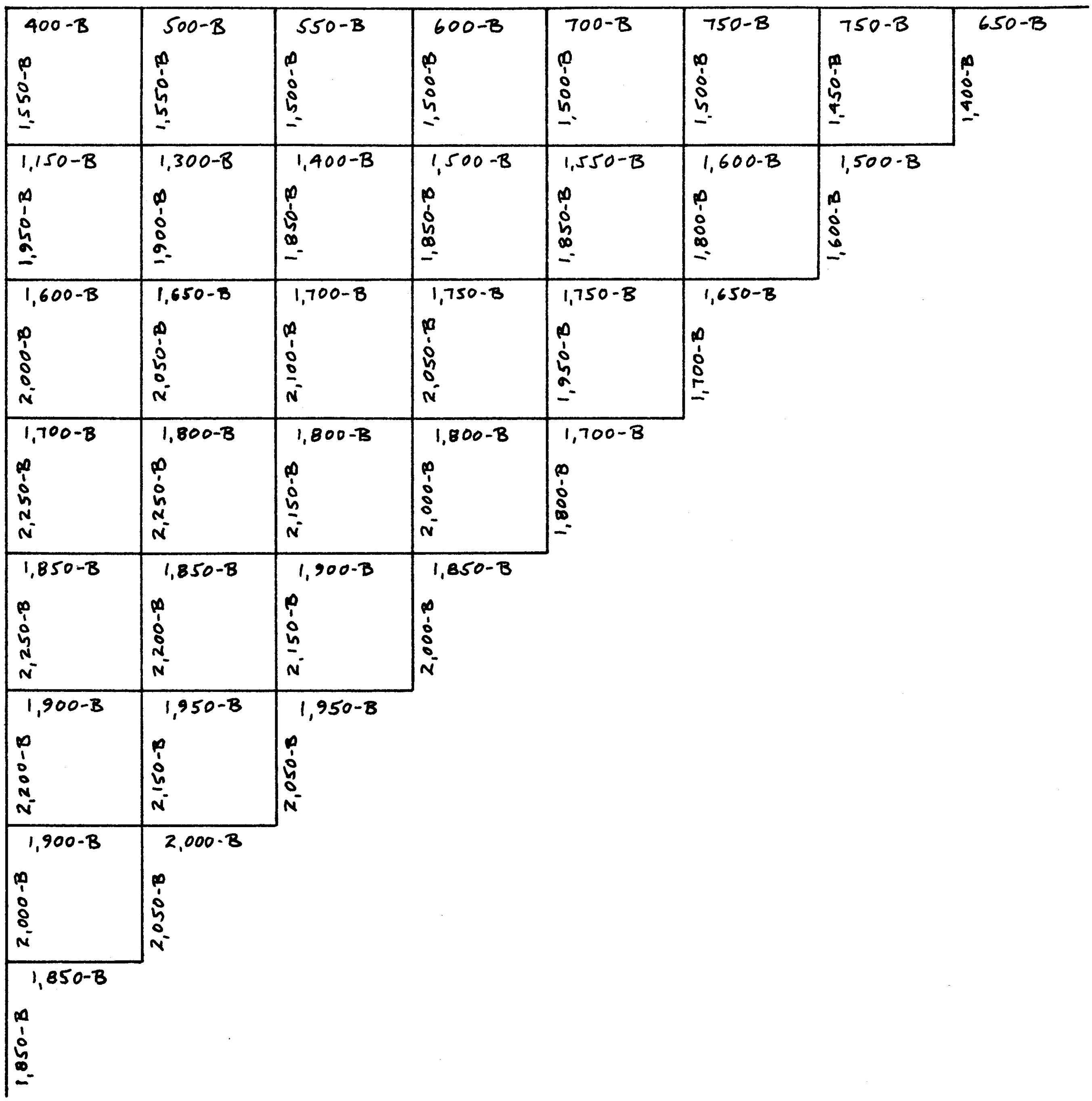
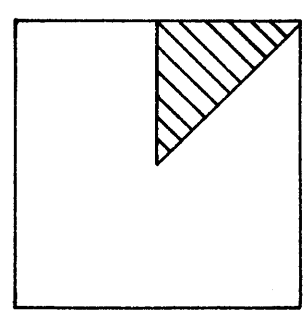


Figure 46.

Peak one-directional flow for ring city.

Ratio of private-public transportation: 0%-100%.



APPENDIX D--

TABULATIONS OF PEAK ONE-DIRECTIONAL FLOW CHARACTERISTICS

The following tables represent tabulations of various characteristics taken from the peak directional flow diagrams given in Appendix C. The figures listed here are for the total city, not just the octant or quadrant depicted in the flow diagrams.

The modal splits are written with the percentage of private transportation given first; thus, for example, 75-25 represents 75 percent private transportation and 25 percent public transportation.

PMT is an abbreviation for the number of person-miles traveled.

	Percent Modal Split:				
	100-0	75-25	50-50	25-75	0-100
2-Lane Major Street					
Miles of road	188	224	284	376	472
PMT by auto	83,200	103,000	108,600	104,000	1,200
Mi. of bus rte.	--	76	212	344	448
PMT by bus	--	17,000	95,400	302,800	822,000
4-Lane Major Street					
Miles of road	136	120	128	88	--
PMT by auto	190,800	149,800	158,200	90,400	--
PMT by bus	--	49,200	158,200	271,800	--
4-Lane Expressway					
Miles of road	24	40	24	8	--
PMT by auto	51,600	82,400	47,200	14,000	--
PMT by bus	--	27,600	47,200	42,000	--
6-Lane Expressway					
Miles of road	52	52	20	20	--
PMT by auto	145,400	139,400	52,200	51,800	--
PMT by bus	--	46,600	52,200	85,600 on 12 mi.	--
4-Lane Freeway					
Miles of road	44	32	16	--	--
PMT by auto	160,400	129,800	52,000	--	--
PMT by bus	--	55,800	52,000	--	--
6-Lane Freeway					
Miles of road	36	8	20	4	--
PMT by auto	208,200	42,000	103,600	18,000	--
PMT by bus	--	14,000	103,600	--	--
8-Lane Freeway					
Miles of road	28	24	4	--	--
PMT by auto	263,000	194,000	36,200	--	--
PMT by bus	--	51,800 on 20 mi.	--	--	--
2-Track Rail					
Miles of track	--	--	4	12	24
PMT by train	--	--	36,200	124,200	279,400
Total PMT by Road	1102,600	840,400	558,000	278,200	1,200
Total PMT by Bus	--	262,000	508,600	702,200	822,000
Actual % Auto Travel	100.00	76.23	50.60	25.19	0.11

Total PMT, all modes, in lesser direction = 109,200

Average Length of Trip = total PMT (both directions)/city pop.
= 1,211,800/126,000 = 9.62 miles

Table 10. Tabulation of peak one-directional flow characteristics for the central city.

	Percent Modal Split:				
	100-0	75-25	50-50	25-75	0-100
2-Lane Major Street					
Miles of road	196	228	336	484	532
PMT by auto	92,000	105,600	142,200	155,800	3,200
Mi. of bus rte.	--	88	272	436	508
PMT by bus	--	19,600	130,200	442,600	817,800
4-Lane Major Street					
Miles of road	188	212	148	48	--
PMT by auto	264,200	265,800	162,600	55,600	--
PMT by bus	--	88,800	162,600	166,600	--
4-Lane Expressway					
Miles of road	52	44	28	8	--
PMT by auto	110,200	88,800	55,600	14,800	--
PMT by bus	--	30,200	55,600	44,400	--
6-Lane Expressway					
Miles of road	52	20	8	4	--
PMT by auto	138,600	57,200	19,200	11,200	--
PMT by bus	--	19,200	19,200	--	--
4-Lane Freeway					
Miles of road	36	28	20	--	--
PMT by auto	148,400	109,400	66,600	--	--
PMT by bus	--	36,400	66,600	--	--
6-Lane Freeway					
Miles of road	12	8	4	--	--
PMT by auto	74,000	44,400	22,400	--	--
PMT by bus	--	14,800	22,400	--	--
8-Lane Freeway					
Miles of road	12	4	--	--	--
PMT by auto	97,600	33,600	--	--	--
PMT by bus	--	11,200	--	--	--
2-Track Rail					
Miles of track	--	--	--	4	12
PMT by train	--	--	--	33,600	104,000
Total PMT by Road	925,000	704,800	468,600	237,400	3,200
Total PMT by Bus	--	220,200	456,500	653,600	817,800
Actual % Auto Travel	100.00	76.19	50.65	25.68	0.36

Total PMT, all modes, in lesser direction = 371,200

Average Length of Trip = total PMT (both directions)/city pop.
= 1,296,200/122,000 = 10.62 miles

Table 11. Tabulation of peak one-directional flow characteristics for the quasi-central city.

	Percent Modal Split:				
	100-0	75-25	50-50	25-75	0-100
2-Lane Major Street					
Miles of road	172	212	292	464	544
PMT by auto	69,200	97,200	123,600	152,800	--
Mi. of bus rte.	--	56	220	432	544
PMT by bus	--	14,000	104,400	436,600	888,000
4-Lane Major Street					
Miles of road	188	240	224	76	--
PMT by auto	280,800	332,400	265,000	67,600	--
PMT by bus	--	112,000	265,000	203,600	--
4-Lane Expressway					
Miles of road	84	24	16	4	--
PMT by auto	185,200	53,200	32,200	6,600	--
PMT by bus	--	17,400	32,200	20,000	--
6-Lane Expressway					
Miles of road	48	56	8	--	--
PMT by auto	141,800	147,800	18,800	--	--
PMT by bus	--	49,000	18,800	--	--
4-Lane Freeway					
Miles of road	48	8	4	--	--
PMT by auto	184,400	28,400	13,400	--	--
PMT by bus	--	9,600	13,400	--	--
6-Lane Freeway					
Miles of road	4	4	--	--	--
PMT by auto	26,600	20,000	--	--	--
PMT by bus	--	6,600	--	--	--
8-Lane Freeway					
Miles of road	--	--	--	--	--
PMT by auto	--	--	--	--	--
PMT by bus	--	--	--	--	--
2-Track Rail					
Miles of track	--	--	--	--	--
PMT by train	--	--	--	--	--
Total PMT by Road	888,000	679,000	453,000	227,000	--
Total PMT by Bus	--	208,600	433,800	660,200	888,000
Actual % Auto Travel	100.00	76.50	51.08	25.59	0.00

Total PMT, all modes, in lesser direction = 479,000

Average Length of Trip = total PMT (both directions)/city pop.
= 1,367,000/122,000 = 11.20 miles

Table 12. Tabulation of peak one-directional flow characteristics for the many-centered city.

	Percent Modal Split:				
	100-0	75-25	50-50	25-75	0-100
2-Lane Major Street					
Miles of road	196	244	306	422	544
PMT by auto	94,200	121,400	122,700	125,500	3,200
Mi. of bus rte.	--	98	246	390	544
PMT by bus	--	23,300	110,300	362,900	1030,100
4-Lane Major Street					
Miles of road	146	148	136	116	--
PMT by auto	202,900	196,400	160,500	126,500	--
PMT by bus	--	65,600	160,500	378,000	--
4-Lane Expressway					
Miles of road	38	38	44	6	--
PMT by auto	79,500	80,100	90,000	9,900	--
PMT by bus	--	26,600	90,000	29,600	--
6-Lane Expressway					
Miles of road	50	38	50	--	--
PMT by auto	136,500	106,000	123,800	--	--
PMT by bus	--	35,700	123,800	--	--
4-Lane Freeway					
Miles of road	72	68	8	--	--
PMT by auto	294,500	244,600	26,100	--	--
PMT by bus	--	81,700	26,100	--	--
6-Lane Freeway					
Miles of road	42	8	--	--	--
PMT by auto	225,700	39,000	--	--	--
PMT by bus	--	13,000	--	--	--
8-Lane Freeway					
Miles of road	--	--	--	--	--
PMT by auto	--	--	--	--	--
PMT by bus	--	--	--	--	--
2-Track Rail					
Miles of track	--	--	--	--	--
PMT by train	--	--	--	--	--
Total PMT by Road	1033,300	787,500	523,100	261,900	3,200
Total PMT by Bus	--	245,900	510,700	770,500	1030,100
Actual % Auto Travel	100.00	76.20	50.60	25.37	0.31

Total PMT, all modes, in lesser direction = 274,000

Average Length of Trip = total PMT (both directions)/city pop.
= 1,307,300/120,000 = 10.89 miles

Table 13. Tabulation of peak one-directional flow characteristics for the layered city.

	Percent Modal Split:				
	100-0	75-25	50-50	25-75	0-100
2-Lane Major Street					
Miles of road	392	488	544	544	544
PMT by auto	188,600	244,600	192,000	105,200	6,800
Mi. of bus rte.	--	188	412	420	496
PMT by bus	--	43,800	167,600	253,000	350,400
4-Lane Major Street					
Miles of road	152	56	--	--	--
PMT by auto	168,600	51,400	--	--	--
PMT by bus	--	16,800	--	--	--
4-Lane Expressway					
Miles of road	--	--	--	--	--
PMT by auto	--	--	--	--	--
PMT by bus	--	--	--	--	--
6-Lane Expressway					
Miles of road	--	--	--	--	--
PMT by auto	--	--	--	--	--
PMT by bus	--	--	--	--	--
4-Lane Freeway					
Miles of road	--	--	--	--	--
PMT by auto	--	--	--	--	--
PMT by bus	--	--	--	--	--
6-Lane Freeway					
Miles of road	--	--	--	--	--
PMT by auto	--	--	--	--	--
PMT by bus	--	--	--	--	--
8-Lane Freeway					
Miles of road	--	--	--	--	--
PMT by auto	--	--	--	--	--
PMT by bus	--	--	--	--	--
2-Track Rail					
Miles of track	--	--	--	--	--
PMT by train	--	--	--	--	--
Total PMT by Road	357,200	296,000	192,000	105,200	6,800
Total PMT by Bus	--	60,600	167,600	253,000	350,400
Actual % Auto Travel	100.00	83.01	53.39	29.37	1.90

Total PMT, all modes, in lesser direction = 333,400

Average Length of Trip = total PMT (both directions)/city pop.
= 690,600/64,000 = 10.79 miles

Table 14. Tabulation of peak one-directional flow characteristics for the homogeneous city.

	Percent Modal Split:				
	100-0	75-25	50-50	25-75	0-100
2-Lane Major Street					
Miles of road	64	64	204	544	544
PMT by auto	39,200	36,400	124,600	224,400	--
Mi. of bus rte.	--	8	204	544	544
PMT by bus	--	3,200	124,600	675,600	901,800
4-Lane Major Street					
Miles of road	328	480	340	--	--
PMT by auto	547,600	646,400	326,600	--	--
PMT by bus	--	214,800	326,600	--	--
4-Lane Expressway					
Miles of road	152	--	--	--	--
PMT by auto	315,000	--	--	--	--
PMT by bus	--	--	--	--	--
6-Lane Expressway					
Miles of road	--	--	--	--	--
PMT by auto	--	--	--	--	--
PMT by bus	--	--	--	--	--
4-Lane Freeway					
Miles of road	--	--	--	--	--
PMT by auto	--	--	--	--	--
PMT by bus	--	--	--	--	--
6-Lane Freeway					
Miles of road	--	--	--	--	--
PMT by auto	--	--	--	--	--
PMT by bus	--	--	--	--	--
8-Lane Freeway					
Miles of road	--	--	--	--	--
PMT by auto	--	--	--	--	--
PMT by bus	--	--	--	--	--
2-Track Rail					
Miles of track	--	--	--	--	--
PMT by train	--	--	--	--	--
Total PMT by Road	901,800	682,800	451,200	224,400	--
Total PMT by Bus	--	218,000	451,200	675,600	901,800
Actual % Auto Travel	100.00	75.80	50.00	24.93	0.00

Total PMT, all modes, in lesser direction = 391,200

Average Length of Trip = total PMT (both directions)/city pop.
= 1,293,000/98,000 = 13.19 miles

Table 15. Tabulation of peak one-directional flow characteristics for the ring city.

APPENDIX E--SAMPLE CALCULATION OF COSTS

In this appendix, the complete set of cost calculations is performed for the quasi-central city with a modal split of 25% private transportation and 75% public transportation.

1. Capital and maintenance costs

484 miles of 2-lane major street @ \$400,000/mile	=	\$193,600,000
48 miles of 4-lane major street @ \$600,000/mile	=	28,800,000
8 miles of 4-lane expressway @ \$800,000/mile	=	6,400,000
4 miles of 6-lane expressway @ \$1,100,000/mile	=	4,400,000
Total construction cost of roads	=	\$233,200,000

Capital recovery factor (CRF) for 5½% interest and 35 year life = .064975. Therefore, the annual construction cost of roads = .064975 x \$233,200,000 = \$15,152,000.

Annual maintenance cost of roads @ \$1,000/lane-mile = \$1,000 x (2 x 484 + 4 x 48 + 4 x 8 + 6 x 4) = \$1,216,000.

Therefore, \$15,152,000 + \$1,216,000 =

Total annual road cost = \$16,368,000

The flow diagrams are drawn only for the direction of heavier flow on each road. Therefore, to obtain two-direction PMT's (person-miles traveled) for any mode of transportation, multiply the one-direction PMT's by a proportionality constant <u>k</u>. This constant <u>k</u> will be equal to the total PMT for the city (both directions) divided by the total one-direction PMT. (The ratios between the different modes of travel are assumed constant for the two directions).

Since $\underline{k}$ = 1,296,200/924,600 = 1.402, the total PMT by bus = 1.402 x (442,600 + 166,600) = 1.402 x 609,200

= 854,000 person-miles on major streets

= 1.402 x 44,400 = 62,000 person-miles on expressways

Assuming maximum efficiency of bus scheduling (all buses always run at full capacity during the rush hour), the capacity of one bus operating on major streets (average speed of 15 miles per hour, including stops) = 50 persons per bus x 15 miles per hour = 750 person-miles per bus (for the one-hour time period).

Therefore, the required number of buses for the major streets = 854,000/750 = 1,140 buses.

And similarly, the required number of buses for the expressways = 62,000/(50x20) = 62 buses.

Therefore, the total number of buses required = 1,202 buses.

At a cost of $30,000 per bus, an interest rate of $5\frac{1}{2}$%, and a life of 12 years (CRF = .116029), the annual purchase cost of the buses = 1,202 x $30,000 x .116029 = $4,184,000.

Annual yard and shop costs @ $4,500 per bus (life of 40 years) = 1,202 x $4,500 x .062320 = $337,000.

Therefore, $4,184,000 + $337,000 =

Total annual bus cost = $4,521,000

Similarly, the total number of PMT's by rail will be equal to 1.402 x 33,600 = 47,000 person-miles.

And the required number of cars = 47,000/(80 persons per car x 35 miles per hour) = 17 cars.

At a cost of \$90,000 per car, an interest rate of $5\frac{1}{2}\%$, and a life of 30 years (CRF = .068805), the annual purchase cost of the cars = 17 x \$90,000 x .068805 = \$105,000.

Annual yard and shop costs @ \$8,000 per car (life of 50 years) = 17 x \$8,000 x .059061 = \$8,000.

For surface rail:

4 miles of track (complete way and structures) @ \$4,000,000 per mile = \$16,000,000.

4 stations (assuming one station per mile of track) @ \$500,000 per station = \$2,000,000.

Therefore, annual construction cost for track and stations (life of 50 years) = \$18,000,000 x .059061 = \$1,063,000.

For underground rail (subway):

4 miles of track @ \$17,500,000 per mile = \$70,000,000.

4 stations @ \$3,000,000 per station = \$12,000,000.

Therefore, annual construction cost for track and stations (life of 50 years) = \$82,000,000 x .059061 = \$4,843,000.

Therefore, \$105,000 + \$8,000 + \$1,063,000 =

Total annual surface rail cost = \$1,176,000

Or, alternatively, \$105,000 + \$8,000 + \$4,843,000 =

Total annual subway cost = \$4,956,000

Therefore, \$16,368,000 + \$4,521,000 + \$1,176,000 = Total annual capital & maint. cost (with surface rail) = \$22,065,000.

Or, alternatively, \$16,368,000 + \$4,521,000 + \$4,956,000 = Total annual capital & maint. cost (with subway) = \$25,845,000.

And $22,066,000/122,000 persons = Per capita capital and maintenance cost (with surface rail) = $180.86.

Or, alternatively, $25,845,000/122,000 persons = Per capita capital and maintenance cost (with subway) = $211.84.

2. Operating costs

(The factor k (= 1.402) is again applied to determine total two-direction PMT's).

1.402 x (155,800+55,600) person-miles traveled by auto on major streets @ $.059 per person-mile = $17,487.

1.402 x 26,000 person-miles by auto on expressways @ $.053 per person-mile = $1,932.

1.402 x 653,600 person-miles traveled by bus @ 50 persons per bus & $.50 per bus-mile = 1.402 x 653,600 x ($.50/50) = $9,163.

1.402 x 33,600 person-miles traveled by rail @ 80 persons per car & $.70 per car-mile = 1.402 x 33,600 x ($.70/80) = $412.

Therefore, $17,487 + $1,932 + $9,163 + $412 =

Total operating cost = $28,994

And $28,994/122,000 persons =

Average operating cost per traveler = 23.77¢

And 23.77¢/10.62 miles per traveler =

Average operating cost per mile = 2.24¢

3. Time costs

(Once again, the factor k (= 1.402) is applied to determine total two-direction PMT's).

1.402x211,400 PMT by auto on maj. st./25 mph = 11,855 pers-hrs

1.402x26,000 PMT by auto on exp'way/35 mph = 1,041 pers-hrs

1.402x609,200 PMT by bus on maj. st./15 mph = 56,940 pers-hrs

1.402x44,400 PMT by bus on exp'way/20 mph = 3,112 pers-hrs

1.402x33,600 PMT by rail transit/35 mph= 1,346 pers-hrs

Total traveling time = 74,294 person-hrs.

To compute the waiting time for bus transit, let:

PMT = number of person-miles traveled by bus (per hour)

N = number of persons traveling by bus (per hour)

L = total length of bus route, in miles

d = average trip length by bus, in miles (assume equal to average trip length by all modes, which is known)

q = avg. flow along bus route, in no. of persons (per hr.)

h = average headway, in hours

w = average waiting time, in hours

W = total waiting time, in person-hours

Then, for the one-hour time period:

$$h = (\text{number of buses per hour})^{-1} = (q/50 \text{ persons per bus})^{-1}$$

$$h = ((PMT/L)/50)^{-1} = 50L/PMT$$

$$w = h/2 = 25L/PMT$$

$$W = wN = (25L/PMT) \times (PMT/d)$$

$$W = 25L/d$$

This is a very interesting result, indicating that the total waiting time is dependent only upon the length of bus route and the average trip length, and is not dependent upon the number of person-miles traveled. In other words, for example, if the PMT on a particular length of bus route is increased (average trip length remaining the same), the number of buses required will increase, and the headway and, consequently, the average waiting time per person, will decrease. But since more people are now waiting for buses, the total waiting time will remain constant.

Since, in this example, $L \approx \underline{k} \times (436+48+8) = 1.402 \times 492 = 690$ miles, and d = 10.62 miles, the total waiting time for buses = 25 x 690/10.62 = 1,624 person-hours.
And similarly, for rail transit, W = 40L/d. And since $L \approx 1.402 \times 4 = 6$ miles, the total waiting time for trains = 40 x 6/10.62 = 23 person-hours.

Also, since it might be useful as a measure of the cost of control which will be required, the average headway for buses = $50L_B/PMT_B$ (in hours) = 60 minutes per hour x 50 persons per bus x $\underline{k}$ x 492 miles/$\underline{k}$ x 653,600 person-miles per hour = 3,000 x 492/653,600 = 2.26 minutes.
And the average headway for rail transit = 60 minutes per hour x 80 persons per car x $\underline{k}$ x 4 miles/$\underline{k}$ x 33,600 person-miles per hour = 4,800 x 4/33,600 = 0.571 minutes for each individual car. Assuming an average of four cars per train, the average headway for trains = 4 x 0.571 = 2.28 minutes.

Assuming that persons can enter the main transportation network only at the nodal points, or route intersections at one-mile spacings (this is not quite accurate in the case of autos traveling via major streets and possibly via expressways, but the error is a small one), some time is required

for traveling <u>to</u> the main transportation network. The average distance traveled for this purpose--assuming within each mile-square block, uniform density, all travel parallel to the grid, and entrance to the system at the nearest nodal point--will be one-half mile. The total preliminary traveling time to the system, then, assuming average pedestrian travel at 3 miles per hour and average automobile travel at 12 miles per hour on the minor streets, will be 25.68% x 122,000 persons x 0.5 miles/12 miles per hour = Preliminary traveling time for motorists = 1,305 person-hours.
And = 74.32% x 122,000 persons x 0.5 miles/3 miles per hour = Prelim. traveling time for transit riders = 15,112 person-hrs.

Therefore, 74,294 + 1,624 + 23 + 1,305 + 15,112 =

Total time for all journeys = 92,358 person-hours

And 92,358 person-hours/122,000 persons =

Average time of journey = 0.757 hours = 45.42 minutes

And 1,296,200 person-miles/92,358 person-hours =

Average speed of complete journey = 14.03 miles per hour