TRAFFIC ALLOCATION METHODS FOR USE
IN IMPACT FEE ASSESSMENT

by

THOMAS FRANCIS ROSSI

B.S. Civil Engineering,
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Submitted to the Department of Civil Engineering
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ABSTRACT

Many areas are experiencing increasing highway congestion resulting from rapid growth. The impact fee is becoming a popular method for financing the roadway improvements necessary to accommodate the increased traffic. These impact fees are charges to developers to pay for the roadway improvements made necessary by the construction of their developments.

This thesis examines the ways in which impact fees are assessed. Methods of allocating improvement costs to developments are analyzed. These methods require that the traffic increases on highways generated by new development be estimated. Traditional methods for traffic estimation are discussed. Problems with using these methods include that they do not provide a way to determine the traffic attributable to each development that treats all developments consistently.

Existing impact fee programs are reviewed next in the thesis. These programs experience the problem of determining consistent traffic allocations to developments. A case study shows that these problems, as well as the assumptions made during traffic estimation can significantly affect the cost allocations and fee assessments.

Several methods for overcoming the problem of determining consistent cost allocations are analyzed. The best method uses an entropy formulation to determine the most likely allocation of traffic among developments. The entropy method ensures that the most accurate transportation planning techniques can be used in a manner in which all developments are treated consistently. An example on a realistic urban network shows that the method can be used in practical settings.

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BIOGRAPHICAL NOTE

Thomas F. Rossi was born and raised in suburban Philadelphia, Pennsylvania. He received the Bachelor of Science degree in Civil Engineering in February 1981 from the Massachusetts Institute of Technology and is a candidate for the Bachelor of Science degree in Mathematics in February 1987.

Thomas was the Transportation Program Manager at the Merrimack Valley Planning Commission in Haverhill, Massachusetts and also worked for the Central Massachusetts Regional Planning Commission in Worcester, Massachusetts.

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I wish to express gratitude toward my family back in Philadelphia for their love and support. Last, but certainly not least, I dedicate this thesis to Lori, whose love has had a profoundly positive impact on my life.
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CHAPTER ONE
INTRODUCTION

The costs of construction, improvement, and maintenance of public highways have traditionally been borne by state, county, and municipal governments. Recently, rapidly rising costs coupled with much slower increases in available revenues have placed a heavy burden on jurisdictions responsible for highway improvements [13]. In response, government officials have begun to seek alternative means of financing highway improvements.

The problem of insufficient funding to maintain acceptable highway service levels has fallen hardest on areas experiencing high growth rates. Local and county officials in these areas—as well as some developers—have begun to realize that existing facilities such as roads, sewer systems, and schools are inadequate to handle the additional burdens placed on them by new development. This realization has led to increasing private participation in funding infrastructure improvements. One mechanism that is becoming more commonplace is the impact fee.
1.1 Background and Motivation

Impact fees are charges paid by developers that are used by counties or municipalities to help defray the costs of capital improvements made necessary by the new developments. These fees are currently being assessed in many areas throughout the United States [2,13]. Impact fees are usually determined by statute or ordinance and are used for both on-site and off-site development-related improvements. On-site improvements, generally specific to an individual development, may include parking facilities as well as access and on-site roadways. Off-site improvements that might be paid for by impact fees include capacity or safety improvements to roads and intersections not located on the development parcel that will be used by traffic generated by the development. These improvements may consist of roadway widening, signalization, channelization of traffic, etc.

1.1.1 Types of Impact Fees

Impact fees are generally classified as flat fees, variable fees, or negotiated fees. These three classifications are described in detail below.

Flat Fees - A flat fee is proportional to some measure of the development's size, such as square footage of floor space or the number of dwelling units, employees, parking spaces, or trips to and from the development. For example, the City of San Francisco in 1981 passed an ordinance requiring developers
of downtown office buildings to pay a one-time fee of $5 per square foot of floor space. The revenues collected from these fees are earmarked for public transportation improvements.

**Variable Fees** - A variable fee is directly related to the amount of traffic generated by the development that uses specific roads that are congested or are targeted for improvement. Thus two developments that are identical in every way except location could be charged different fees under a variable fee system, especially if one development is located in a more congested area. An example of a variable impact fee program is the Broward County (Florida) Land Development Code, which is described in Chapter 3 [2].

**Negotiated fees** - A negotiated fee is one determined by bargaining between the developer and the jurisdiction responsible for approving the development. For example, in Orange County, California, the Irvine Company has provided three freeway off-ramps, two parkways, a new interchange, and other traffic projects worth a total of $60 million in conjunction with the development of a 480 acre complex [15].

The main advantage of a flat fee is its predictability and ease of calculation. Because of these desirable characteristics, developers have generally been more willing to live with a flat fee assessment than a variable fee [13]. The major drawback of a flat fee is the lack of relationship between the fee and the impact it causes, that is, a "rational nexus" for
the fee [12]. For example, a flat fee earmarked for highway improvements would be the same for a development whether it was located in a congested area or next to an underutilized interchange on an uncongested freeway. Obviously, the impact of the development would be much greater in the congested area. Another disadvantage of the flat fee is that it fails to provide incentives for developers to include in their designs mitigating measures that would reduce the impacts of their developments (although developments with such measures could be credited). Such measures might include carpooling incentives or flexible work schedules.

The variable fee resolves the principal problem with the flat fee since the variable fee can vary depending on the characteristics of the development and its location. A specific relationship between the fee and the traffic impact of the development can be used in assessing the fee. The disadvantages of the variable fee are the difficulty in calculating the impact of a development—particularly when several developments impact the same area—and the unpredictability of the size of the fee for the developer. The traditional urban transportation planning process is typically used to determine the traffic impacts of developments. The nature of the distribution and assignment models used in this process results in the reliance of the calculated impacts (and thus the fees) on the assumptions made during the process. Thus the determi-
nation of the impacts can be ambiguous.

In an examination of bargaining between governments and developers in California, Kirlin and Kirlin [10] conclude that bargaining is the best available alternative for financing public works because it does not diminish private property rights and it is legally defensible. However, the bargaining process can be slow because of the number of actors involved, and the results may be dependent on political or other considerations [12]. Another potential problem with negotiated impact fees is that the revenue needed to implement the necessary improvements may not be collected in full.

1.1.2 Objectives in Setting Impact Fees

As a rule impact fee programs must fairly charge developers for impacts related to their developments so that those using the development derive benefits from the improvements that are made. Consequently, much care must be taken in designing impact fee programs, particularly with regard to improvements made necessary by more than one development.

Governments that collect impact fees may have several objectives in setting them. One such objective is covering the costs (attributable to developers) of the necessary improvements [12]. In other words, the revenues from the collected fees should, along with available public monies (for
example, gasoline tax revenues), be sufficient to implement the improvements. It should be pointed out that the amounts of flat and variable fees can be tailored so that this objective is met. Although a jurisdiction may have cost coverage as an objective of negotiation, there is no guarantee that a negotiated fee program will do so unless there is statutory backing for the objective.

A second important objective that jurisdictions may have in setting impact fees is consistency among fees charged to different developers and over time [12]. Negotiated fees cannot guarantee consistency. If consistency is measured in terms of the actual impacts of developments, then flat fees cannot guarantee consistent fees either. If two identical developments are constructed, one in a congested location and one in an uncongested area, they will be charged the same amount under a flat fee program even though the development in the congested area has far greater impacts. Variable impact fees can be used to ensure consistency among developments. It should be noted however, that some developers view consistency in terms of development size [13], preferring the predictability of flat fees.
1.1.3 Important Issues Concerning Impact Fees

There are several issues concerning impact fees that have not been thoroughly dealt with in the literature or in existing programs. These are summarized below.

**Legal Issues** - Some developers may regard the concept of impact fees as "legalized extortion" [13]. Impact fees have been challenged, but courts have generally upheld the legality of fees used to pay for improvements that can be related directly to the development's construction. This stipulation is similar to the objective of consistency among fees allocated to developments. The ease with which impact fees can be assessed, however, varies from state to state. Courts in some states have upheld impact fee programs while others have required specific enabling legislation in order to enact the programs [13,16].

**Administration of impact fee programs** - As a practical matter, an impact fee system must be administratively feasible and economical to administer. Even for the simplest impact fee system, there is a cost to the government agency administering it. These costs may include those for accounting, performance of necessary traffic analyses, and review of development plans. These costs must be funded either through collection of higher impact fees or through some other source. In general, jurisdictions with impact fee programs in use have been
willing to pay for their administration because of the need for revenues to pay for the improvements. Existing impact fee programs have been kept simple enough to be administratively feasible.

Social and Equity Incidence Issues (Who really pays?) - A social issue concerning impact fees is the issue of who actually pays for the improvement. For example, if an impact fee is charged for a housing development, the developer would be likely to pass the amount of the fee along to the home buyers in the form of a price increase rather than to pay for it out of his own profit. Thus although the developer actually pays the government the amount of the fee, it is the homeowners who actually pay it. While this may seem reasonable for the case of a housing development (since those living in the homes make the trips that cause the impacts on the highways), the issue becomes more complicated in the case of rental of development units, such as for a shopping center or an office park. The developer may pass along the cost of the impact fee to tenants in the form of increased rents, but the offices' employees or the shopping center's customers will be making the bulk of the trips. Those actually causing the impacts may be difficult to identify or charge. Most existing impact fee programs do not explicitly address incidence issues.
Another problem with impact fees that relates to incidence is that differences between different developments may lead to socially undesirable fees from the point of view of the consumer's "ability to pay." For example, under a flat fee system, the fee charged to a developer of a $50,000 home would be the same as that charged to a $150,000 home. (Under a variable fee system, the fee for the $50,000 home might be slightly lower because it could be expected to generate fewer trips than the more expensive home.) If the fees are passed on to the home buyer as expected, both buyers would pay the same additional amount. Not only would the price increase be much higher as a percentage for the $50,000 home, but the fee might put the home out of the price range of the buyer of the less expensive house.

Economic efficiency - Economic theorists believe that the most efficient form of fee system would be one in which each developer is charged for the "external cost" his development imposes on other highway users. This is equivalent to setting the fee equal to the short-run marginal cost (to the highway users) resulting from the development's construction. Unfortunately, the use of economically efficient fees will generally not ensure that costs are covered or that any revenue target can be met. Other problems with using economically efficient fees include the difficulties in calculating and administering such fees, the resultant
undesirable (from the perspective of other objectives) levels of development or traffic, and the conflict between efficiency and other objectives such as equity. These problems with economically efficient fees have in general precluded the use of such fees.

Demand induced or generated by improved highway facilities - Once a highway is improved, traffic demand will increase, particularly when capacity is increased significantly. It is impossible to measure the effects of induced demand by using solely traditional traffic distribution and assignment techniques. Furthermore, since the induced traffic will also benefit from the improved facility, if developers are charged for the entire cost of improvements, they will be charged for benefits not enjoyed by the developers or the users of the developments. Unfortunately, most existing impact fee programs ignore the issue of traffic generated by improvements.

Assumption of static development scenario - The development process in an area, even a small area, is constantly changing. The developments that create the need for a particular highway improvement may be constructed over a period of many years. The schedules for completion of various phases of development change over time, and the sizes and compositions of the developments may also be modified, perhaps radically. Some developments may be cancelled, or new developments may be planned.
The dynamic nature of the development process may pose substantial problems for the impact fee assessors. To determine the traffic impacts of a group of developments and necessary levels of improvement, particular levels of development must be assumed. A jurisdiction may wait until the actual construction of a development, when the specifics of the development are final, to determine the amount of an impact fee. This would pose problems, however, if the development were one of a set of projects that all affect a certain highway since (as will be shown later) the impact of the individual project may be different from its allocated share of the impacts of the entire group of developments. Determining the impact fee for each development individually amounts to an incremental allocation procedure, which is described in detail in the next chapter. Incremental procedures are widely used in existing impact fee programs.

Another argument against impact fees is that they may unfairly penalize a development that is "the straw that breaks the camel's back." That is, if traffic increases due to a development necessitate improvements on a highway, impact fees may be assessed on the development, but no fee is assessed on the existing traffic. If the impact fees are designed to cover costs, developers could be required to pay for the entire cost of improvements. In Newport Beach, California, for example, a development that would cause any signalized
intersection in the city to operate at over 90% of capacity must improve the intersection so that the volume/capacity (v/c) ratio is below 90% [13]. The developer must pay for the improvement with no contribution of public funds. Subsequent developments could then be constructed taking advantage of the additional capacity without having to pay to further improve the intersection (as long as the additional traffic did not once again raise the v/c ratio to 90%). While other impact fee programs may require developers to pay only for the share of additional capacity required by traffic generated by the development [2,14], public funds are seldom used to pay for the share of improvements that benefit existing traffic.

Developer responsibility for dual-ended trips - Under many impact fee programs, a developer is entirely responsible for any traffic increases resulting from the construction of his development. This, however, can lead to "double-counting" of trips made between two new developments. The previously cited Newport Beach ordinance [13] makes developers fully responsible for any new trips generated by their developments; thus the potential for double-counting exists. In contrast, to attempt to avoid double-counting, Broward County [2], for example, charges developers for only 50% of development-generated trips. This practice, however, means that the objective of fully covering costs can seldom be met. The "other end" of a development-generated trip may be at an
existing trip generator or a generator located outside the 
jurisdiction of the locality administering the impact fee. The issue of whether a development is responsible for each 
entire trip it generates or only half of each trip, even when 
the generator at the other end of the trip cannot practically 
be charged an impact fee, remains unresolved.

Ambiguities resulting from assumptions of traditional trip 
distribution and assignment models - To determine a develop-
ment's share of responsibility for a necessary highway 
improvement, the number of trips using the facility from each 
development must be known. Unfortunately, the most accurate 
traffic assignment methods cannot unambiguously allocate trips 
among various developments [18]. This problem results from 
the nonuniqueness of path flows for an origin-destination pair 
in these methods. Many existing programs get around this 
problem by using incremental cost and traffic allocation meth-
ods and alternate traffic assignment methods. This problem is 
the focus of this thesis and is discussed in greater detail 
below.

Although impact fees are growing in popularity, many of 
these issues have not been addressed despite their potentially 
substantial effect on the amounts of fees. It is important 
that future research efforts into impact fees address these 
issues.
1.2 Thesis Objective

The major focus of this thesis is to address the problems associated with the allocation of highway improvement costs to ensure equitable impact fees among a group of developments affecting the same facility. It is assumed that a variable impact fee program is necessary to achieve the goals of cost coverage and consistency among developments. It will be assumed that the other issues mentioned above are satisfactorily addressed as part of the impact fee program.

As stated above, traditional traffic assignment techniques do not provide enough information to determine an equitable allocation of the traffic on a highway section among developments. The major objective of the thesis is to develop a method for determining such an allocation and to show how it can be used in a realistic application. Secondary objectives of the thesis include determining the variations that occur among different assumptions concerning the cost allocation and traffic assignment processes, and the testing of alternative methods for dealing with this problem.
1.3 Research Approach

The thesis describes existing cost allocation and traffic estimation techniques and explains the characteristics of these techniques that prevent them from determining consistent allocations to developments. Existing impact fee systems are examined in terms of whether they have this problem and how they deal with it. Several methods to overcome the problem are examined and analyzed. One technique, which uses an entropy formulation, is recommended because of its accuracy and practicality. This method finds the "most likely" allocation of the trips made on the link among the developments. The thesis develops the method and demonstrates its use on a sample problem of a real urban area.

1.4 Thesis Structure

The thesis is organized as follows: Chapter 2 provides information on methods for allocating costs among developments using traffic estimates for the affected highways. This chapter also details traditional methods for traffic estimation that can be used to provide the projections for the highways of interest. Chapter 3 describes in detail two existing impact fee programs that demonstrate many of the advantages and drawbacks associated with the concept. Several other programs are also summarized in Chapter 3. In Chapter 4 an empirical study using an actual community demonstrates that the use of traditional techniques can cause significant varia-
tions in the allocations of traffic and costs in practice.
Chapter 5 discusses several methods that can be used to over-
come the problem of allocating traffic among developments and
presents the recommended "maximum likelihood" method. An
example of the maximum likelihood method used on a realistic
urban highway network is presented in Chapter 6. Chapter 7
summarizes and presents the conclusions of the thesis.
Several important objectives of impact fee programs were discussed in Chapter 1, including that impact fees should fairly charge developers for the impacts that their developments cause and that the fees collected should meet a revenue target, perhaps the costs of highway improvements to be made. The former objective may need to be satisfied for the impact fee program to be legally binding on developers.

The objectives mentioned above are similar to those a government jurisdiction might have in assessing highway user charges to various user classes. These charges might take the form of tolls or other user fees such as taxes. The methods used to determine the amounts that each user class will be assessed are known as highway cost allocation procedures.

One of the difficulties in setting impact fees is the problem of how to allocate the costs of improving a highway among several developments whose traffic impacts the highway. One suggested method for doing this is the use of highway cost allocation procedures [12]. Highway cost allocation procedures can be applied to impact fee assessment by defining each vehicle (user) class as the traffic generated by a single
development.

In traditional highway cost allocation, the traffic levels for each vehicle class are assumed known or estimated. For example, on a toll road, the amount of traffic using the road in the previous year may be used to determine the next year's traffic levels along with appropriate growth factors. This process is not as simple for the case of developments that have not yet been constructed. Traditional urban transportation planning techniques are one method for providing estimates of traffic generated by future development.

This chapter describes some common highway cost allocation methods and discusses how they may be used to determine impact fee charges. Also included in this chapter is a presentation of traditional techniques for determining the amount of traffic generated on individual highways under different development scenarios. These methods can be used to provide the traffic volume information necessary to use the cost allocation methods in the determination of impact fees. Some of the problems and limitations associated with the use of these techniques are discussed as well.
2.1 Highway Cost Allocation Methods

Three common highway cost allocation methods are incremental allocation, proportional allocation, and the uniform removal method. These methods are described briefly below.

2.1.1 Incremental Allocation

This method sequentially introduces (or removes) vehicle classes from the total traffic stream. As each class is introduced, the traffic and impacts of the class are determined, and the necessary costs are determined. Any additional costs that have been incurred since the introduction of the previous vehicle class are allocated to the current vehicle class. The procedure continues until all costs have been allocated.

An advantage of using the incremental allocation method to determine impact fee assessments is that it can be easily performed using urban transportation planning methods as is described later in this chapter. The major drawback to incremental allocation is that the ordering of the vehicle classes affects the cost allocation results. To illustrate this problem, consider the use of incremental allocation to determine impact fees to be paid by two developments to improve a certain road. Say the two developments each generate 800 vehicle trips on the road and that before the developments the road has an excess capacity of 1000 vehicles. Under the incrementa-
tal cost allocation procedure, the first development to be considered would not be allocated any costs; there would be no need to improve the road as 200 vehicles of excess capacity would still exist. The second development, however, would be allocated the cost of improving the road since the additional 800 vehicles would put the road over capacity. Obviously, reversing the order in which the developments are considered would reverse the results; the costs would be allocated to the first development. In this case neither result is desirable; the objective of consistency between the costs allocated to the two developments would require that costs be allocated equally between the two developments.

It should be pointed out that incremental allocation can refer to either the allocation of costs as in the above example or allocation of traffic. The latter method is described later in this chapter as traffic assignment procedures are discussed.

2.1.2 Proportional Allocation

In this method costs are allocated to each vehicle class in proportion to its use. The use of a facility can be measured in appropriate terms for the allocation problem (e.g. traffic volume, passenger-car or single axle load equivalents, vehicle weight). For use in determining impact fees, use would be defined in terms of traffic volume in vehicles or
The concept of proportional allocation is appealing because of its inherent fairness; developments are responsible for their own shares of the traffic increase. It overcomes the problem of ordering the vehicle classes (unless they are arbitrarily ordered in the traffic assignment process) and thus insures consistency among developments. The disadvantage of this method is that the volumes attributable to each developer cannot be measured solely using traditional transportation techniques unless the developments are arbitrarily ordered in the assignment process. This fact will be demonstrated later in this chapter.

2.1.3 Uniform Traffic Removal

This method was introduced in the Federal Highway Cost Allocation Study [4] and is described in detail by Hendrickson and Kane [6]. It is based on a cost function which, in the case of impact fee assessment, relates the cost of improving a facility to the traffic generated by developments using the improvement. The uniform removal technique uniquely satisfies four properties [6]:

--the sum of costs allocated to each development equals the total cost to be allocated. This property corresponds to the objective of covering improvement costs.
Note that the total cost can be defined as something other than total construction costs; for instance, it can account for user costs, the "double-counting" problem, etc.

--costs allocated to any development are nonnegative.
--the cost allocation procedure is additive. This property means that if a development is redefined as two smaller developments whose total size equals that of the original development, the total costs allocated to the new developments equal the cost that would have been allocated to the original.
--cost allocation is consistent; developments that are identical in their effect on costs are allocated costs in proportion to their use of the facility. This property corresponds to the objective of consistent fee assessment among developments.

The uniform traffic removal method is derived as follows. Let \( \mathbf{x} = (x_1, \ldots, x_n) \) be the vector of traffic generated by each of \( n \) development sites, where \( x_i \) is the traffic generated by development \( i \). Let \( f(\mathbf{x}) \) be the cost function associated with \( \mathbf{x} \) where \( f(\mathbf{0}) = 0 \). It is assumed that the cost function is continuous and has a nonnegative first derivative, i.e. \( \frac{\partial f}{\partial x_i} \geq 0 \). The cost function may in reality be a step function for roadway improvements since capacity is added by lane and not on a continuous basis. A suitable approximation such
as a logistic curve may be used to ensure that the restrictions on \( f(x) \) are satisfied.

The uniform removal method is applied by simultaneously removing equal portions of each development's traffic from the total traffic stream \( x \) until all costs are attributed. The allocation to development \( i \) is given by [6]:

\[
c_i(x) = x_i \int_0^1 f(t \cdot x_1, \ldots, t \cdot x_n) \, dt
\]

Since a vehicle has the same effect on improvement costs regardless of which development it is generated by, it can be shown that, for a single project:

\[
c_i(x) = f(x) \left( \frac{x_i}{x_t} \right)
\]

where \( x_t = \sum_{i=1}^{n} x_i \)

In other words, for the impact fee assessment problem, the uniform removal technique is equivalent to a proportional allocation.

2.2 Traffic Determination Methods

Regardless of the cost allocation method used, a method of determining traffic levels on individual highway segments is needed to determine variable impact fee assessments based on traffic. This method must be able to estimate traffic lev-
els for any given development scenario. Traditionally, such estimation is performed using urban transportation planning techniques.

The traditional urban transportation planning approach consists of a four-step process: trip generation, trip distribution, mode choice, and traffic assignment [19]. The process is carried out by dividing the study area into analysis zones and modeling the highway system as a network. The analysis zones are generally subareas of relatively homogeneous tripmaking activity. Zone centroids are highway network nodes that serve as the origins and destinations of trips generated in the individual zones.

Trip generation is the process of estimating the number of trips that begin or end within each zone. This procedure is usually accomplished through the use of generalized rates per unit of various types of development (retail, housing, industrial, etc.) [7,19]. Trip distribution consists of determining the origins and destinations of the trips identified during trip generation. The result is a trip table containing the number of trips from each origin zone to each destination. Common distribution methods include estimation from survey data and the gravity model. The gravity model distributes trips based on a formula that predicts that the number of trips between two zones is proportional to the num-

-34-
ber of trips generated in the zones and inversely related to the travel time between them. Mode choice refers to the estimation of the number of trips for each origin-destination pair that use each of the available transportation modes (private automobile, bus, carpool, etc.).

In traffic assignment the routes taken by trips specified in the trip table (primarily automobile trips) are determined. If proportional allocation is used, two trip tables are assigned: the base trip table (no development) and the total trip table, including trips generated by all new developments. The difference in traffic on a given road between the two assignments is the traffic generated by the new developments; it is this traffic that is allocated proportionally among the developments. The difficulties in doing this under certain assignment assumptions are described later in this section.

In incremental allocation, trip tables are sequentially created during trip distribution beginning with the base trip table, with each successive table adding the trips to and from an additional development until all developments have been added. Under incremental cost allocation the costs of improvements made necessary on a highway by the additional traffic assigned when a development is added are allocated to that development. Under incremental traffic allocation the difference in traffic between the assignments before and after
a development is added is allocated to the development; total costs are then allocated to each development proportionately to the traffic allocated to it. As mentioned in the above discussion of incremental allocation, the ordering of the developments affects the allocations to the developments.

Two proposed allocation methods that use the concept of incremental allocation but avoid the problem of ordering the developments are referred to as the "addition method" and the "subtraction method." In the addition method, a trip table is constructed for each development including only base trips plus trips generated by that development. The differences in the traffic volumes assigned from the new trip table and the base trip table are allocated to the development. In the subtraction method, the trip table constructed for each development includes trips to all developments except that development; the allocated traffic is the difference between the new trip table and the total trip table. To ensure that costs are covered, the volumes for each development can be factored so that the sum of the volumes on each link attributable to the developments equals the difference between the volumes obtained by assigning the base trip table and the total trip table. However, while the addition and subtraction methods are not order-dependent, they do not necessarily yield consistent results as is shown in Chapter 5.
Some common traffic assignment methods are described below:

**All-or-Nothing** - In this method the shortest paths between each pair of zone centroids are found based on the travel times for the links in the network. These travel times may be estimated, free-flow times, or obtained from field observations. The trips between each origin and destination are then assigned to each link on the calculated path.

**Incremental Capacity Restraint** - First, the number of iterations and the percentage of total traffic to be assigned during each iteration are determined. For example, four iterations could be performed with 40% of the traffic being assigned on the first iteration, 30% on the second, 20% on the third, and 10% on the fourth. The free-flow travel time on each link is then calculated. The next step is to find the shortest paths between each pair containing an origin and destination zone, as in the all-or-nothing assignment. For each origin-destination pair, the percentage of trips to be assigned during the current iteration between the origin and destination is added to the volumes of the links on the calculated path between them. Then, using link performance functions, the link travel times are recalculated based on the volumes assigned so far. These travel times are used in the next iteration to find the shortest paths. The process
of recalculating link travel times, finding "shortest" paths, and assigning traffic is continued until all traffic has been assigned.

Iterative Capacity Restraint - This assignment procedure is similar to the incremental capacity restraint assignment except that all traffic is assigned during each iteration. The result is a series of all-or-nothing assignments with updated travel times that can be continued until a desired number of iterations is completed or some convergence criterion has been met. The concept is that the travel times should eventually converge to approximate equilibrium travel times with an all-or-nothing assignment performed with these more accurate times.

Equilibrium Assignment - An equilibrium assignment is one in which no commuter can improve his own travel time by changing routes and thus has no incentive to do so [18]. This concept is complicated by the fact that as more vehicles use a highway, the more congested it becomes and the higher the travel time along it. Equilibrium assignment uses link performance functions to relate travel time on a link to the volume using it. The equilibrium assignment is performed by solving a nonlinear optimization; the most common method for doing this is the Frank-Wolfe "convex combinations" algorithm [5].
In an equilibrium assignment an increase in the number of trips to be assigned between two zones would result in an increase in traffic along all routes used to travel between the two zones (and possibly the introduction of travel along other routes). An important characteristic of equilibrium assignment is that while the link volumes obtained for a given trip table and set of link performance functions are unique, the path volumes for each route taken between any origin and destination are not [18]. While equilibrium assignment is a preferred assignment technique, it has some drawbacks, notably that the effects of junction congestion and delay are not modeled [9].

Historically, equilibrium assignment over large networks with many zones has been cumbersome, even when using efficient computer programs. Thus many other assignment techniques have been used in practice, with the result of less accurate modeled traffic volumes. Some of these techniques—for example, capacity restraint techniques—are intended to approximate equilibrium conditions while others (e.g. all-or-nothing assignment) are simply attempts to substantially decrease the amount of computation in and to simplify the assignment process. The simpler methods are in more widespread use than equilibrium assignment because of compatibility with past modeling efforts and the variety of available computer software.
The urban transportation planning procedure can easily be applied to the estimation of traffic volumes generated by developments [3]. First existing conditions are modeled. When the model has been calibrated—that is, when it simulates existing traffic conditions fairly accurately—the assignment procedure can be applied to a future trip table containing the additional trips generated by new developments. Thus the link volumes resulting from the developments can be identified. This assignment could also be used as a basis for determining where future highway improvements may be needed.

When there is more than one development under consideration, the volumes attributable to each individual development must be known in order to assess impact fees. In this case, however, equilibrium assignment does not provide this information. As previously mentioned, although the volume assigned to each link under equilibrium assignment is unique, path volumes between individual origins and destinations are not. To illustrate this property, consider the network shown in Figure 2-1.

Sample Network 1 consists of a simple four-node network where two nodes (A and B) represent developments (origins) and one node (D) a destination. Assume for now that links 1 and 2 are equivalent in terms of length and capacity. Assume that
Figure 2-1
Sample Network 1
there is a demand of 200 vehicles between A and D and 200 vehicles between B and D. Equilibrium assignment would result in volumes of 200 on both Link 1 and Link 2. However, the path volumes are unknown. For example, the 200 vehicles on Link 1 could be all from Node A, all from Node B, or some from each origin. While in this simple network it is easy to determine the allocation that is consistent among the developments (100 vehicles on each link from each origin), it would be extremely difficult to do so for a realistic network with hundreds of nodes and links.

Equilibrium assignment cannot identify the origin and destination zones of individual vehicles using a link. This is not the case with all-or-nothing assignment since there is only one path for each origin-destination pair. Similarly, when using equilibrium approximation techniques that are iterative and use series of all-or-nothing assignments (e.g. capacity restraint), the origins and destinations of traffic along a link can be identified. These techniques, however, are inferior to equilibrium assignment in terms of the accuracy of modeled volumes.

2.3 Summary

Highway cost allocation methods can be used to devise impact fee programs that meet the objectives of assessing costs consistently among developments and meeting a revenue...
target. The incremental allocation method does not guarantee consistency, but the proportional and uniform removal allocation methods, which are equivalent for the case of impact fee assessment, do provide consistent allocations among developments.

To assess impact fees using the proportional or uniform removal allocation methods, the projected traffic attributable to each development must be known. This is traditionally determined through the use of urban transportation planning techniques, which consist of trip generation, trip distribution, mode choice, and traffic assignment. The choice of trip distribution and assignment methods may affect the allocations to individual developments. The preferred method for traffic assignment is equilibrium assignment.

Equilibrium assignment can be used to provide estimates of the total traffic generated on any given highway by a group of developments. Due to the nonuniqueness of path volumes, traditional equilibrium assignment is incapable of providing the information necessary to determine the traffic generated by any individual development within the group. Thus a need exists to develop a technique for determining vehicle origins and destinations from an equilibrium assignment.
The next chapter describes some existing impact fee programs and discusses how they deal with some of the aforementioned problems. Chapter 4 presents an empirical study of the effects of different assignment and distribution techniques that supports the statements made in this chapter about their effect on cost allocations. Methods that attempt to solve some of the problems described above are described in Chapter 5.
Chapter 2 introduced some of the well-known highway cost allocation methods as well as the traditional transportation planning techniques that can be used in determining impact fees. Also described were some of the problems associated with the use of these techniques. In this chapter some of the existing impact fee programs are described. Some programs use some of the methods described in the last chapter and have some of the corresponding problems.

3.1 Existing Impact Fee Applications

Impact fees have been used for several years. There are many current examples of all types of impact fee programs. Two of these are described in detail below while others are briefly summarized. These examples are chosen to demonstrate specific types of programs and to point out some of the problems and drawbacks to using impact fees.

3.1.1 Broward County TRIPS Model

The TRIPS (Traffic Review and Impact Planning System) model [2] was developed by the Broward County (Florida) Office of Planning and its consultants. The model was developed to enforce the county's Land Development Code, which mandates the adequacy of public facilities prior to the issuance of devel-
Development orders. The TRIPS model consists of three steps—trip generation, trip distribution, and traffic assignment—corresponding to the traditional urban transportation planning procedure described in Chapter 2. (Mode choice is accounted for by generating only automobile trips.)

The trip generation step consists of determining, for a given development, the number of new automobile trips that will be generated. Trip distribution is done among "centers of influence" (corresponding to analysis zones) through the use of a gravity model. Traffic assignment is performed though the all-or-nothing method for the development-generated trips; base traffic, which includes traffic generated by previously approved developments, is not reassigned. Thus it is easy to determine the additional traffic on each highway link that can be attributed to the development.

The additional traffic on a link is multiplied by a factor of 0.43 to obtain the traffic attributable to the development. This factor results from a 14% decrease to account for the relatively coarse highway network used (recognizing that some traffic would use roads not on the network) and a 50% reduction to eliminate the "double-counting" problem described in Chapter 1.
An interesting aspect of the Broward County procedure is the way the impact fees are assessed. The county's Regional Transportation Plan contains a listing of proposed highway improvements, generally capacity-increasing projects. If the additional traffic attributed to a development causes a highway slated for improvement to operate at an unacceptable level of service (or adds more traffic to a road that will operate unacceptably due to previously approved developments), an impact fee is assessed. The amount of the fee corresponds to the percentage of the total capacity increase provided by the improvement that is used by traffic attributed to the development. The fee paid by the developer is put into a fund that will eventually be used to pay for the improvement when it is constructed.

A simplified example illustrates how the TRIPS model works. Assume that a certain proposed development will cause an increase of 500 vehicles per day (vpd) on a highway, according to the TRIPS model. Assume further that there is a proposal on the Regional Transportation Plan to widen the road to increase its capacity from 16,000 vpd to 36,000 vpd also assume that current traffic is 12,000 vpd while additional traffic from previously approved developments totals 4000 vpd. (Assume that a volume/capacity ration of less than 1.0 is considered acceptable for this highway.) The cost of the proposed improvement is $1,000,000. Thus the cost of the
improvement on a per vehicle of capacity basis is $1,000,000 + (36,000 - 16,000) or $50. Since the highway's base volume is equal to its capacity, the additional trips attributed to the development will be in excess of existing capacity. Thus the developer is assessed for 500 x 0.43 = 215 trips at $50 per trip for a total of $10,750.

There are several drawbacks to the TRIPS model that might make it unsuitable in some jurisdictions. Since some development-generated trips may have one end at an existing trip generator or outside Broward County, the other 50% of the cost of the trip might never be collected. Since some trips will undoubtedly fall into this category, the costs of improvements will not be covered. The problem of responsibility for externally generated trips, however, is not as great when fees are assessed on a countywide rather than on a smaller (e.g. municipal) level. A second potential problem is the inconsistency of the allocations over time. For example, a development larger than the one in the example above could have been charged no fee if it were one of the "previously approved" developments contributing to the 4000 trips per day above current traffic. This is the result of an incremental cost allocation where the developments are ordered chronologically by the times of their approvals.
There are some characteristics of the TRIPS model that could cause some errors in the traffic impacts attributed to developments. For example, the all-or-nothing assignment procedure limits the number of links for which a development can be charged an impact fee. Only those links that lie along the shortest paths from the development to the other "centers of influence" will have new traffic assigned to them. Furthermore, traffic along many of these links will be understated if in fact the traffic generated by the development uses paths other than the shortest paths. The errors resulting from the traffic assignment will be small for developments that generate small amounts of traffic. They could be significant, however, for large developments or when nearby approved developments have had significant volumes already assigned to links along the shortest paths to other "centers of influence." This problem is the result of a tradeoff between the savings in computation time—which is substantial for a large network such as Broward County's—associated with all-or-nothing assignment and the greater accuracy of equilibrium or equilibrium approximation assignment techniques. The errors are assumed to be minor for the large network due to the relatively small volumes generated by developments relative to the larger base volumes already on the network.

In general, Broward County officials feel that the impact fee ordinance and the TRIPS model are working well [20].
Since the implementation of the TRIPS model, there have been no legal challenges to the fees by developers, and the fees collected have been used to help pay for needed roadway improvements.

3.1.2 Newport Beach Ordinance

The City of Newport Beach, California passed an ordinance requiring developers to make improvements at any signalized intersection that would operate at over 90% of capacity if the development were constructed [13]. The developer is required to conduct a traffic analysis—which is reviewed by the city traffic engineer—and to construct any improvements necessary to reduce the intersection's volume/capacity ratio to 90% or lower. (The method of traffic analysis is left to the developer and is subject to review by the city engineer.) If the intersection is already operating at more than 90% of capacity, the developer is required to improve the intersection to its existing level of operation prior to development. Compliance with the ordinance is necessary in order for the development to obtain necessary building and occupancy permits.

Since the developer is responsible for conducting the necessary traffic analysis, there is no single distribution or assignment technique used. This could lead to inconsistencies among the methods used to determine traffic impacts although
the municipal review of the traffic studies should somewhat alleviate this concern. It should be noted that only major intersections are analyzed. Any method of sharing improvement costs among a group of developers of costs attributable to all of them is solely up to the developers themselves [21].

The Newport Beach ordinance differs from Broward County's in several ways. First, the Newport Beach ordinance is only a municipal ordinance, meaning that neither a development's impacts outside the city nor the impacts in Newport Beach of a development located outside the city are included. These external impacts are more likely to be significant in a small city than in a larger geographic area like an entire county.

Another major difference between the two ordinances is that under the Newport Beach ordinance the developers are responsible for making the improvements themselves rather than contributing a portion of their costs. Thus no fees are collected by the city, and the developer has an incentive to construct the improvements as cost-efficiently as possible. A third difference between the ordinances is that the Newport Beach ordinance is set up so that the development dictates the nature of the improvements, while Broward County's Regional Transportation Plan dictates the improvements for which developers are to be assessed.
Finally, Newport Beach charges developers for the entire traffic impacts of their developments while Broward County charges developers only for half of each new trip. In other words, in Newport Beach the development is responsible for all new trips generated regardless of the locations of the other ends of the trips. This means that the double-counting problem is not addressed and that it is possible for intersection improvements to be overdesigned. On the other hand, covering the costs of making the needed improvements is ensured.

Newport Beach officials are generally pleased with the ordinance and feel that it is working well. Eighteen intersections had been improved through 1985 by developers because of the ordinance [21]. Although some developers have complained about making roadway improvements, they must accept the provisions of the ordinance if they desire to build in Newport Beach.

3.1.3 Other Impact Fee Programs

There are many other impact fee programs being used throughout the United States. Some of the more interesting are briefly described below.

Palm Beach County, Florida [22] - Under this system, forty impact zones are defined within the county. New developments within any one of these zones are assessed a flat fee based on
the number of trips they are expected to generate at the time the building permit for the development is issued. The collected fees are placed into a fund used for traffic improvements on the major roads and bridges located within the zone. Developers may also make road improvements themselves, the costs of which are credited against the impact fee.

Impact fees are calculated from the following formulae:

\[
\text{Residential fees} = \frac{1}{2} \times \frac{\text{external trips}}{\text{capacity of one lane}} \times \text{(Cost to construct one lane for three miles)}
\]
\[
\text{Nonresidential fees} = \frac{1}{2} \times \frac{\text{external trips}}{\text{capacity of one lane}} \times \text{(Cost to construct one lane for one mile)}
\]

In these formulae, "external" trips refer to trips that leave the development site. Residential developments are charged a greater fee per trip because it is assumed that more of the trips generated by nonresidential developments are captured from traffic already using the major highway system.

The fees charged by Palm Beach County are classified as flat fees since they are based solely on the size of the development as measured by the number of trips it generates. The fees do not account for the fact that the traffic impacts of developments may vary by their locations. The impact zones, which are roughly six-mile radius circles, are used in an attempt to ensure that the developer paying the fee receives a benefit in the form of improved highways.
The major advantages of the Palm Beach County system are the ease of the fee calculation and the predictability for the developer. Developers, in fact, have been quoted as preferring the Palm Beach system to that in neighboring Broward County because of its predictability. The problem with the approach is that it is a flat fee system and that the fee is not directly tied to the actual impact of the development. Even the use of the impact zones does not address this concern since the fee is constant for a development regardless of whether it is located in a zone needing many or few highway improvements or where within the hundred square mile zone it is situated.

**Orange County, California** - Orange County levies fees on developments in order to finance new freeway construction [15]. Corridors were defined corresponding to three new freeways that are to be built, and all new developments within these corridors are charged impact fees. The fees are proportional to the amount of traffic generated, and they are designed so as to yield over 60% of the constructions costs of the new freeways.

The Orange County system is similar to Palm Beach's in that impact zones—in this case corridors—are used to relate the fee to benefits to be enjoyed by the developers. Fees collected can be used only to pay for freeway construction in
the corridor in which the development is located. The advantages and disadvantages of both systems are therefore similar. The major difference between the two programs is that the revenues from the Orange County system are used to finance new highway construction as opposed to improving existing roads.

Hudson, New Hampshire - The Town of Hudson, New Hampshire and its consultant have developed an impact fee program that uses transportation planning procedures and the proportional allocation method [14]. The system predetermines the cost of improving each major intersection and highway link along the corridor experiencing the greatest traffic congestion. This is similar to Broward County's system in that the fees are used to pay for a previously approved set of highway improvement projects.

The Hudson impact fee system allocates only a portion of the total improvement costs to new developments. The proportion of the capacity of the highway or intersection (after improvement) that is not used by existing traffic is calculated (referred to as available reserve capacity), and this fraction of the improvement cost is not allocated to new developments. This is done to account for the benefits of the highway improvement that are received by existing highway users.
The impact fee that a developer is charged is calculated as follows:

1) The percentage of improvement costs to be allocated to new developments is calculated for each highway link and intersection in the corridor.

2) Determine for the development the amount of traffic it will generate on each highway link and at each intersection in the corridor (expressed as a fraction of the available reserve capacity). This requires a traffic assignment of development-generated trips to the corridor. Developers may reduce their traffic impacts by adopting demand reduction strategies (ridesharing, etc.).

3) Allocate costs for each link and intersection based on the fraction calculated in 2) applied to the portion of improvement costs to be allocated to new developments.

4) Any unused portion of reserve capacity will result in that portion of costs being borne by the state or municipal government.

The corridor highway network consists of a single highway with roads branching off at intersections. Hence the network is a tree, and there is only one path between the development site and any other origin or destination node on the network.
The resulting assignment using any technique will be all-or-nothing. Fees are allocated proportionally to the traffic on each network component and are consistent among developments since traffic allocations are the same regardless of when a development is added (unless it is added after the improvements are made).

The advantages of Hudson's impact fee program include its ease of application and its consistent treatment of developments. There are drawbacks to the system, including:

-- while the needs of the corridor are the most pressing in Hudson, the effects of induced traffic from the improvements or of traffic diversions to other routes due to congestion are not considered. This is a result of the tree network where no alternative paths for trips to and from a development site or for through traffic are considered.

-- although the traffic assignment method used is irrelevant to the amount of fees, the trip distribution method can have a significant effect on the cost allocation (as will be demonstrated in Chapter 4). No single trip distribution technique is specified.

-- no timetable for improvements is specified in the program. Fees collected from developers may sit in government accounts for many years before they are used.
-- no statutory authority exists for the town to collect impact fees. Currently the town uses the leverage of the building permit for the development to ensure that the developer pays the fee. Statutory authority for impact fees in New Hampshire on a local option basis may come in the near future.

3.2 Summary

This chapter has described two well-known impact fee ordinances and some of the advantages and problems with the two approaches. The Broward County ordinance requires developers to submit development plans to the county planning office for analysis of the traffic impacts of the development. Its advantages are the use of a well-tested technical model and its relative ease of use for impact fee determination. Drawbacks include the potential for improvement costs not being covered by the fees collected and possible inconsistencies among fees charged to different developers due to the incremental nature of the cost allocation method used and the use of all-or-nothing assignment for development-generated trips.

The Newport Beach ordinance requires each developer to provide a traffic analysis showing the effect of his development on the city's major intersections. If the development's construction causes any intersection to operate at an unac-
ceptable level of service, the developer is required to improve the intersection before the development is permitted to open. Advantages include that the costs of all improvements are covered by the developers and that the needed improvements must be made. Disadvantages include the lack of provision for impacts on roads other than those on the pre-specified list of major intersections, the lack of consideration of external impacts (outside the city), the potential for double-counting generated trips and thus overdesigning an intersection, and the potential for inconsistency among the traffic analyses for different developments.

Other impact fee programs reviewed in this chapter are administered in Palm Beach County, Florida, Orange County, California, and Hudson, New Hampshire. The former two are flat fee programs and thus do not relate the fee charged to the actual impact of the development.

This chapter focused on potential problems that could theoretically occur with existing impact fee systems. Chapter 4 presents a case study that provides empirical evidence that some of these problems, as well as those described in Chapters 1 and 2, can happen in practice.
CHAPTER FOUR

ILLUSTRATION OF THE SENSITIVITY OF IMPACT FEES TO TRAFFIC MODELING ASSUMPTIONS

As described in Chapter 2, there are many problems associated with some of the cost allocation and traffic assignment methods used in impact fee determination. These include:

Cost Allocation Methods:

--**Incremental Allocation** - ordering the developments causes inconsistencies among the allocations of traffic among developments.

--**Proportional Allocation** - traffic cannot be allocated simply by running a series of assignments on different trip tables associated with the various development scenarios.

Assignment Techniques:

--**All-or-Nothing Assignment** - traffic is assigned to only one path for each origin-destination pair, yielding an inaccurate assignment if any congestion is present.
--Capacity Restraint Assignment (Incremental or Iterative) - more accurate than all-or-nothing assignment, but still an approximation. Increased accuracy comes only at the cost of increased computational time.

--Equilibrium Assignment - provides accurate assignment, but the characteristic of nonunique path flows leaves no method of determining origin or destination zones of traffic on a road. Thus no unambiguous method for determining traffic allocation to developments is provided.

To illustrate the effects of these problems, a case study was performed on an actual urban highway network. This study was performed to:

--compare the traffic allocations among different assignment and distribution assumptions and thus illustrate the sensitivity of impact fees to these assumptions.

--illustrate the problems associated with incremental allocation.

--demonstrate the effects of using equilibrium approximation techniques.
4.1 Case Study Description

A community in New Jersey was chosen for analysis in the case study. This suburban community in the New York metropolitan area is experiencing rapid office and residential development. Several roads, including the interstate highway passing through the town, are operating near capacity, and six proposed developments totaling two million square feet of new office space in the next few years are expected to greatly exacerbate the congestion. The increased traffic would require major roadway improvements, including widening of the interstate, to ensure acceptable levels of service.

A traffic study done for the town by an engineering consultant was used to provide information needed to perform the three-step modeling process (mode choice was excluded since nearly all trips in the town are made by private auto). The data included roadway configurations, lengths, and capacities, trip generation information for the community and the proposed developments, and origin-destination trip tables based on survey information. The modeling tasks were performed using the software package MicroTRIPS [17], developed by PRC Engineering, on an IBM PC microcomputer. Performing the distribution and assignment tasks for a small network on a microcomputer made the analysis of a large number of alternative assignments, distribution, and development scenarios possible. MicroTRIPS includes programs to perform trip generation, trip
distribution (using a gravity model), and traffic assignment using a variety of techniques including incremental capacity restraint, iterative capacity restraint, and all-or-nothing assignment procedures. These are the most commonly used traffic assignment techniques in realistic applications. A procedure for equilibrium assignment is not included in MicroTRIPS.

Figure 4-1 shows the highway network for the case study. The six developments are located in six different zones throughout the town; thus it was a simple task to separate the traffic effects of the individual developments. The zones experiencing development are: 14, 15, 23, 24, 26, and 27. Each development is labeled throughout this chapter by the zone in which it is located; Development 14, for example refers to the development in zone 14.

4.2 Effects of Different Assignment Models

Three different assignment procedures were used to analyze peak hour development traffic: all-or-nothing, incremental capacity restraint, and iterative capacity restraint. The incremental and iterative assignments were performed for a total of four iterations, with the incremental procedure assigning 40% of traffic during the first iteration, 30% during the second, 20% during the third, and 10% during the fourth.
Figure 4-1
Network for Case Study
A total of fourteen different development scenarios were modeled in the case study:

--the base scenario (no development)
--the total development scenario (all developments)
--six scenarios that included the base scenario along with one of the six developments
--six scenarios that included the total development scenario without one of the six developments.

These fourteen scenarios provide the information necessary to determine the traffic attributable to each of the six developments using both the addition and subtraction methods introduced in Chapter 2. The same survey-based trip distribution obtained from the consultant's report was used for all fourteen scenarios. Table 4-1 displays peak hour traffic volume data for eleven selected links for the three assignment procedures under six selected development scenarios. These scenarios correspond to the trip tables necessary to determine allocations to Developments 14 and 24 using the addition and subtraction methods:
Table 4-1
Peak Hour Traffic Volumes for Eleven Selected Links
for Selected Development Scenarios
under Three Assignment Procedures

<table>
<thead>
<tr>
<th>NODE</th>
<th>NODE</th>
<th>BASE SCENARIO</th>
<th>AON C</th>
<th>INCREM</th>
<th>ITERATIVE</th>
<th>VOL. V/C</th>
<th>VOL. V/C</th>
<th>VOL. V/C</th>
</tr>
</thead>
<tbody>
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<td></td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>44</td>
<td>1228 0.81</td>
<td>1232 0.82</td>
<td>1228 0.81</td>
<td>1228 0.81</td>
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<td></td>
<td></td>
</tr>
<tr>
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<td>6943 1.16</td>
<td>6938 1.16</td>
<td>6943 1.16</td>
<td>6943 1.16</td>
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</tr>
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<td>54</td>
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<td>6602 1.10</td>
<td>6602 1.10</td>
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Table 4-1 (cont'd)
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for Selected Development Scenarios
under Three Assignment Procedures

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Similarly, Table 4-2 shows turning movement information for two nodes for the base scenario, Scenario 24 - Addition, Scenario 24 - Subtraction, and the total scenario. This information is necessary to determine the traffic allocations to Development 24 at these two major intersections.

Tables 4-3 and 4-4 show respectively the peak hour traffic volumes and turning movements attributable to selected developments for the three assignment procedures. For example, the volume on link 12-77 in Table 4-3 attributable to Development 14 using the addition method is the difference between the volumes on the link for Scenario 14 - Addition and the Base Scenario (4484 - 4426 = 58). The tables show some large differences among the assignment procedures and between the addition and subtraction methods. In some cases, negative numbers were calculated for the traffic attributable to a development; this occurred when traffic was diverted from a
Table 4-2
Turning Movement Volumes for Selected Development Scenarios under Three Assignment Procedures
Nodes 54 and 57

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Turning Movement Volumes for Selected Development Scenarios under Three Assignment Procedures
Nodes 54 and 57

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Table 4-3
Peak Hour Traffic Volumes on Eleven Selected Links
Attributable to Selected Developments
under Three Assignment Procedures

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-72-
road during the assignment procedure when the trips from a
development were added. The large differences among assign-
ment and allocation procedures and the negative traffic
assessments are explained in the next section of this chapter.

4.3 Effects of Different Distribution Models

Two different models of the distribution of trips among
the analysis zones in the town were analyzed—the origin-
destination trip tables based on survey information from the
consultant's report and the gravity model. Assumptions made
in performing the gravity model distribution included: total
trips in and out of each zone the same as in the consultant
report, no intrazonal trips modeled (less than 0.1% of trips
from the consultant's trip table were intrazonal), interzonal
travel times estimated from free-flow highway network speeds,
and impedances proportional to the square of the travel times.
All external-external trips (those beginning and ending out-
side the town) were modeled directly using external zones
(numbered 1 through 13) in the gravity model except for
through trips on the interstate (between zones 4 and 12),
which were adjusted to reflect the high demand for travel
through town on this highway.

A summary of modeled traffic volumes under both distribu-
tion assumptions for four development scenarios for eleven
selected links is shown in Table 4-5. Volumes are shown for
the base scenario (no development), with Development 24 only, with all developments except Development 24, and with the developments in all zones. For consistency the incremental assignment procedure was used in all cases; as will be described later in the chapter, it is felt to be superior to the other available methods. As shown in Table 4-5, volumes are generally lower under the gravity model distribution than under the survey distribution for all four scenarios. The differences between the two sets of traffic figures are significant for some links, as much as 32% lower for the gravity model distribution.

Table 4-6 shows the traffic volumes attributed to Development 24 for the eleven links analyzed using both the addition and subtraction methods. Several links have traffic volumes attributed to the development that differ greatly between the two distribution models. In particular, links 77-54, 83-84, and 84-56 attribute several times more traffic to Development 24 under the gravity model distribution than under the survey distribution. These three links were assigned total traffic volumes near capacity under the survey distribution but much lower volumes under the gravity model; thus there was more capacity available for the development traffic under the assumptions of the gravity model distribution.
### Table 4-5
Modeled Traffic Volumes for Selected Links and Development Scenarios
Survey and Gravity Model Distributions

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GM - Gravity Model Distribution

### Table 4-6
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Survey and Gravity Model Distributions

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<td>721</td>
<td>1231</td>
</tr>
<tr>
<td>77</td>
<td>12</td>
<td>3503</td>
<td>3562</td>
<td>3693</td>
</tr>
<tr>
<td>77</td>
<td>54</td>
<td>5489</td>
<td>4974</td>
<td>5498</td>
</tr>
<tr>
<td>83</td>
<td>84</td>
<td>1409</td>
<td>1117</td>
<td>1549</td>
</tr>
<tr>
<td>84</td>
<td>56</td>
<td>1557</td>
<td>1170</td>
<td>1696</td>
</tr>
<tr>
<td>93</td>
<td>83</td>
<td>1423</td>
<td>1303</td>
<td>1849</td>
</tr>
</tbody>
</table>

GM - Gravity Model Distribution
4.4 Analysis of Case Study Results

The case study results reveal that there are significant differences in assigned traffic volumes among models using different distribution and assignment techniques. Traffic volumes attributable to individual developments were not consistent among techniques, and some assignment techniques attributed unreasonable or negative volumes to certain developments. This section attempts to explain some of the possible reasons for these problems and their effect on the use of transportation planning-based methods for determining impact fees.

4.4.1 Analysis of Assignment Techniques

A simple example can be used to demonstrate the differences among the three assignment techniques analyzed. Consider the simple four-link network (Sample Network 2) shown in Figure 4-2. Assume that the free-flow travel times on links 1-A, 1-B, and A-2 are all 10.00 minutes and that the free-flow travel time on link B-2 is 10.01 minutes. Assume further that the capacity of each link is 1000 vph and that there is an origin-destination flow of 1000 vehicles from node 1 to node 2 during the peak hour. In an all-or-nothing assignment all 1000 vehicles would be assigned to the path 1-A-2 and nothing would be assigned to links 1-B and B-2. If an incremental capacity restraint assignment were used with the same parameters as in the case study, 500 vehicles would be assigned to
Figure 4-2
Sample Network 2
each of the two O-D paths (400 in iteration 1 and 100 in iteration 4 to path 1-A-2 and 300 in iteration 2 and 200 in iteration 3 to path 1-B-2). In an iterative capacity restraint assignment, the assignment of all 1000 vehicles would flip-flop between the two routes during each iteration. If an even number of iterations is run, all vehicles would be assigned to route 1-B-2; after an odd number of iterations, 1000 vehicles would be assigned to route 1-A-2. Obviously, the incremental method produces what is intuitively the most reasonable assignment and the best approximation to expected equilibrium conditions, which would be close to a 50-50 split between the two routes.

Although Sample Network 2 was oversimplified to emphasize the differences between assignment techniques, large differences among the techniques' results can also be seen in the case study volumes. Some of these differences occur in the base scenario; these variations then carry over to the development scenarios. If, for example, the all-or-nothing assignment yielded a link volume 500 vehicles higher for the base scenario than the incremental assignment, it could also be expected that the assigned volume for that link would be 500 vehicles higher for the development scenarios. This occurrence was, in fact, common on many links in the case study. The traffic attributed to a particular development on such a link would be unaffected by the choice of assignment technique
(assuming use of the addition method) since the difference between the development and base scenario volumes would be the same.

As more traffic is assigned to the link for the development scenarios, however, the link could become more congested. In the incremental method, the travel time would increase during each iteration, and some traffic could be diverted to other routes. (The iterative method might divert all of the traffic from certain O-D pairs to other routes.) In this case the traffic on that link attributed to a development would be lower under the incremental method than all-or-nothing. Traffic would also be attributed to the development on links to which the incremental method diverted trips whereas no traffic would be attributed to the development on these links under an all-or-nothing assignment.

As an example, consider the turning movement volumes at node 57 attributed to Development 24 (using the addition method) shown in Table 4-4. The all-or-nothing method attributed only 159 northbound left turns at the intersection to the development. The incremental assignment attributed an increase of only 65 northbound left turns and also predicted a shift of vehicles leaving the intersection from the westbound to the southbound leg, due to downstream congestion to the west. The iterative method predicted a decrease in eastbound
left turns as well as an unreasonably large increase (1524 vehicles) in demand for left turns from the east. The latter increase is probably due to diversions from other congested parts of the network. Throughout the fourteen scenarios, the iterative method produced far more cases of "unreasonable" (unusually large or negative) traffic volumes attributable to individual developers than the other two methods. It should be noted that the use of equilibrium assignment would ensure that no negative traffic allocations to a development would result. Under equilibrium assignment, a volume decrease would lead to a travel time decrease on a link, and thus traffic would increase when the equilibrium assignment is attained.

Since the incremental capacity restraint assignment method is superior to the all-or-nothing method, it is reasonable to assume that all-or-nothing assignment is used only when incremental methods are unavailable due to time or resource constraints or lack of available computer software. Given the significant differences between the traffic assignment results (and thus the resultant impact fee assessments), it would make sense for those determining impact fees to prefer the incremental assignment to all-or-nothing wherever possible. Since computation requirements are the same for both the incremental and iterative procedures, the incremental method is always preferable to the iterative.
4.4.2 Analysis of Distribution Techniques

As shown in Table 4-5, the modeled traffic volumes obtained using the gravity model distribution were lower than those obtained from the survey distribution. This result, however, is due not to the nature of the gravity model formula itself but to the assumptions made during this particular application of the gravity model. In general, the lower volumes can be attributed to the direct modeling of external-external trips. Because most external-external trips travel across the town, their travel times within the town are usually longer than those of trips that begin or end in the town. The gravity model, which distributed trips in inverse proportion to the square of the travel time between two zones, distributed relatively few external-external trips. In reality, however, the large traffic volumes entering the town from certain external zones was probably due to the large demand for through traffic. The assumptions made did not reflect the large demand for external-external traffic except on the interstate.

External-external trips are often modeled separately when a gravity model is being employed. Some software packages require the user to input the external-external trip table before the internal zones are modeled. This approach was not used in the case study because in a small geographic area, such as a single town, the ratio of external to internal trip
ends is much greater than in an entire urban area such as those traditionally model using transportation planning methods. A model of a Massachusetts community smaller than the town modeled in the case study showed that over 90% of the trips modeled had at least one external end [1]. If external trips were not modeled directly, the origin-destination tables used in the two distribution models might not have differed substantially enough for a comparison to be useful.

The higher survey distribution volumes during the base scenario resulted in greater congestion on highway network links than under the gravity model distribution. Thus when development traffic was added onto base traffic, it was more likely that traffic would have been diverted from the congested links. The traffic increases on these congested links attributable to development, which included many of those selected for analysis, could be expected to be lower than those with smaller base volumes, which have more capacity with which to accommodate traffic increases.

Since modeled traffic volumes obtained using survey distributions can differ significantly from those obtained from gravity models, the results obtained will always be dependent on the distribution model chosen. It is recognized that the choice of a distribution model is often limited (for example, survey data may not be available). The case study results
show that both the choice of a distribution model and the assumptions behind the model chosen can affect the traffic results that are obtained.

4.4.3 Analysis of "Addition" Vs. "Subtraction" Method of Allocation

As Tables 4-3, 4-4, and 4-6 demonstrate, the addition and subtraction methods described earlier in the paper can provide different results in determining the amount of traffic attributable to an individual development. The addition method in effect assumes that the development being analyzed will be the first of the group to be constructed while the subtraction method assumes that it will be the last. The differences in volume assessments lead to the conclusion that the ordering of developments can have a substantial effect on the assessments. This is true regardless of the type of assignment procedure used. In fact the ordering of developments is important even in when using equilibrium assignment.

The overall traffic impacts of a group of developments can be easily determined as was done in the case study (the "total development" scenario). However, allocating traffic to individual developments separately or adding them incrementally provides order-dependent results. Since impact fees charged to a development are determined by the amount of traffic attributed to the development, the order-dependent prop-
The propriety of these allocation methods is inconsistent with the objective of consistency among fees charged to developers.

4.5 Conclusions

Difficulties may arise in allocating the traffic generated by several developments on a facility to individual developments. The choice of distribution and assignment models can affect the results of the traffic allocation. While a true equilibrium assignment would be desirable, this is not always available, and alternative methods can yield differing results. Incremental capacity restraint is preferable to iterative capacity restraint or all-or-nothing assignment, but it takes more computational time and effort than all-or-nothing. Even if incremental capacity restraint is performed, it can yield unreasonable results. Use of all-or-nothing assignment can produce allocations to developments that are significantly different. Only equilibrium assignment can ensure that traffic allocations to developments are nonnegative. Care should also be taken in producing trip tables that are as accurate as possible since differences in these tables can also cause variation in the traffic allocations to developments.

Chapter 2 demonstrated that using incremental allocation leads to inconsistent allocations among the developments. This fact is borne out by the case study. The study also
showed that the addition and subtraction methods, although not order-dependent, also can yield undesirable and inequitable results.

The case study presented in this chapter used all-or-nothing and capacity restraint assignment techniques. The next chapter examines some of the ways in which traffic can be allocated to developments when the superior technique of equilibrium assignment is used.
As stated in Chapter 2, there is no normative method for allocating traffic between an origin and destination to individual routes when using equilibrium assignment. As described in Chapter 3, some existing impact fee systems get around this problem by using other assignment procedures such as all-or-nothing assignment. Chapter 4 demonstrated some of the problems with using traffic assignment procedures other than equilibrium assignment. Even when equilibrium assignment is used, the allocation of traffic on a particular highway segment to an individual development is not determined solely from the traffic assignment. The nonuniqueness of path flows is the cause for this problem, as stated in Chapter 2.

There are several approaches that can be used to attempt to overcome the problem of allocating traffic increases to individual developments. These include: the use of incremental allocation, averaging incremental allocation results, using the intermediate steps in the Frank-Wolfe algorithm, and the use of an entropy formulation. These methods, which are described in detail later in the chapter, are summarized briefly below.
Use of Incremental Allocation - The developments are ordered, perhaps chronologically. A base traffic assignment is done, and assignments are performed as each development's trips are added to the trip table. The increase in traffic volume for each link as a development is added is attributed to that development.

Averaging Incremental Allocation Results - All possible orderings of developments are considered, and incremental allocation as described above is performed for each ordering. The results of all allocations are averaged.

Intermediate Steps in the Frank-Wolfe Algorithm - As the Frank-Wolfe algorithm is used to perform the equilibrium assignment, the assigned volumes in the all-or-nothing assignment performed at each iteration are saved. These volumes are allocated to the developments after convergence in the algorithm is reached.

Entropy Formulation - A nonlinear program is solved, yielding the maximum likelihood allocation of traffic among the developments and other trip generation points.
As this chapter demonstrates, only the entropy formulation satisfies the objective of consistency among developments while providing a problem of manageable size in realistic applications. The focus of the formulation is that while the path flows cannot be uniquely determined in an equilibrium assignment, the most likely distribution of the origin-destination flows among the paths can be determined. This provides a consistent method of allocating traffic to individual developments or traffic generators.

5.1 Use of Incremental Allocation

As previously discussed, the incremental allocation technique can be used directly along with urban transportation planning methods to determine the traffic volumes attributable to individual developments. First, the four-step process is performed for the base condition (without any new developments). Then the developments are considered sequentially, and the four-step process is repeated as each development is added. For each development, trip generation consists of determining the number of trips to and from the development. Trip distribution consists of determining the origin zones of trips to the development and the destinations of trips from the development. These trips are then added to the base trip table. Traffic assignment consists of assigning the new trip table. The difference between the traffic assigned on each link before and after the development's trips are added to the
The incremental allocation method has several desirable qualities including its simplicity and its suitability for use in conjunction with traditional transportation planning software packages. Its major drawback is that the developments must be arbitrarily ordered, usually in chronological order of their application for construction permits (as in Broward County) or their actual completion (which may be unknown at the time the impact fee is determined). Unfortunately, different orderings yield different results. Thus the objective that fees be consistent among developments cannot be met when applying incremental allocation directly.

One proposed allocation method that uses the concept of incremental allocation but avoids the problem of ordering the developments was introduced in Chapter 2 as the addition method. In this method, to ensure that costs are covered, the volumes for each development can be factored so that the sum of the volumes on each link attributable to the developments equals the difference between the volumes obtained by assigning the base trip table and the "total" trip table (base plus trips from all developments). A similar factoring technique can be used when using the subtraction method.
While the addition and subtraction methods are not order-dependent, they do not necessarily yield results that are consistent among developments. Consider the example of Sample Network 3 shown in Figure 5-1. Let nodes A, B, and C represent development sites and D the destination of trips from the developments (assume that in the time period under study, there are no trips to the developments). Assume that a total demand before development of 10,000 vehicles exists between nodes 1 and D and that Developments A, B, and C will generate 2000, 3000, and 4000 trips respectively to node D. The equilibrium volumes on Link 1 for all possible development scenarios are shown in Table 5-1.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Equilibrium Volume on Link 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base (no development)</td>
<td>2486</td>
</tr>
<tr>
<td>Development A only</td>
<td>2534</td>
</tr>
<tr>
<td>Development B only</td>
<td>2572</td>
</tr>
<tr>
<td>Development C only</td>
<td>2620</td>
</tr>
<tr>
<td>Developments A and B</td>
<td>2680</td>
</tr>
<tr>
<td>Developments A and C</td>
<td>2748</td>
</tr>
<tr>
<td>Developments B and C</td>
<td>2831</td>
</tr>
<tr>
<td>All developments</td>
<td>3022</td>
</tr>
</tbody>
</table>
Figure 5-1
Sample Network 3

Link 1
Inspection of this simple network reveals that after the initial link (site access), the paths for the three origins are identical. Thus, in order to be consistent among the developments, the desired traffic allocation would be an allocation of the traffic increase on link 1 proportional to the total number of trips generated for each development. This would yield an allocation of 119 trips to Development A, 179 to Development B, and 238 to Development C.

Using the addition method, Development A would be responsible for \((2543 - 2486 =)\) 48 trips, Development B for 86 and Development C for 134. Factoring these numbers so that the total development-generated traffic of 536 is allocated, the allocations become 96, 172, and 268 for Developments A, B, and C respectively. Using the subtraction method, different results are obtained. A total of 191 trips are allocated to Development A, 274 to Development B, and 342 to Development C. After factoring these allocations become 127, 182, and 227 for Developments A, B, and C respectively. The addition method allocations are far from the expected results, and while the subtraction method results are reasonably close, they still undercharge Development C at the expense of Development A.
5.2 Averaging Incremental Allocation Results

Another procedure that would eliminate the order-dependence property of incremental allocation is the averaging of incremental allocation results. There is a finite number of ways to order the developments for an incremental allocation procedure. For example, if two developments are under consideration, there are two ways to order the developments; if there are three developments, they may be ordered in six ways. One would expect that if incremental allocation is performed for every ordering of developments and the results are averaged, a reasonable allocation of traffic would result. This allocation would not be order-dependent. This procedure is performed for the example used to illustrate the addition and subtraction methods (Sample Network 3); the results are shown in Table 5-2. As the table shows, the averaging yields the expected proportional allocation.

The major drawback to the averaging method is that it is far more time-consuming than simple incremental allocation. In the example above, eight assignments are needed as opposed to four for simple incremental allocation and five for either the addition or the subtraction method. As the number of developments increases, the number of necessary assignments becomes prohibitively high since the number of different orderings is equal to the factorial of the number of developments. The maximum number of necessary assignments is $2^n,$
Table 5-2
Traffic Allocations for Sample Network 3
Under All Possible Orderings of Developments

<table>
<thead>
<tr>
<th>Development Ordering</th>
<th>Traffic Allocation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>A B C</td>
<td>48</td>
</tr>
<tr>
<td>A C B</td>
<td>48</td>
</tr>
<tr>
<td>B A C</td>
<td>108</td>
</tr>
<tr>
<td>B C A</td>
<td>191</td>
</tr>
<tr>
<td>C A B</td>
<td>128</td>
</tr>
<tr>
<td>C B A</td>
<td>191</td>
</tr>
<tr>
<td>Average</td>
<td>119</td>
</tr>
</tbody>
</table>

where \( n \) is the number of developments. Thus if six developments are considered, there are 720 possible orderings of developments, and up to 64 assignments could be needed.

5.3 Intermediate Steps in the Frank-Wolfe Algorithm

As previously discussed, the need to determine an algorithm for allocating traffic increases to developments arises from the property of equilibrium assignment that origin-destination paths are not unique. This problem does not arise in all-or-nothing assignment or procedures that are combinations of successive all-or-nothing assignments, such as capacity restraint assignment. The most common method of equilibrium assignment, the Frank-Wolfe "convex combinations" algorithm [5], also uses a weighted series of all-or-nothing assignments. Thus the results of the all-or-nothing assignments in the Frank-Wolfe algorithm can be used to determine origins and destinations for the vehicles using each link.
The additional computation required to use the intermediate steps in the Frank-Wolfe algorithm in allocation is minimal. No additional computations are necessary; only additional storage (or output) of the intermediate results is required. Since the Frank-Wolfe algorithm converges fairly quickly to an equilibrium assignment, the results can be easily obtained. Unfortunately, the rapid convergence of the Frank-Wolfe algorithm causes inconsistencies in the treatment of various developments. These are illustrated using Sample Network 4 shown in Figure 5-2.

In this network, nodes A and B represent development sites while node D is the destination of trips from the site (again, assume no trips to the site). Development A generates 400 trips while Development B generates 800. Table 5-3 shows the equilibrium assignment results for the network and the allocation of traffic to the two developments using the intermediate steps in the Frank-Wolfe algorithm.

<table>
<thead>
<tr>
<th>Link</th>
<th>Equilibrium Volume</th>
<th>Traffic Allocation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>A-1</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>B-1</td>
<td>559</td>
<td>0</td>
</tr>
<tr>
<td>B-D</td>
<td>241</td>
<td>0</td>
</tr>
<tr>
<td>1-D</td>
<td>448</td>
<td>224</td>
</tr>
<tr>
<td>1-D (1)</td>
<td>511</td>
<td>176</td>
</tr>
</tbody>
</table>

Table 5-3
Assignment Results for Sample Network 4 and Allocations Using Intermediate Steps in Frank-Wolfe Algorithm
Figure 5-2
Sample Network 4
Note that the two links 1-D are assigned different volumes because they have different characteristics (length, capacity). However, the two developments are allocated equal proportions of the traffic on link 1 while on link 2 Development B is allocated almost twice as much of the traffic as Development A. This counterintuitive result violates the objective of consistency between the developments. If link 1 were scheduled for improvement, Development A would be responsible for half of the cost (to be paid for by impact fees) while if link 2 were to be improved, Development A would be allocated only 34% of the costs. The desired result would be an allocation proportional to the traffic each development generates traveling into node 1, or 41% for Development A and 59% for Development B. The expected allocated traffic would be 187 for Development A, 213 for Development B on Link 1 and 261 for Development A, 298 for Development B on Link 2.

It should be noted that the accuracy (in terms of consistency) of this method depends on the geometry of the analysis network. For some networks the method will provide reasonably accurate results while for others the allocations will differ greatly from the desired consistent allocations.
5.4 **Entropy Formulation**

An entropy formulation is one in which the maximum likelihood distribution of a set of variables given a set of constraints is determined [23]. Applications of entropy formulations are widespread. An entropy formulation can be used to determine the maximum likelihood allocation to developments of link volumes given the constraints of the origin-destination flows (the trip table) and the equilibrium link volumes. This section describes one possible entropy formulation.

In this description, only trips originating at the development sites will be considered. The process can be easily reversed to deal with trips to the development site. The formulation will be described in terms of a simple example using Sample Network 1 (Figure 2-1). This network consists of two origin nodes (A and B), one destination node (D), and two paths for O-D pair A-D and two for O-D pair B-D. For each pair, one path reaches D via link 1 and one via link 2.

To describe the entropy formulation, several terms must be defined. A "flow condition" will be defined as an allocation of the flows on each network link to the origin nodes. Thus the objective function of the entropy formulation is to find the most likely flow condition among those that result in the equilibrium traffic assignment. Referring to Sample Network 1, assume that the equilibrium volumes are 3 on link 1.
and 3 on link 2 and that Developments A and B generate 2 and 4 trips respectively. Thus there are three possible flow conditions as shown in Table 5-4. For example, for flow condition 1, 2 of the 3 vehicles on link 1 are from Development A and the other from Development B.

A "state" will be defined as an allocation of each trip in the trip table to its path. For Sample Network 1, there are twenty states as shown in Table 5-5. For example, in state 1 the first vehicle from Development B is on Link 1 and the other three vehicles are on link 2. In the entropy formulation it is assumed that each state is equally likely; thus, in the sample network, each state has a 1/20 probability of occurring. The maximum likelihood flow condition is associated with the greatest number of states. In the sample network, states 1-4 are associated with flow condition 1; states 5-16 with flow condition 2; and states 17-20 with flow condition 3. Thus flow condition 2 is the maximum likelihood condition, with a 60% probability of occurring.
### Table 5-4
Possible Flow Conditions on Sample Network 1

<table>
<thead>
<tr>
<th>Identification Number</th>
<th>Link 1 A</th>
<th>Link 1 B</th>
<th>Link 2 A</th>
<th>Link 2 B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

### Table 5-5
States for Sample Network 1

<table>
<thead>
<tr>
<th>State No.</th>
<th>Origin A</th>
<th>Origin B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Veh. 1</td>
<td>Veh. 2</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>11</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>14</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>17</td>
<td>2</td>
<td>2</td>
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<tr>
<td>18</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>19</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>20</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>
For a large network like those typically used in urban transportation planning applications, the number of states is extremely large. Fortunately, all states need not be enumerated to determine the maximum likelihood flow condition. The number of states associated with a given flow condition is given by the following formula:

\[ S_i = \prod_{O-D's} \frac{q_{rs}!}{\prod_{paths k} f_{k,rs}!} \]

where:

- \( S_i \) = number of states associated with flow condition \( i \)
- \( q_{rs} \) = flow for O-D pair \( rs \)
- \( f_{k,rs} \) = flow on path \( k \) for O-D pair \( rs \) in flow condition \( i \)

For example, in Sample Network 1, \( q_{AD} = 2 \), \( q_{BD} = 4 \), and, for flow condition 2, \( f_{1,AD} = 1 \), \( f_{2,AD} = 2 \), \( f_{1,BD} = 1 \), and \( f_{2,BD} = 2 \).

Thus:

\[ S_2 = \frac{2! \cdot 4!}{1! \cdot 1! \cdot 2! \cdot 2!} = 12 \]

The entropy formulation can be expressed as the following nonlinear program:

\[ \max \prod_{rs} \frac{q_{rs}!}{\prod_{rs} f_{k,rs}!} \]
subject to:

\[ \sum_{k} f_{k}^{rs} = q_{rs} \quad \text{for all O-D pairs } rs \]

\[ \sum_{rs} \sum_{k} f_{k}^{rs} d_{ak}^{rs} = x_{a} \quad \text{for all links } a \]

where:

\[ x_{a} = \text{equilibrium volume on link } a \]

\[ d_{ak}^{rs} = \begin{cases} 
1 & \text{if path } k \text{ from } r \text{ to } s \text{ includes link } a \\
0 & \text{otherwise} \end{cases} \]

The first constraint requires that the sum of the flows on all paths from an O-D pair equals the assigned volume for that pair from the trip table. The second constraint ensures that the equilibrium volume on each link equals the sum of the volumes on all paths using the link.

In most maximum likelihood estimations, the logarithmic form of the objective function is used. In this case the objective function would become:

\[ \sum_{rs} [(\ln q_{rs}) - \sum_{k} (\ln f_{k}^{rs})] \]

Since the \( q_{rs} \)'s are fixed (values from the trip table), the first term can be dropped from the objective function, leaving:

\[ - \sum_{rs} \sum_{k} (\ln f_{k}^{rs}). \]

The minus sign can be dropped and the objective changed to the minimization of this function.
For realistic networks, the traffic volumes and origin-destination flows are usually large. To evaluate the objective function, Stirling's approximation of \( \ln x! \) must be used. Stirling's approximation is \( \ln x! \approx x \ln x - x \). The objective function then becomes:

\[
\sum_{rs} \left[ \sum_{k} f_{k}^{rs} \ln f_{k}^{rs} - \sum_{k} f_{k}^{rs} \right] \\
- \sum_{rs} \left[ \sum_{k} f_{k}^{rs} \ln f_{k}^{rs} - q_{rs} \right]
\]

Again, \( q_{rs} \) is a constant and can be dropped from the objective function. Thus the nonlinear program to be solved is:

\[
\min \sum_{rs} \sum_{k} f_{k}^{rs} \ln f_{k}^{rs} \tag{5-1}
\]

subject to:

\[
\sum_{k} f_{k}^{rs} = q_{rs} \quad \text{for all 0-D pairs rs} \tag{5-1a}
\]

\[
\sum_{rs} \sum_{k} f_{k}^{rs} d_{ak}^{rs} = x_{a} \quad \text{for all links a} \tag{5-1b}
\]

To demonstrate how this program is used, consider once again the network shown in Figure 5-2. Let the paths be denoted as shown in Table 5-6. Let \( F_{i} \) denote the path volume on path \( i \). Program 5-1 for this example is thus:

\[
\min F_{1} \ln F_{1} + F_{2} \ln F_{2} + F_{3} \ln F_{3} + F_{4} \ln F_{4} + F_{5} \ln F_{5}
\]

subject to:

\[
\begin{align*}
(1) \quad F_{1} + F_{2} & = 400 \\
(2) \quad F_{3} + F_{4} + F_{5} & = 800 \\
(3) \quad F_{5} & = 241 \\
(4) \quad F_{1} + F_{3} & = 448 \\
(5) \quad F_{2} + F_{4} & = 511
\end{align*}
\]
(In this example, for simplicity the $f_{kRS}^r$s have been denoted $F_1, F_2$, etc. where $F_1 = f_{1AD}^r$, etc.) Some redundant constraints have been omitted. For example, constraint (1) represents both the O-D flow constraint for pair A-D and the link volume constraint for link A-1. There is one more constraint listed above than necessary for solution.

Some other observations can be made regarding the program. Since $F_5$ is a constant (=241), the last term can be dropped from the objective function since it will not affect its minimization. Furthermore, the constraints allow all of the remaining path flow variables to be expressed in terms of $F_1$:

\[
F_2 = 400 - F_1 \\
F_3 = 448 - F_1 \\
F_4 = 111 + F_1
\]

The objective function can be minimized through differentiation:
\[ \frac{\partial z}{\partial F_1} = \ln F_1 + 1 + (\ln F_2 + 1)(-1) + (\ln F_3 + 1)(-1) + (\ln F_4 + 1)(1) \]

= 0

\[ \ln F_1 + \ln F_4 = \ln F_2 + \ln F_3 \]

\[ (F_1)(F_4) = (F_2)(F_3) \]

\[ (F_1)(F_1 + 111) = (400 - F_1)(448 - F_1) \]

\[ F_1 = 187 \]

\[ F_2 = 213, F_3 = 261, F_4 = 298 \]

These values are identical to those expected (as described in the earlier example on the intermediate steps in the Frank-Wolfe algorithm).

It should be pointed out that, in general, to solve the program, the paths used for every O-D pair involving a development site must be known. The assignment program used would have to be altered to provide that information by finding all shortest paths between origins and destinations once the equilibrium travel times have been found. An integrated computer software package could be developed that would translate the path enumerations into constraints for use in an optimization program.

Because it involves solving a nonlinear program with perhaps thousands of constraints, the entropy formulation entails considerably more computational effort than most of the other allocation methods mentioned above. In the next chapter, an example of the entropy formulation, using an actual network from a transportation planning application, is provided.
5.5 Solution procedures

This section presents brief descriptions of the procedures for solving the two parts of the entropy formulation—the equilibrium assignment and the nonlinear optimization. Also included is a discussion of the method used to find all shortest paths between each origin and destination for use in developing the constraints for the nonlinear program.

5.5.1 Solving for an Equilibrium Traffic Assignment

An equilibrium traffic assignment is obtained by the solution of the following program [18]:

\[
\min z(\mathbf{x}) = \sum_{a} t_a(w) \, dw
\]

subject to:

\[
\sum_{k} f^{k}_{rs} = q_{rs} \quad \text{for all } r, s
\]

\[
f^{k}_{rs} \geq 0 \quad \text{for all } k, r, s
\]

where \( \mathbf{x} \) is the vector of link volumes \( (x_1, \ldots, x_m) \), \( t_a(x) \) is the link performance function (time as a function of traffic volume) for link \( a \), and the variables \( x_a, f^{k}_{rs} \), and \( q_{rs} \) are defined as in section 5.4.

In the Frank-Wolfe algorithm, at each iteration a current solution (set of link traffic volumes) and corresponding travel times are known from previous iterations. During the iteration, the current solution is updated to another solution satisfying the constraints of the program that is closer to
the program solution than the current solution. This new solution is obtained by determining a descent direction (i.e. a vector along which the new solution will be found moving from the previous solution) and the move size, $\alpha$, that is the distance to the new solution from the previous solution.

A linear program is solved at each iteration which defines the descent direction for the update of the existing solution. Sheffi [18] shows that solving this program is equivalent to performing an all-or-nothing assignment based on the current set of link travel times. A line search is then performed to determine the move size, $\alpha$. This line search consists of finding $\alpha$ that solves:

$$
\min_{0 \leq \alpha \leq 1} \sum_{0}^{\infty} t_a(w) \, dw
$$

where $x_n = (x_1^n, \ldots, x_m^n)$ is the current solution and $y_n = (y_1^n, \ldots, y_m^n)$ is the new solution for iteration $n$.

Thus $y_n - x_n$ is the descent direction for iteration $n$. A recommended method for performing the above line search is to use the bisection search—that is, to determine the derivative of the objective function at the endpoints of the range over which the function is minimized and successively replacing the endpoint with the higher derivative with the midpoint of the range until the minimum has satisfactorily converged.
The current solution is set to the zero vector and the link travel times set to the free-flow times for the first iteration. A convergence test or number of iterations is used to stop the algorithm.

To determine the volumes to be used in the intermediate steps method (Section 5.3), in addition to saving and updating the link volumes, the path volumes are saved and updated as well. This requires additional storage space to be set aside by the program.

Sheffi [18] shows that it is easy to develop a program to perform equilibrium assignment using the Frank-Wolfe algorithm and notes that it is now included in some transportation planning packages. PASCAL code for such a program is presented in Appendix A.

5.5.2 Identification of Shortest Paths

Included in the program in Appendix A is a routine that finds and outputs all shortest paths between all origins and destinations. This procedure uses a modified version of the label-correcting procedure used by the program to perform the all-or-nothing assignment at each iteration of the Frank-Wolfe algorithm. (The label-correcting procedure is described by Sheffi [18].) Instead of simply finding a shortest path from
each origin to the destinations (using the equilibrium link travel times), the modified label correcting algorithm saves all paths to each node reached from the origin within a user-supplied tolerance of the shortest path found to the node. For the program given in Appendix A, the tolerance chosen was 0.025 minutes.

5.5.3 Nonlinear Optimization

There are several methods available for solving nonlinear optimization problems. The Frank-Wolfe algorithm described in the last section is one method that works particularly well for the objective function of the equilibrium assignment program. For the nonlinear optimization step in the entropy formulation, other methods are more efficient.

The general optimization program GINO uses a version of the generalized reduced gradient (GRG) algorithm to find the solution of a nonlinear program [11]. This algorithm follows the general method of Frank-Wolfe in that at each iteration a descent direction and move size are determined to update the current solution. In GRG the gradient of the objective function at the current solution is used to determine the descent direction.

One common method for choosing the descent direction is to choose the negative gradient at the current solution. The
most efficient method used by GINO is called the Broyden-Fletcher-Goldfarb-Shanno (BFGS) Quasi-Newton method. This method requires the storage of an $n \times n$ matrix in an $n$-variable problem. Other methods that are less efficient but require less storage are available in GINO; these include Fletcher-Reeves, Polak-Ribiere and one-step BFGS. These latter methods are referred to as conjugate gradient methods and are used by GINO when there is insufficient storage available for BFGS.

The line search portion of the optimization may be solved by the bisection search described in section 5.5.1. GINO uses a more efficient procedure: An initial guess for the move size is chosen and the value of the objective function for this move size and the previously calculated descent direction is computed. The initial guess is increased or decreased (depending on whether the objective function value of the initial guess was lower or higher than the value at the current solution) and a new value of the objective function computed. New guesses are continued in this manner until the objective function begins to increase (if it initially decreased). A quadratic is then fitted to the last three values (the middle of which is the lowest) and the minimum of the quadratic is used as the optimal move size.
5.6 Summary

In order to determine cost allocations to developments that are consistent, the traffic volumes attributable to each development must be known. While assignment techniques that are series of successive all-or-nothing assignments provide the necessary information for cost allocation, equilibrium assignment does not because of its property of nonunique path flows between an origin and destination. This chapter analyzed four methods for determining allocations to developments when equilibrium assignment is used.

Two of the methods analyzed—the use of incremental allocation and the use of the intermediate steps in the Frank-Wolfe algorithm—were the simplest to implement in terms of computational time and effort. Unfortunately, neither of these methods yield consistent results for all networks. The averaging of incremental allocation results did yield consistent allocations, but is computationally impractical.

The recommended method to overcome the problem of allocating traffic under an equilibrium assignment is the use of an entropy formulation. This method determines, using a non-linear program, the maximum likelihood allocation to the developments of the additional traffic using an improved facility. While the method is quick and accurate for small networks, extensive testing on larger networks is needed to
determine its efficiency for use in realistic applications. Chapter 6 provides an example of the use of the entropy formulation on a real urban network to allocate highway improvement costs.
Chapter 5 examined several traffic allocation methods that could be used for impact fee assessment. The most promising method introduced is based on an entropy formulation that determines the most likely paths taken by trips to and from new developments. The method requires the solution of a nonlinear program that can have many hundreds of variables in realistic applications. The purpose of this chapter is to present such a realistic example to determine how difficult it would be to implement the procedure in practice.

This example is based on a simplified network used in a transportation planning model development example [8]. To take advantage of the personal computer software available for optimization, the highway network used in this example is coarser than many used in actual transportation planning applications. The example network, therefore, has fewer links and nodes than real-life networks. The limits of the personal computer software used to solve the optimization program were taxed by the size of this example. Much larger problems can be solved, however, with other software packages or on larger computers. This example is provided to demonstrate that the entropy method can be used in a realistic application at a reasonable cost and within a reasonable time period.
6.1 Description of Example Highway Network

The highway network used in the example is based on one used by Janson et al [8] in the development of the NETPEM model for the U.S. Department of Energy. The network was a simplified version of the highway system of the eastern portion of the Pittsburgh urbanized area. The network used in the model development example was further modified for use in this chapter's example. The final network used for this example is shown in Figure 6-1.

In the example network nodes 1 through 7 represent trip generation points (zone centroids). Nodes 8 and 9 represent locations of new developments. These hypothetical developments can be considered to be located in zones 6 and 2 respectively but are depicted as separate zones for ease in distinguishing the trips generated by the new developments. The trip table containing the number of trips between each origin and destination for the morning peak period (assumed known) is displayed in Table 6-1.

The trips contained in the trip table were assigned to the highway network using the PASCAL equilibrium assignment program written for this purpose, which is shown in Appendix A. The program's output provided the traffic volumes on the network's links and a listing of the minimum travel time paths.
Figure 6-1
Highway Network for Entropy Formulation Example
Table 6-1
Trip Table for Example Application

<table>
<thead>
<tr>
<th>Trips from Zone:</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1174</td>
<td>73</td>
<td>0</td>
<td>107</td>
<td>369</td>
<td>40</td>
<td>74</td>
<td>235</td>
<td>2072</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1424</td>
<td>0</td>
<td>0</td>
<td>68</td>
<td>131</td>
<td>0</td>
<td>27</td>
<td>283</td>
<td>1933</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>369</td>
<td>149</td>
<td>0</td>
<td>0</td>
<td>137</td>
<td>62</td>
<td>27</td>
<td>74</td>
<td>818</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>493</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>99</td>
<td>592</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>54</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>11</td>
<td>65</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>0</td>
<td>3514</td>
<td>222</td>
<td>0</td>
<td>175</td>
<td>637</td>
<td>102</td>
<td>128</td>
<td>702</td>
<td>5480</td>
</tr>
</tbody>
</table>

for each origin-destination pair. The output is shown in Figure 6-2. The traffic assignment program was run twice--once without and once with the new developments (i.e. trips to and from zones 8 and 9). This determined the traffic increase on each link resulting from the new development and would allow the determination of the necessary improvements on each link.

6.2 Entropy Program Formulation

The equilibrium assignment program's output, along with the trip table provides the information necessary to develop the entropy formulation (program 5-1 from Chapter 5) for this example. For simplicity, the path flow variables are numbered $f_1, \ldots, f_n$ as shown in Table 6-2. For example, $f_1^{12}$ in the notation of Chapter 5 is denoted $f_1$, $f_2^{12}$ is denoted $f_2$, and so on up to $f_3^{79}$, which is denoted $f_50$. Using the revised
Figure 6-2  
Equilibrium Assignment Program Output  
for Example Network

User equilibrium flows:

<table>
<thead>
<tr>
<th>Link</th>
<th>A-Node</th>
<th>B-Node</th>
<th>Volume</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1866</td>
<td>0.293</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>4</td>
<td>206</td>
<td>0.312</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>9</td>
<td>702</td>
<td>0.001</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>5</td>
<td>815</td>
<td>0.198</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>7</td>
<td>3137</td>
<td>0.057</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>3</td>
<td>375</td>
<td>0.101</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>5</td>
<td>649</td>
<td>0.179</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>2</td>
<td>412</td>
<td>0.140</td>
</tr>
<tr>
<td>9</td>
<td>5</td>
<td>11</td>
<td>1057</td>
<td>0.130</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>12</td>
<td>412</td>
<td>0.016</td>
</tr>
<tr>
<td>11</td>
<td>6</td>
<td>2</td>
<td>1510</td>
<td>0.100</td>
</tr>
<tr>
<td>12</td>
<td>6</td>
<td>8</td>
<td>128</td>
<td>0.001</td>
</tr>
<tr>
<td>13</td>
<td>7</td>
<td>6</td>
<td>2275</td>
<td>0.181</td>
</tr>
<tr>
<td>14</td>
<td>7</td>
<td>13</td>
<td>825</td>
<td>0.140</td>
</tr>
<tr>
<td>15</td>
<td>8</td>
<td>6</td>
<td>0</td>
<td>0.001</td>
</tr>
<tr>
<td>16</td>
<td>9</td>
<td>2</td>
<td>0</td>
<td>0.001</td>
</tr>
<tr>
<td>17</td>
<td>10</td>
<td>2</td>
<td>583</td>
<td>0.135</td>
</tr>
<tr>
<td>18</td>
<td>11</td>
<td>2</td>
<td>1057</td>
<td>0.010</td>
</tr>
<tr>
<td>19</td>
<td>12</td>
<td>2</td>
<td>412</td>
<td>0.124</td>
</tr>
<tr>
<td>20</td>
<td>13</td>
<td>2</td>
<td>242</td>
<td>0.141</td>
</tr>
<tr>
<td>21</td>
<td>13</td>
<td>10</td>
<td>583</td>
<td>0.006</td>
</tr>
</tbody>
</table>

Paths (in reverse order) from 1 to 2  

2 5 3 1  
2 5 4 1  
2 11 5 3 1  
2 11 5 4 1  
2 12 5 3 1  
2 12 5 4 1  
2 6 7 3 1  
2 13 7 3 1  
2 10 13 7 3 1

Paths (in reverse order) from 1 to 3  

3 1
Figure 6-2 (cont’d)
Equilibrium Assignment Program Output
for Example Network

Paths (in reverse order) from 1 to 5
5  3  1
5  4  1

Paths (in reverse order) from 1 to 6
6  7  3  1

Paths (in reverse order) from 1 to 7
7  3  1

Paths (in reverse order) from 1 to 8
8  6  7  3  1

Paths (in reverse order) from 1 to 9
9  2  5  3  1
9  2  5  4  1
9  2 11  5  3  1
9  2 11  5  4  1
9  2 12  5  3  1
9  2 12  5  4  1
9  2  6  7  3  1
9  2 13  7  3  1
9  2 10 13  7  3  1

Paths (in reverse order) from 3 to 2
2  5  3
2 11  5  3
2 12  5  3
2  6  7  3
2 13  7  3
2 10 13  7  3

Paths (in reverse order) from 3 to 5
5  3

Paths (in reverse order) from 3 to 6
6  7  3

Paths (in reverse order) from 3 to 8
8  6  7  3
Figure 6-2 (cont’d)
Equilibrium Assignment Program Output
for Example Network

Paths (in reverse order) from 3 to 9
9 2 5 3
9 2 11 5 3
9 2 12 5 3
9 2 6 7 3
9 2 13 7 3
9 2 10 13 7 3

Paths (in reverse order) from 4 to 2
2 5 4
2 11 5 4
2 12 5 4

Paths (in reverse order) from 4 to 3
3 4

Paths (in reverse order) from 4 to 6
6 7 3 4

Paths (in reverse order) from 4 to 7
7 3 4

Paths (in reverse order) from 4 to 8
8 6 7 3 4

Paths (in reverse order) from 4 to 9
9 2 5 4
9 2 11 5 4
9 2 12 5 4

Paths (in reverse order) from 5 to 2
2 5
2 11 5
2 12 5

Paths (in reverse order) from 5 to 9
9 2 5
9 2 11 5
9 2 12 5

Paths (in reverse order) from 7 to 2
2 6 7
2 13 7
2 10 13 7

Paths (in reverse order) from 7 to 9
9 2 6 7
9 2 13 7
9 2 10 13 7
Table 6-2
Definition of Path Flow Variables for Example Application

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>O-D pair</th>
<th>Path number for O-D pair (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>f₁</td>
<td>1-3</td>
<td>1</td>
</tr>
<tr>
<td>f₂</td>
<td>1-3</td>
<td>2</td>
</tr>
<tr>
<td>f₃</td>
<td>1-3</td>
<td>3</td>
</tr>
<tr>
<td>f₄</td>
<td>1-3</td>
<td>4</td>
</tr>
<tr>
<td>f₅</td>
<td>1-3</td>
<td>5</td>
</tr>
<tr>
<td>f₆</td>
<td>1-3</td>
<td>6</td>
</tr>
<tr>
<td>f₇</td>
<td>1-3</td>
<td>7</td>
</tr>
<tr>
<td>f₈</td>
<td>1-3</td>
<td>8</td>
</tr>
<tr>
<td>f₉</td>
<td>1-3</td>
<td>9</td>
</tr>
<tr>
<td>f₁₀</td>
<td>1-5</td>
<td>1</td>
</tr>
<tr>
<td>f₁¹</td>
<td>1-5</td>
<td>2</td>
</tr>
<tr>
<td>f₁²</td>
<td>1-9</td>
<td>1</td>
</tr>
<tr>
<td>f₁³</td>
<td>1-9</td>
<td>2</td>
</tr>
<tr>
<td>f₁₄</td>
<td>1-9</td>
<td>3</td>
</tr>
<tr>
<td>f₁₅</td>
<td>1-9</td>
<td>4</td>
</tr>
<tr>
<td>f₁₆</td>
<td>1-9</td>
<td>5</td>
</tr>
<tr>
<td>f₁₇</td>
<td>1-9</td>
<td>6</td>
</tr>
<tr>
<td>f₁₈</td>
<td>1-9</td>
<td>7</td>
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<tr>
<td>f₁₉</td>
<td>1-9</td>
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</tr>
<tr>
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<td>1-9</td>
<td>9</td>
</tr>
<tr>
<td>f₂¹</td>
<td>3-2</td>
<td>1</td>
</tr>
<tr>
<td>f₂²</td>
<td>3-2</td>
<td>2</td>
</tr>
<tr>
<td>f₂₃</td>
<td>3-2</td>
<td>3</td>
</tr>
<tr>
<td>f₂₄</td>
<td>3-2</td>
<td>4</td>
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<tr>
<td>f₂₅</td>
<td>3-2</td>
<td>5</td>
</tr>
<tr>
<td>f₂₆</td>
<td>3-2</td>
<td>6</td>
</tr>
<tr>
<td>f₂₇</td>
<td>3-9</td>
<td>1</td>
</tr>
<tr>
<td>f₂₈</td>
<td>3-9</td>
<td>2</td>
</tr>
<tr>
<td>f₂₉</td>
<td>3-9</td>
<td>3</td>
</tr>
<tr>
<td>f₃₀</td>
<td>3-9</td>
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</tr>
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<td>f₃¹</td>
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</tr>
<tr>
<td>f₃₂</td>
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</tr>
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</tr>
<tr>
<td>f₃₄</td>
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<tr>
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<tr>
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<td>f₃₇</td>
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<td>f₃₈</td>
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<tr>
<td>f₄₀</td>
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</table>
Table 6-2 (cont'd)
Definition of Path Flow Variables for Example Application

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>O-D pair</th>
<th>Path number for O-D pair (k)</th>
</tr>
</thead>
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<tr>
<td>$f_{41}$</td>
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<td>3</td>
</tr>
<tr>
<td>$f_{42}$</td>
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</tr>
<tr>
<td>$f_{43}$</td>
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<tr>
<td>$f_{44}$</td>
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<tr>
<td>$f_{45}$</td>
<td>7-2</td>
<td>1</td>
</tr>
<tr>
<td>$f_{46}$</td>
<td>7-2</td>
<td>2</td>
</tr>
<tr>
<td>$f_{47}$</td>
<td>7-2</td>
<td>3</td>
</tr>
<tr>
<td>$f_{48}$</td>
<td>7-9</td>
<td>1</td>
</tr>
<tr>
<td>$f_{49}$</td>
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<td>2</td>
</tr>
<tr>
<td>$f_{50}$</td>
<td>7-9</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 6-3
Program 5-1 to Be Solved for Example Network

$$\min \sum_{i=1}^{50} f_i \ln f_i$$

subject to:

$$f_1 + f_2 + f_3 + f_4 + f_5 + f_6 + f_7 + f_8 + f_9 = 1174$$
$$f_{10} + f_{11} = 107$$
$$f_{12} + f_{13} + f_{14} + f_{15} + f_{16} + f_{17} + f_{18} + f_{19} + f_{20} = 235$$
$$f_{21} + f_{22} + f_{23} + f_{24} + f_{25} + f_{26} = 1424$$
$$f_{27} + f_{28} + f_{29} + f_{30} + f_{31} + f_{32} = 283$$
$$f_{33} + f_{34} + f_{35} = 369$$
$$f_{36} + f_{37} + f_{38} = 74$$
$$f_{39} + f_{40} + f_{41} = 493$$
$$f_{42} + f_{43} + f_{44} = 99$$
$$f_{45} + f_{46} + f_{47} = 54$$
$$f_{48} + f_{49} + f_{50} = 11$$
$$f_1 + f_3 + f_5 + f_7 + f_8 + f_9 + f_{10} + f_{12} + f_{14} + f_{16} + f_{18} + f_{19} + f_{20} = 1311$$
$$f_3 + f_4 + f_{14} + f_{15} + f_{22} + f_{28} + f_{34} + f_{37} + f_{40} + f_{43} = 1057$$
$$f_5 + f_6 + f_{16} + f_{17} + f_{23} + f_{29} + f_{35} + f_{38} + f_{41} + f_{44} = 412$$
$$f_7 + f_{18} + f_{24} + f_{30} + f_{45} + f_{48} = 1510$$
$$f_8 + f_{19} + f_{25} + f_{31} + f_{46} + f_{49} = 237$$
$$f_9 + f_{20} + f_{26} + f_{32} + f_{47} + f_{50} = 588$$

$f_i > 0 \quad i = 1, \ldots, 50$
notation, Table 6-3 shows the formulation of program 5-1 for this problem.

An explanatory note concerning the flow variables must be given here. Note that no flow variables for origin-destination pairs with only one path (e.g. $f_{1}^{13}$, $f_{1}^{46}$) are included in the program given in Table 6-3. These path flows are unnecessary in the solution of the program and are, in fact, known since for such a pair $rs$, $f_{1}^{rs} = q_{rs}$. For this network, these variables are left out to simplify the program along with the O-D constraints for these pairs. Note, however, that the values of the link volumes for links included in such a path must be reduced by the number of trips along the path when used in the constraint for that link. For example, constraint 12 in Table 6-3 represents the link flow conservation constraint for link 1-3. The equilibrium volume for this link is 1807, but the right-hand side of the constraint is reduced by the sum of the flows for pairs 1-3, 1-6, 1-7, and 1-8 to come up with a value of 1311 for the constraint.

The program in Table 6-3 was solved using the general nonlinear optimization software package GINO [11]. The actual GINO model is presented in Appendix B. The solution of this program is displayed in Table 6-4. (GINO does not provide integer solutions; the values in Table 6-4 are rounded to

-122-
<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Integer Value</th>
<th>Value</th>
<th>Integer Value</th>
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<td>f_34</td>
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Table 6-4 (cont'd)
Solution to Program in Table 6-3

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<tr>
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<tr>
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<td>21.768462</td>
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<tr>
<td>$f_{45}$</td>
<td>34.895383</td>
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<td>$f_{46}$</td>
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<td>$f_{48}$</td>
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</tr>
<tr>
<td>$f_{49}$</td>
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<td>1</td>
</tr>
<tr>
<td>$f_{50}$</td>
<td>2.738648</td>
<td>3</td>
</tr>
</tbody>
</table>

provide meaningful flow values. Thus some constraints may be off by a rounding error of one vehicle, which would not seriously affect the value of an impact fee assessment.) Thus the number of trips generated by an individual zone can be determined from this solution. For example, the number of vehicles generated by zone 9 on link 13-2 is $f_{19} + f_{31} + f_{49} = 16 + 22 + 1 = 39$.

The entire procedure was accomplished in a matter of hours once the network parameters were determined. The most time-consuming tasks in the procedure were the developing of the GINO input files shown in Appendix B (discussed below) and the running of GINO itself. Because of the size limitations of the GINO version used and the size of the program to be solved, GINO could not use its most efficient optimization routine (BFGS as described in Chapter 5).
6.3 Optimization Results and Applications

To show how impact fee assessments could be determined using these results, consider the following hypothetical example. Say that impact fee revenues are to be used to improve link 7-6. The number of trips generated by the development in zone 9 is given by $f_{18} + f_{30} + f_{48} = 104 + 141 + 7 = 252$. As it turns out, all trips to zone 8 use link 7-6, and so the column total for zone 8 from the trip table (= 128) gives the number of trips generated by this development using the link. Thus the development in zone 9 generates 66% of the new traffic and should be charged about twice as much as the development in zone 8 for improvements to link 7-6. (Note that under a flat fee system, the ratio between the developments' sizes could be used to determine the ratio between the impact fees charged. Assuming that generated trips are proportional to size, the column totals from the trip table could be used to determine this ratio. In this case the development in zone 9 would be responsible for 85% of the fees collected.) The actual amounts of fees collected would be determined by the costs of making the improvement and the particular objectives of the government in collecting the fees.
6.4 Implementation Details and Problems

The two computer routines needed to implement the entropy method are an equilibrium assignment program (including output of all shortest paths) and an optimization routine. As mentioned above, a program to perform the assignment procedure using the Frank-Wolfe algorithm was written for this purpose as is displayed in Appendix A. Sheffi [18] notes that the Frank-Wolfe algorithm is now included in some transportation planning packages. Many packages, however, particularly those designed for microcomputers, do not provide equilibrium assignment routines. In an actual application such a routine could probably be obtained without too much difficulty.

As previously indicated, the GINO program was used to perform the optimization phase of the procedure. The version of GINO used limits the size of the program to be solved to fifty variables and thirty constraints, excluding simple bounds on individual variables (such as the nonnegativity constraints on flow variables). Thus programs larger than the one formulated in the example (in terms of the number of variables) cannot be solved with this version of GINO although larger versions of GINO are available. There are other programs available for microcomputers that will solve programs with more variables, and much larger programs, of course, can be solved on mainframe computers.
Probably the most difficult task in a realistic application would be the interface between the assignment and optimization routines. In the example, the assignment program output was used to determine the path flow variables and to enumerate the constraints. Extraneous and redundant constraints were eliminated by inspection. The resulting program was then input as a text file and read by GINO.

In a larger application, this process would have been more complicated and time-consuming. Ideally, a routine to create the input file for the optimization program should be provided for use by agencies responsible for determining impact fee assessments. This routine would allocate one path flow variable for each shortest travel time path between every origin and destination, except for those O-D pairs with only one shortest path. It would output into a file readable by the optimization program an objective function of the flow variables of the form of equation 5-1. The interface routine would have to create a matrix of constraints in the form $Ax = b$, where $x$ is the vector of flow variables and $b$ is the vector of the right-hand sides of the constraints. The value $b_i$ is either an origin-destination flow $q_{rs}$ or a link volume (less the flows between unique-path O-D pairs using the link), depending on whether the constraint is an O-D flow or link volume constraint. The value of $A_{ij}$ is 1 if path $j$ is of the O-D pair for O-D flow constraint $i$ or if path $j$ uses the link.
for link volume constraint i; \( A_{ij} = 0 \) otherwise. Extraneous constraints could be eliminated by deleting rows of the matrix \( A \) that are linearly dependent on other rows. The routine would then write the constraints to the optimization input file.

Many optimization programs (including GINO) allow the user to input a starting point from which the search for the optimal solution will begin. Choice of a solution close to the optimal one will greatly reduce the convergence time for the optimization process. A simple initial solution that satisfies many of the constraints (which was used for this example) is to assign all path flow variables for an O-D pair an equal share of the flow for the pair. This initial solution automatically satisfies the O-D flow constraints and is probably much closer to the feasible region for the program than a random initial solution.

This process is certainly feasible if the optimization program takes input from files created outside the program itself. The key is writing the file in a readable form.
6.5 Conclusions

The example described in this chapter shows that it is possible to use the entropy formulation developed in Chapter 5 for impact fee assessment in a realistic-sized application. A simple equilibrium assignment program was written to perform the traffic assignment task for the network, and the GINO program was used to solve the nonlinear program. The information necessary for variable impact fee assessment for any highway project in the network was available in a matter of hours.

Many improvements can be made on the procedure used in this example to make the procedure more practical in actual use. A more efficient optimizer with more relaxed limits on problem size would probably have to be used in practice. An interface program between the assignment program and the optimizer should be provided as well. These issues are relatively easy to solve for any jurisdiction wishing to use transportation planning procedures and the entropy traffic allocation procedure for impact fee assessment.
CHAPTER SEVEN
SUMMARY AND CONCLUSIONS

Many areas are experiencing increased highway congestion resulting from rapid growth. In areas where highway congestion can be alleviated by highway widening and improvements, the impact fee is becoming a popular method for financing the improvements necessary to accommodate the increased traffic. Impact fees are charges to developers to pay for the roadway improvements made necessary by the construction of their developments.

Impact fees may be flat fees proportional to the size of the development, variable fees related to the impact of the development, or negotiated between the developer and the government. Only the variable fee can ensure that certain desirable objectives are met, including that the costs of improvements are covered and that costs are allocated equitably among developments according to the traffic impacts the developments have on the roads to be improved. Variable fees must be set so that certain legal, administrative, economic, and technical issues are addressed.

One way in which improvement costs are being allocated to developments in the setting of impact fees is through the use of highway cost allocation methods. Three common allocation
methods are incremental allocation, proportional allocation, and uniform traffic removal. Uniform removal is equivalent to proportional allocation when applied to impact fee assessment since a vehicle from any development is assumed to have equal traffic impacts on a road. While incremental allocation is easier to apply using traditional methods such as urban transportation techniques, it does not meet the goal of consistent allocations among developments because developments must be arbitrarily ordered. Proportional allocation can be used to determine consistent allocation, but it is much more difficult to apply. This difficulty arises from the need to know the split of traffic on a roadway among the developments generating the trips.

Equilibrium traffic assignment is the preferred method for determining the total traffic increases on roadways resulting from the construction of a group of developments. Unfortunately, equilibrium assignment does not determine unique flows on the paths from an origin to a destination. This property means that the number of trips using a highway segment that were generated by any particular development cannot be determined in a proportional allocation. Other commonly used assignment methods do not have this property, but they are inferior to equilibrium assignment in terms of the accuracy of assigned traffic volumes.
Most existing impact fee programs use methods other than equilibrium assignment and proportional allocation. Incremental allocation may be employed, or an all-or-nothing or capacity restraint assignment may be performed. These provide results that may be inaccurate or inconsistent among developments. A case study presented in this thesis demonstrates that this can occur quite easily in practice, and that the traffic allocations are sensitive to the modeling assumptions made.

Several methods were examined in an attempt to provide consistent allocations when equilibrium assignment is used. Averaging all possible incremental allocation orderings for a group of developments provides consistent allocations, but the computational cost associated with this method is too high to be practical when there are many developments under consideration. Using the intermediate steps in the Frank-Wolfe algorithm commonly used in performing equilibrium assignment was shown not to provide consistent allocations for many networks. The method that was the most effective among those analyzed employed an entropy formulation to determine the most likely allocation of trips to paths between each origin and destination.

The entropy formulation involves solving a nonlinear program that can have many variables in realistic applications.
An example of an actual urban network was used to show that the entropy formulation can be used in a practical setting. A general optimization program was used to solve the program. An interface between the equilibrium assignment and optimization programs would have to be provided for the method to become useful in most real-life settings.

Many impact fee programs are in place today, and many more will continue to be used in high-growth areas. To date, however, these programs have not been designed to assess fees that are consistent among different developments. Highway cost allocation and urban transportation planning procedures can be used to assess equitable fees if the entropy method is employed in conjunction with them. This will ensure that all developments are treated equitably and that the fees are assessed so that they reflect the true impacts associated with individual developments.
REFERENCES


Appendix A
Equilibrium Assignment Program Code

The program code displayed in this appendix solves for the user equilibrium traffic flows on a network. The program uses the Frank-Wolfe algorithm and the methods described in Section 5.5.1. This program was used to perform the traffic assignment task in the example of Chapter 6.

This program was written in Turbo PASCAL to run on an IBM PC microcomputer. It reads the network and origin destination data from either the keyboard or a disk file. (While this data cannot be edited in this program, two companion programs are used to edit data.) The output is to a printer although the program could be easily modified to provide output to a different output device. An example of the output is shown in Figure 6-2.

This program also performs the task of finding all shortest paths between each origin and destination. The method described in Section 5.5.2 is used. These paths are provided as part of the program's output (see Figure 6-2).
program paths (input, output);

const
  NoOfIterations=200;  {user-defined convergence criterion}
  TTT=0.025;  {tolerance for shortest-path finding routine}
  epsilon=0.0001;  {tolerance for line search}
  MaxT=9999; MaxOD=9; MaxNodes=13; MaxLinks=21;

type
  NodeArrayI=array[1..MaxNodes] of integer;
  NodeArrayR=array[1..MaxNodes] of real;
  LinkArrayI=array[1..MaxLinks] of integer;
  LinkArrayR=array[1..MaxLinks] of real;
  ODArray=array[1..MaxOD,1..MaxOD] of integer;
  TitlString=string[18];
  Node10Array=array[1..MaxNodes,1..10] of integer;
  Point=record
    Valu:integer;
    end;
  Net=record
    BVal:integer;
    AVal:real;
    CVal:real;
    end;
  ODNode=record
    Valu:integer;
    end;
  OMat=record
    ODVal:array[1..MaxOD] of integer;
    end;
var
  i,j,k,nodes,iteration,links,origins,dests:integer;
  alpha:real;
  z:LinkArrayI;
  x,y,a,c,tt:LinkArrayR;
  pntr,orig,dest,p:NodeArrayI;
  OD:ODArray;
  Titl:TitlString;
  FileName:String[10];
  ans:Char;
function deriv(aa:real;a,c:LinkArrayR;x,y:LinkArrayR):real;
{calculates derivative for line search}
var
  dum1,dum2,dum3,dum4,dum5:real;
  k:integer;
begin
  dum5:=0;
  for k:=1 to links do
  begin
    dum :=y[k]-x[k];
    dum2:=x[k]+aa*duml;
    dum3:=a[k]*(1+0.15*Sqr(Sqr(dum2/c[k])));
    dum4:=duml*dum3;
    dum5:=dum5+dum4;
  end;
  deriv:=dum5;
end;

procedure SwapI(var x,y:integer);
{swaps the values of 2 integer variables--used in sorting}
var temp:integer;
begin
  temp:=x;
  x:=y;
  y:=temp;
end;

procedure SwapR(var x,y:real);
{swaps the values of 2 real variables--used in sorting}
var temp:real;
begin
  temp:=x;
  x:=y;
  y:=temp;
end;

procedure bisect(var alpha:real);
{perform bisection line search to find α}
var done:boolean;al,b1,xx:real;
begin
  a1:=0;
  b1:=1;
  repeat
    xx:=(b1+a1)/2;
    if deriv(xx,a,c,x,y)<0 then a1:=xx else b1:=xx;
    if (b1-a1)<2*epsilon then done:=true;
    until done;
  alpha:=(b1+a1)/2;
end;
procedure ReadNet;
{read in network data from disk file}
var
    PointFile: file of Point;
    PointRec: Point;
    NetFile: file of Net;
    NetRec: Net;
    i: integer;
begin
    assign(PointFile, FileName+'PNT');
    reset(PointFile);
    seek(PointFile, 0); read(PointFile, PointRec);
    links:= PointRec.Valu;
    seek(PointFile, 1); read(PointFile, PointRec);
    nodes:= PointRec.Valu;
    for i:= 1 to nodes+1 do
    begin
        seek(PointFile, i+1); read(PointFile, PointRec);
        with PointRec do
        begin
            pntr[i]:= Valu;
        end;
    end;
    close(PointFile);
    assign(NetFile, FileName+'NET');
    reset(NetFile);
    for i:= 1 to links do
    begin
        seek(NetFile, i-1); read(NetFile, NetRec);
        with NetRec do
        begin
            z[i]:= BNod; a[i]:= AVal; c[i]:= CVal;
        end;
    end;
    close(NetFile);
end;

procedure WriteNet;
{write network data to disk file}
var
    PointFile: file of Point;
    PointRec: Point;
    NetFile: file of Net;
    NetRec: Net;
begin
  writeln('Name of file (do not include extension)??');
  readln(FileName);
  assign(PointFile,FileName+'.PNT');
  rewrite(PointFile);
  with PointRec do
  begin
    Valu:=1;
    write(PointFile,PointRec);
    Valu:=nodes;
    write(PointFile,PointRec);
    for i:=1 to nodes+1 do
      begin
        Valu:=pntr[i];
        write(PointFile,PointRec);
      end;
    end;
  close(PointFile);
  assign(NetFile,FileName+'.NET');
  rewrite(NetFile);
  with NetRec do
  begin
    BNode:=0;AVal:=0;CVal:=0;
    for i:=1 to links do
      begin
        BNode:=z[i];AVal:=a[i];CVal:=c[i];
        write(NetFile,NetRec);
      end;
    end;
  close(NetFile);
end;

procedure EnterNet;
{enter network data from keyboard}
var
  xx,yy:LinkArrayI;
  aa,cc:LinkArrayR;
  ans:char;
  i,j,k,x,y:integer;
begin
  nodes:=0;
  links:=0;
  ans:='Y';
  while ans<>'N' do
  begin
    ClrScr;
    links:=links+1;
    writeln('Link # ',links);
    writeln;
    writeln('Enter endpoints--separate by space');
    readln(x,y);
    xx[links]:=x;
    yy[links]:=y;
end;
if x1>nodes then nodes:=x1;
if y1>nodes then nodes:=y1;
write('Link performance functions will be of ');
writeln('form:');
writeln;
writeln('  T = A*(1+.15*(X/C)^4)');
writeln;
write('Enter A and C values for this link--');
writeln('separate by space');
readln(aa[links],cc[links]);
write('Enter another link (Y/N)?');
readln(ans);
if ans='n' then ans:='N';
end;
pntr[1]:=1;
for j:=2 to nodes do
  pntr[j]:=0;
for i:=1 to links do
  begin
    pntr[xx[i]+1]:=pntr[xx[i]+1]+1;
  end;
for j:=2 to nodes do
  begin
    pntr[j]:=pntr[j]+pntr[j-1];
  end;
pntr[nodes+1]:=links+1;
for j:=1 to nodes do
  begin
    k:=pntr[j];
    i:=1;
    while k<pntr[j+1] do
      begin
        if xx[i]=j then
          begin
            z[k]:=yy[i];
            a[k]:=aa[i];
            c[k]:=cc[i];
            k:=k+1;
          end;
        i:=i+1;
      end;
  end;
end;
for i:=1 to nodes do
  for j:=pntr[i] to pntr[i+1]-2 do
    for k:=pntr[i] to pntr[i+1]-2 do
      begin
        if z[k] > z[k+1] then
          begin
            SwapI(z[k], z[k+1]);
            SwapR(a[k], a[k+1]);
            SwapR(c[k], c[k+1]);
          end;
      end;

write('Save network data in file (Y/N)?');
readln(ans);
if ans='y' then ans:='Y';
if ans='Y' then WriteNet;
end;

procedure WriteOD;
{write O-D data to file}
var
  NodeFile:file of ODNode;
  NodeRec:ODNode;
  ODFile:file of ODMat;
  ODRec:ODMat;
begin
  writeln('Name of file (do not include extension)?');
  readln(FileName);
  assign(NodeFile, FileName+'.NOD');
  rewrite(NodeFile);
  with NodeRec do
    begin
      Valu:=origins;write(NodeFile, NodeRec);
      Valu:=dests;write(NodeFile, NodeRec);
      for i:=1 to origins do
        begin
          Valu:=orig[i];
          write(NodeFile, NodeRec);
        end;
      for i:=1 to dests do
        begin
          Valu:=dest[i];
          write(NodeFile, NodeRec);
        end;
    end;
  close(NodeFile);
  assign(ODFile, FileName+'.OD');
  rewrite(ODFile);
end;
with ODRec do
begin
  for i:=1 to origins do
    begin
      for j:=1 to dests do
        ODVal[j]:=OD[i,j];
      write(ODFile,ODRec);
    end;
  close(ODFile);
end;

procedure EnterOD(var total:integer;var list:NodeArrayI;
Title:TitleString);
{enter O-D data from keyboard}
  var temp,i:integer;
  begin
    temp:=1;
    total:=0;
    while temp>0 do
      begin
        ClrScr;
        writeln(Title);
        writeln;
        i:=1;
        while i<=total do
          begin
            write('i :=i+1;
            list[i];
          end;
        writeln;
        writeln;
        write('Enter number of new node ');
        write('(Enter "0" to end list ) ');
        readln(temp);
        if temp>0 then
          begin
            total:=total+1;
            list[total]:=temp;
          end;
      end;
end;
procedure ReadOD;
{Read O-D data from file}
var
  NodeFile: file of ODNode;
  NodeRec: ODNode;
  ODFile: file of ODMat;
  ODRec: ODMat;
begin
  assign(NodeFile, FileName+' .NOD');
  reset(NodeFile);
  seek(NodeFile, 0); read(NodeFile, NodeRec);
  origins := NodeRec.Valu;
  seek(NodeFile, 1); read(NodeFile, NodeRec);
  dests := NodeRec.Valu;
  for i := 1 to origins do
    begin
      seek(NodeFile, i+1); read(NodeFile, NodeRec);
      with NodeRec do
        begin
          orig[i] := Valu;
        end;
    end;
  for i := 1 to dests do
    begin
      seek(NodeFile, i+origins+1); read(NodeFile, NodeRec);
      with NodeRec do
        begin
          dest[i] := Valu;
        end;
    end;
  close(NodeFile);
  assign(ODFile, FileName+' .OD');
  reset(ODFile);
  for i := 1 to origins do
    begin
      seek(ODFile, i-1); read(ODFile, ODRec);
      with ODRec do
        begin
          for j := 1 to dests do
            OD[i, j] := ODMat[j];
        end;
    end;
  close(ODFile);
end;
procedure ShortPath;
{find shortest paths from each origin to all destinations using label-correcting algorithm}
var
  j,k,temp,top:integer;
  SeqEmpty:boolean;
  seq:NodeArray1;
  L:NodeArrayR;
begin
  top:=orig[1];
  for j:=1 to nodes do
    begin
      p[j]:=0;
      if j=top then
        begin
          seq[j]:=MaxT;
          L[j]:=0;
        end
      else
        begin
          seq[j]:=0;
          L[j]:=MaxT;
        end;
    end;
  SeqEmpty:=false;
  while not SeqEmpty do
    begin
      k:=pntr[top];
      while k<pntr[top+1] do
        begin
          if L[top]+tt[k]<L[z[k]] then
            begin
              L[z[k]]:=L[top]+tt[k];
              p[z[k]]:=top;
              if seq[z[k]]<>0 then
                begin
                  seq[z[k]]:=seq[top];
                  seq[top]:=z[k];
                end
              else if seq[z[k]]<0 then
                begin
                  j:=0;
                  repeat j:=j+1 until seq[j]=MaxT;
                  seq[j]:=z[k];
                  seq[z[k]]:=MaxT;
                end;
            end
          k:=k+1;
        end;
    end;
end;
procedure assignment;
{assign O-D flows to paths found in ShortPath procedure}
var j,k,bnode:integer;
begin
  for j:=1 to dests do
  begin
    if (OD[i,j]>0) and (orig[i]<.dest[j]) then
    begin
      bnode:=dest[j];
      while bnode<>orig[i] do
      begin
        k:=ptr[p[bnode]]-1;
        repeat
          k:=k+1;
          if z[k]=bnode then
            y[k]:=y[k]+int(OD[i,j]);
        until z[k]=bnode;
        bnode:=p[bnode];
      end;
    end;
  end;
end;

procedure WriteNodes(bnode:integer;count:integer;
p2:Node10Array;path:NodeArrayI);
{procedure to output nodes in shortest paths found in
FindPaths procedure}
var
  anode,z,k,h:integer;
  MakePath:boolean;
begin
  if (p2[bnode,1]>0) and (bnode<>orig[i]) then
  begin
    z:=0;
    repeat z:=z+1 until p2[bnode,z+1]=0;
    count:=count+1;
    for k:=1 to z do
    begin
      anode:=p2[bnode,k];
      MakePath:=True;
      for h:=1 to count-1 do
      begin
        if anode=path[h] then MakePath:=False;
if MakePath then
    begin
        path[count]:=anode;
        WriteNodes(anode,count,p2,path);
    end;
end
else
    begin
        for k:=1 to count do
            write(LST,path[k]:4);
        writeln(LST);
    end;
end;

procedure PrintPaths(bnode:integer;p2:Node10Array);
{ print shortest paths found by FindPaths procedure }
var count:integer;
    path:NodeArrayI;
begin
    count:=1;
    path[1]:=bnode;
    WriteNodes(bnode,count,p2,path);
end;

procedure FindPaths;
{ find all shortest paths from each origin to every destination for input to entropy program }
var c,k,temp,top,n:integer;
    SeqEmpty:boolean;
    seq:NodeArrayI;
    L:NodeArrayR;
    p2:Node10Array;
begin
    writeln(LST);
    write(LST,'Paths (in reverse order) from ',orig[i]);
    writeln(' to ',dest[j]);
top:=orig[i];
for c:=1 to nodes do
    begin
        for temp:=1 to 10 do
            p2[c,temp]:=0;
        if c=top then
            begin
                seq[c]:=MaxT;
                L[c]:=0;
            end
            else
        begin
            ...
else
  begin
    seq[c] := 0;
    L[c] := MaxT;
  end;
  end;
SeqEmpty := false;
while not SeqEmpty do
begin
  k := ptr[top];
  while k < ptr[top+1] do
begin
  if abs(L[top] + tt[k] - L[z[k]]) < TTT then
begin
    n := 0;
    repeat n := n + 1 until p2[z[k], n] = 0;
    p2[z[k], n] := top;
  end
else if L[top] + tt[k] < L[z[k]] then
begin
  L[z[k]] := L[top] + tt[k];
  p2[z[k], 1] := top;
  for n := 2 to 10 do
  p2[z[k], n] := 0;
  if seq[z[k]] < 0 then
begin
    seq[z[k]] := seq[top];
    seq[top] := z[k];
  end
else if seq[z[k]] = 0 then
begin
  c := 0;
  repeat c := c + 1
  until seq[c] = MaxT;
  seq[c] := z[k];
  seq[z[k]] := MaxT;
end;
  k := k + 1;
end;
  temp := top;
  top := seq[top];
  seq[temp] := -1;
  if top = MaxT then SeqEmpty := true;
end;
PrintPaths(dest[j], p2);
end;
begin {main program}
ClrScr;
{input network and O-D data)
writeln('Name of input file for network data');
writeln('<RETURN> to enter data from keyboard');
readln(FileName);
if FileName<>'' then ReadNet else EnterNet;
ClrScr;
writeln('Name of input file for origin-destination data');
write('<RETURN> to enter data from keyboard ');
readln(FileName);
if FileName<>'' then ReadOD else
begin
  Titl:='Origin Nodes:';
EnterOD(origins,orig,Titl);
  Titl:='Destination Nodes:';
EnterOD(dests,dest,Titl);
  for i:=1 to origins do
    begin
      ClrScr;
      writeln('Enter origin-destination flows');
      writeln;
      for j:=1 to dests do
        begin
          if orig[i]=dest[j] then
            OD[i,j]:=0
          else
            begin
              write('Flow from node ',orig[i]);
              write(' to node ',dest[j],': ');
              readln(OD[i,j]);
            end;
        end;
      end;
      write('Save O-D data in file (Y/N)?');
      readln(ans);
      if ans='y' then ans:='Y';
      if ans='Y' then WriteOD;
    end;
for k:=1 to links do
begin
  tt[k]:=a[k];
  x[k]:=0;
  y[k]:=0;
end;
iteration:=0;


repeat
ClrScr;
writeLn('Running iteration ',iteration);
for i:=1 to origins do
begin
  ShortPath;
  assignment;
end;
if iteration>0 then bisect(alpha) else alpha:=1;
for k:=1 to links do
begin
  \{volume update for current iteration\}
  x[k]:=x[k]+(y[k]-x[k])*alpha;
  tt[k]:=a[k]*(1+0.15*sqr(sqr(x[k]/c[k])));
  y[k]:=0;
end;
iteration:=iteration+1;
until iteration>NoOfIterations;
\{output to printer\}
writeLn(LST);
writeLn(LST,'User equilibrium flows:');
writeLn(LST);
writeLn(LST,' Link A-Node B-Node Volume Time');
writeLn(LST);
j:=1;
for k:=1 to links do
begin
  write(LST,k:8);
  while pntr[j+1]<k do j:=j+1;
  writeLn(LST,j:8,z[k]:8,x[k]:8:0,tt[k]:8:3);
end;
writeLn(LST);
for i:=1 to origins do
for j:=1 to dests do
  if (orig[i]<dest[j]) and (OD[i,j]>0) then FindPaths;
end.
Appendix B
GINO Model for Entropy Example

This appendix contains a listing of the model used by GINO to solve the nonlinear program in the example of Chapter 6. The solution procedures for the model are described in Section 5.5.3.

The appendix consists of two of the input files read by GINO for the example problem. The first is denoted "MODEL" by GINO and consists of the nonlinear program to be solved. Equation 1) in the model is the objective function for the entropy formulation. Equations 2) through 18) are the equality constraints of the formulation; these include the O-D flow constraints and the link volume constraints. Note that the model corresponds to the formulation in Table 6-2.

The second file consists of the nonnegativity constraints for the path flow variables. "SLB" stands for "simple lower bound"; thus SLB Xl 0.00 means that the variable Xl must be greater than or equal to zero.

Also input to GINO were the initial input values for the flow variables as described in Section 6.4. This file consists only of data and is not presented here.
MODEL:

1) \[ \text{MIN} = \log(x_1) + \log(x_2) * x_2 + \log(x_3) * x_3 + \log(x_4) * x_4 + \log(x_5) * x_5 + \log(x_6) * x_6 + \log(x_7) * x_7 + \log(x_8) * x_8 + \log(x_9) * x_9 + \log(x_{10}) * x_{10} + \log(x_{11}) * x_{11} + \log(x_{12}) * x_{12} + \log(x_{13}) * x_{13} + \log(x_{14}) * x_{14} + \log(x_{15}) * x_{15} + \log(x_{16}) * x_{16} + \log(x_{17}) * x_{17} + \log(x_{18}) * x_{18} + \log(x_{19}) * x_{19} + \log(x_{20}) * x_{20} + \log(x_{21}) * x_{21} + \log(x_{22}) * x_{22} + \log(x_{23}) * x_{23} + \log(x_{24}) * x_{24} + \log(x_{25}) * x_{25} + \log(x_{26}) * x_{26} + \log(x_{27}) * x_{27} + \log(x_{28}) * x_{28} + \log(x_{29}) * x_{29} + \log(x_{30}) * x_{30} + \log(x_{31}) * x_{31} + \log(x_{32}) * x_{32} + \log(x_{33}) * x_{33} + \log(x_{34}) * x_{34} + \log(x_{35}) * x_{35} + \log(x_{36}) * x_{36} + \log(x_{37}) * x_{37} + \log(x_{38}) * x_{38} + \log(x_{39}) * x_{39} + \log(x_{40}) * x_{40} + \log(x_{41}) * x_{41} + \log(x_{42}) * x_{42} + \log(x_{43}) * x_{43} + \log(x_{44}) * x_{44} + \log(x_{45}) * x_{45} + \log(x_{46}) * x_{46} + \log(x_{47}) * x_{47} + \log(x_{48}) * x_{48} + \log(x_{49}) * x_{49} + \log(x_{50}) * x_{50} = 1311 \]

2) \[ x_1 + x_2 + x_3 + x_4 + x_5 + x_6 + x_7 + x_8 + x_9 = 1174 \]

3) \[ x_{10} + x_{11} = 107 \]

4) \[ x_{12} + x_{13} + x_{14} + x_{15} + x_{16} + x_{17} + x_{18} + x_{19} + x_{20} = 235 \]

5) \[ x_{21} + x_{22} + x_{23} + x_{24} + x_{25} + x_{26} = 1424 \]

6) \[ x_{27} + x_{28} + x_{29} + x_{30} + x_{31} + x_{32} = 283 \]

7) \[ x_{33} + x_{34} + x_{35} = 369 \]

8) \[ x_{36} + x_{37} + x_{38} = 74 \]

9) \[ x_{39} + x_{40} + x_{41} = 493 \]

10) \[ x_{42} + x_{43} + x_{44} = 99 \]

11) \[ x_{45} + x_{46} + x_{47} = 54 \]

12) \[ x_{48} + x_{49} + x_{50} = 11 \]

13) \[ x_1 + x_3 + x_5 + x_7 + x_8 + x_9 + x_{10} + x_{12} + x_{14} + x_{16} + x_{18} + x_{19} + x_{20} = 1311 \]

14) \[ x_3 + x_4 + x_{14} + x_{15} + x_{22} + x_{28} + x_{34} + x_{37} + x_{40} + x_{43} = 1057 \]

15) \[ x_5 + x_6 + x_{16} + x_{17} + x_{23} + x_{29} + x_{35} + x_{38} + x_{41} + x_{44} = 412 \]

16) \[ x_7 + x_{18} + x_{24} + x_{30} + x_{45} + x_{48} = 1510 \]

17) \[ x_8 + x_{19} + x_{25} + x_{31} + x_{46} + x_{49} = 237 \]

18) \[ x_9 + x_{20} + x_{26} + x_{32} + x_{47} + x_{50} = 588 \]

END
| SLB | X1 | .000000 |
| SLB | X2 | .000000 |
| SLB | X3 | .000000 |
| SLB | X4 | .000000 |
| SLB | X5 | .000000 |
| SLB | X6 | .000000 |
| SLB | X7 | .000000 |
| SLB | X8 | .000000 |
| SLB | X9 | .000000 |
| SLB | X10 | .000000 |
| SLB | X11 | .000000 |
| SLB | X12 | .000000 |
| SLB | X13 | .000000 |
| SLB | X14 | .000000 |
| SLB | X15 | .000000 |
| SLB | X16 | .000000 |
| SLB | X17 | .000000 |
| SLB | X18 | .000000 |
| SLB | X19 | .000000 |
| SLB | X20 | .000000 |
| SLB | X21 | .000000 |
| SLB | X22 | .000000 |
| SLB | X23 | .000000 |
| SLB | X24 | .000000 |
| SLB | X25 | .000000 |
| SLB | X26 | .000000 |
| SLB | X27 | .000000 |
| SLB | X28 | .000000 |
| SLB | X29 | .000000 |
| SLB | X30 | .000000 |
| SLB | X31 | .000000 |
| SLB | X32 | .000000 |
| SLB | X33 | .000000 |
| SLB | X34 | .000000 |
| SLB | X35 | .000000 |
| SLB | X36 | .000000 |
| SLB | X37 | .000000 |
| SLB | X38 | .000000 |
| SLB | X39 | .000000 |
| SLB | X40 | .000000 |
| SLB | X41 | .000000 |
| SLB | X42 | .000000 |
| SLB | X43 | .000000 |
| SLB | X44 | .000000 |
| SLB | X45 | .000000 |
| SLB | X46 | .000000 |
| SLB | X47 | .000000 |
| SLB | X48 | .000000 |
| SLB | X49 | .000000 |
| SLB | X50 | .000000 |