A TRAFFIC ASSIGNMENT MODEL PROPOSAL FOR SUSTAINABLE URBAN TRANSPORTATION

(SÜRDÜRÜLEBİLİR KENT İÇİ ULAŞIM İÇİN BİR TRAFİK ATAMA MODELİ ÖNERİMİ)

by

Ayla ALKAN, B.S.

Thesis

Submitted in Partial Fulfillment
of the Requirements
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ABSTRACT

Today, both in developed and developing countries urban population is increasing and cities are growing without adequate planning. As a natural conclusion, urban transportation problem is getting bigger. The solutions those arise when only economic part is taken into account have lost validity since they do not usually present social equity and are not usually environmentalist. Otherwise, sustainability is an emerging issue as a direct consequence of the continued city population increase and transportation should be discussed as a giant part of it. In this study, general sustainability measures are defined at first, and specialized for transportation. Many transportation effects are studied and categorized as social, environmental and economical, to create a system which succeeds a sustainable traffic management. A mathematical model is formed by using traffic impacts' cost functions acquired from literature. Apart from other studies in this field, our model is formed as a multi-objective model. In accordance with the definition of sustainability, one objective function minimizes the social and environmental costs and the other minimizes the economic costs. Moreover, our model has a bi-level structure which avails us to manage traffic in upper part, and to assign traffic to links in lower part. We apply the Pareto simulated annealing algorithm to solve our problem while we use the Frank-Wolfe algorithm to do traffic assignment in user equilibrium structure. Both algorithms are coded in Matlab program and run over a well-known city network. Finally, the arrangements which have been done during programming are presented, conclusions are discussed and proposals for future search are added.

RESUMÉ

De nos jours, dans les pays développés ou en voie de développement la population urbaine augmente et les villes s’accroissent sans planification suffisante. En conséquence, les problèmes de transport urbain augmentent. Les solutions trouvées, en ne prenant compte que le côté économique, ne sont plus efficaces car elles ne sont pas écologiques et n’offrent pas d’égalité sociale. Pourtant la continuation, qui est un résultat direct de l’augmentation urbaine, est un sujet qui devrait être traité en urgence et les transports en ville devraient être considérés comme un de ces aspects. Dans cette étude, les critères de la continuation générale ont été définis en premier et ont été appliqués aux transports. Afin de créer un système qui assure une gestion de la circulation, nous avons travaillé sur les effets de la circulation et ceux-ci ont été classifiés du point de vue économique, environnemental et social. Un modèle mathématique a été créé en utilisant les fonctions qui donnent le coût des effets de la circulation acquis par la documentation technique. Notre modèle a été formé comme étant multi fonctionnel, ce qui est différent des autres recherches effectuées dans ce domaine. En accord avec la définition de la continuation, l’un des objectifs est la fonction sociale et environnementale des coûts minimums et l’autre est la fonction économique des coûts minimums. D’autre part, notre modèle va nous permettre de gérer la circulation supérieure et possède une structure à deux niveaux.qui pourra réaliser la nomination de la circulation inférieure. Pour résoudre notre problème, nous avons appliqué une assimilation de l’algorithme d’amorcement Pareto et nous avons utilisé l’algorithme Frank-Wolfe pour nommer la circulation qui s’imprègne de la structure équilibrée usagère. Ces deux algorithmes ont été utilisés sur un réseau urbain connu et codifié selon le programme Matlab. Enfin, les réglementations réalisées pendant la programmation ont été présentées. Nous avons discuté des résultats et nous avons fait des propositions pour les travaux à venir.

ÖZET

Günümüzde hem gelişmiş hem de gelişmekte olan ülkelerde kent popülasyonu artmakta ve şehirler yeterli planlama olmadan büyümektedirler. Bunun doğal bir sonucu olarak, kent içi ulaşım problemi büyümektedir. Sadece ekonomik tarafın hesaba katılması ile oluşan çözümler sosyal eşitlik sunmadığı ve çevreci olmadıkları için geçerliliklerini yitirmişlerdir. Halbuki, sürdürülebilirlik süregelen kent popülasyonu artışının doğrudan bir sonucu olarak acil ele alınması gereken bir konudur ve kent içi ulaşım bunun büyük bir parçası olarak müzakere edilmelidir. Bu çalışmada, ilk olarak genel sürdürülebilirlik ölçütleri tanımlanmış ve ulaşım için özelleştirilmiştir. Sürdürülebilir bir trafik yönetimi sağlayan bir sistem yaratmak için, ulaşımın çok sayıda etkisi üzerinde çalışılmış ve bunlar sosyal, çevresel ve ekonomik olarak sınıflandırılmıştır. Literatürden edinilen trafik etkilerinin maliyetlerini veren fonksiyonlar kullanılarak bir matematiksel model oluşturulmuştur. Bu alanda yapılan diğer araştırmalardan farklı olarak, bizim modelimiz çok-amaçlı bir model olarak oluşturulmuştur. Sürdürülebilirliğin tanımı ile uyumlu olarak, bir amaç fonksiyonu sosyal ve çevresel maliyetleri enküçükler, diğeri ekonomik maliyetleri enküçükler. Bundan başka, modelimiz üst kısımda trafiği yönetmemizi sağlayacak ve alt kısımda yollara trafik atamasını yapacak şekilde iki-seviyeli bir yapıya sahiptir. Problemimizi çözmek için Pareto tavlama benzetimi algoritması uygulanmış, kullanıcı-dengeli yapıyı benimseyen trafik ataması yapmak için Frank-Wolfe algoritması kullanılmıştır. Her iki algoritma da Matlab ile kodlanmış ve iyi bilinen bir şehir ağı üzerinde çalıştırılmıştır. Son olarak, programlama esansında yapılan düzenlemeler sunulmuş, sonuçlar üzerinde tartışılmış ve gelecekteki çalışmalar için önerilerde bulunulmuştur.

1 INTRODUCTION

In today's world, economic bias, technological development and accompanying obligations, centralization of education opportunities drive people to live in cities. As a consequence cities are getting larger and managing life in cities gets harder. Sustainability is getting an obligate issue in solutions for city problems. Problem in urban transportation is similar with the other problems in city life. Growing demand in transportation systems causes people to lose more time in traffic and loss of productivity accompanies. Growing damages to social life and health of humans, resuming more resources to construct facilities, growing damages to environment and ecology are giant problems. Thus, sustainable traffic management is indispensible part of sustainable cities.

Social awareness is also influencing transportation policy everywhere for concerns with the environment and with the social costs of existing transportation systems are evident everywhere. Hence transportation is widely viewed not merely from a narrow traditional economic perspective but also in terms of how it impacts environmental and ecological systems as well as the society as a whole, and the rural poor in particular [1]. Transportation agencies and providers strive to keep their assets in acceptable condition so as to offer desirable levels of service in the most cost-effective manner not only regarding economical but also socially and environmentally too. Consistent with such efforts is the need for best traffic management method based on impacts of existing transportation systems.

Transportation planning can be grouped in four phases, as trip generation, trip distribution, modal split and traffic assignment. Modal split and traffic assignment are the ways of traffic management and you can reach sustainable solutions by running these phases. Modal split is applied when different modes are available for forecasting travel amount for each mode. Traffic assignment is last step and applied to determine the exact routings of trips. Traffic assignment is of use to reach a comfort, balanced traffic and is base way for sustainable transportation. Traffic assignment has some tools for preventing from congestion on ways: Toll optimization, district pricing, road adding and road widening. Using these tolls traffic manager could find best solution satisfying his object for a city network.

There are several studies on sustainable traffic management in the literature. Some of them propose decision making rules basing on spatial statistical results, some of them propose simulation tolls basing on observed data and forecasting and some of them propose analytical solution methods by forming mathematical models. Up to present, mathematical models have been formed on decreasing or increasing one effect of traffic and used general optimization techniques to solve. They usually formed their models with an objective function decreasing emission level or increasing income from tolls of ways, in bi-level form and solved with algorithms which are poor in reaching global optimum.

Despite many studies in the literature, lack of a comprehensive study which takes whole impacts of traffic into account and reaches a good solution is felt. Our study first explores and evaluates all impacts of urban transportation, then gathers cost functions of these impacts from several studies to study on. Whole impacts are categorized as economic, social and environmental in accordance with sustainability and a multi-objective model is formed which could be of use to get a balancing solution between these impacts. Pareto simulated annealing method, a strong solution algorithm for large problems, is applied to solve the model. Toll pricing scenario is used as traffic management tool. A program is written in Matlab language and run over a widely known city network, Sioux Falls network. The program is tried for several times with different parameters and arrangements to reach a good solution concept. After then, many replications are done and a new solution cluster is obtained in each replication. The solution clusters are compared and non-dominated solutions are presented as Pareto front to give the chance to traffic manager to choose his own best fitting solution. Comments and some proposals for future work are done at the end.

This thesis is organized as follows: In Chapter 2, transportation system and sustainability, transportation planning phases and bi-level programming is described. In Chapter 3, transportation impacts are explained in detail and grouped, and our model is formed. Chapter 4 includes explanation about solution algorithms, explanation about computer program and results of computations. Finally, we conclude the thesis and give some possible ideas for future research in Chapter 5.

2 LITERATURE REVIEW

2.1 TRANSPORTATION SYSTEM

The transportation system in many countries often constitutes the largest public-sector investment. The economic vitality and global competitiveness of a region or country are influenced by the quantity and quality of its transportation infrastructure because such facilities provide mobility and accessibility for people, goods and services, and thereby play an important role in the economic production process.

The new millennium is characterized by continued growth in commercial and personal travel demand, and transportation agencies and providers strive to keep their assets in acceptable condition so as to offer desirable levels of service in the most cost-effective manner and within available resources. Consistent with such efforts is the need for best-practices evaluation and monitoring of the expected impacts of alternative investment decisions, policies and other stimuli on the operations of existing or planned transportation systems and their environments [2]. Growing demand results in resuming more resources, growing damages to environment and ecology each day, meanwhile social equity for both in available and planned project is still a challenge.

2.2 SUSTAINABILITY IN TRANSPORTATION

As we enter the twenty-first century it has become increasingly clear that existing transportation systems throughout the world suffer from major deficiencies and are not promoting sustainable development. Every country in the world recognizes the central role that transportation plays in economic growth and feels compelled to meet proliferating demands for mobility because of the pressures imposed by globalization.

Passenger transportation is also subject to similar pressures, as people demand ever faster, reliable, and convenient travel service [3].

Social awareness is also influencing transportation policy everywhere for concerns with the environment and with the social costs of existing transportation systems are evident everywhere. Hence transportation is widely viewed not merely from a narrow traditional economic perspective but also in terms of how it impacts environmental and ecological systems as well as the society as a whole, and the rural poor in particular [1].

The challenge, therefore, is to develop the transportation system in a sustainable manner. While this is a laudable goal, one of the difficulties for transportation professionals is that there are many definitions for sustainable development and sustainable transportation. Sustainable transportation can be considered as a subset of sustainable development (development that ensures intergenerational equity by simultaneously addressing the multi-dimensional components of economic development, environmental stewardship, and social equity). There are very few quantifiable metrics that can be used to assess sustainability at disaggregate or individual vehicle level [4].

The idea of sustainable transportation emerges from the concept of sustainable development in the transport sector and can be defined as follows [5], “Sustainable transportation infrastructure and travel policies that serve multiple goals of economic development, environment stewardship and social equity, have the objective to optimize the use of transportation systems to achieve economic and related social and environmental goals, without sacrificing the ability of future generations to achieve the same goals”. The concept of sustainable development and sustainable transportation systems can be understood by exploring their evolution. In the 18th century economist and philosopher Thomas Malthus hypothesized that improvements in the quality of life would stimulate population surges that would outpace increases in the means of subsistence. The term sustainable development was first used by World Conservation Strategy (WCS) in 1980 to emphasize the significance of resource conservation without which humanity has no future. Sustainable transportation is an expression of sustainable development in the transport sector. A review of the literature has shown a growing emphasis on developing sustainable transportation systems as well as policy-oriented studies to address transportation related negative externalities such as air and noise pollution, accidents, congestion and social exclusion, and to meet current and future mobility and accessibility needs without creating excessive negative externalities. The reviews also established that sustainable transportation systems require a dynamic balance between the main pillars of sustainable development, i.e., environmental protection, social equity, and economic efficiency for current and future generations. Balancing of the various economic, social, and environmental factors is difficult so various attempts, have been made to list indicators that may assist examination of the sustainability of transportation systems [6].

However, one deficiency in the literature seems to be the lack of consensus on which policies or initiatives will result in a sustainable transportation system, while another deficiency is the lack of social aspects/indicators because of a lack of knowledge and of techniques for assessing the social impact of transportation system changes.

To begin with, transportation systems consume enormous amounts of materials of all kinds. They require millions of tons of concrete and steel to build highways, airports, and other facilities, and also millions of tons of plastic and ferrous and non-ferrous metals to build the vehicles that use the infrastructure.

Even more important is the degree to which the transportation sector consumes non-renewable resources in the form of fossil fuels, notably petroleum. Globally, this sector consumes more than 60% of the world’s total oil products. Oil now accounts for 98% of all energy utilized by transportation, an increase from 92% in 1960. Within the sector, motorized transport accounts for over 80% of all the oil used, aviation accounts for about 15%, rail and shipping for the remainder. Many governments have attempted to design policies to promote the use of other sources of energy for transportation but these efforts have obviously had little impact, despite the potential of new technologies and such policies as efficiency fuel standards and travel demand management.

This heavy reliance upon oil also has important environmental implications for it leads to a tremendous amount of pollution. Air pollution is caused locally by carbon monoxide, unburned hydrocarbons and lead (in those areas where leaded gasoline continues to be used), and more globally by carbon dioxide, from motorized vehicles. Studies have demonstrated that transportation is responsible for almost 90% of carbon monoxide emissions and a large percentage of other pollutants. This is particularly evident in large cities throughout the world. Noise pollution inflicts psychological and physiological damage upon people.

Water pollution is another implication caused indirectly by the seepage of fuels and other contaminants at airports, garages, filling stations and the like, and directly through the use of waterways.

Furthermore, these impacts are not limited geographically. On the contrary, they are felt regionally as well as locally, often crossing national boundaries to damage forests, water resources and crops far from the pollution source; their cumulative effects are also felt at the global level for they contribute in major ways to ozone depletion and global warming.

The numerous other ways in which existing transportation systems are not consonant with sustainability also deserve consideration. They consume vast amounts of land for roads, airports, and railroads and more for parking facilities, manufacturing and maintenance plants. Over 65% of Los Angeles is paved. Furthermore, automobiles have created urban sprawl, which in turn generates additional demands for transportation that can be met only by more automobiles. The increasing reliance upon this mode of transport also has negative consequences for social life. Although automobiles provide people with freedom and mobility, they do so only for those who can utilize them. Such groups as the poor, the elderly, the handicapped can easily be marginalized and isolated from community life if alternative transportation modes are not available. In short, transportation can isolate groups and regions from the mainstream and poorly devised highway and other infrastructural projects can carve up communities as happened frequently during the interstate construction phase in the US in the 1970s. Also, the large number of traffic fatalities and accidents that occur every day and the heavy costs imposed by congestion cannot be ignored.

What is particularly significant is that these negative trends show no signs of abating; on the contrary, they are actually accelerating, creating difficult dilemmas for anyone concerned with achieving sustainable development. The data are compelling. Globally, the number of people and the amount of freight moving by road continue to increase. Although the proportion of trips by automobile has remained constant in the OECD countries, increased mobility translates into a substantial growth in personal automobile travel. In the US, for example, intercity passenger traffic by automobile increased by 57% between 1980 and 1996 whereas rail passenger traffic rose by only 26%. In the rest of the world, private automobile usage is growing extremely fast: in China, for example, by 100% a year. Similarly, freight is moving increasingly by road. In Europe, 51% of freight movements were by road in 1970 as compared with 70% in 1990. Clearly, existing transportation systems in the developed world are unsustainable and their present course promises to exacerbate what is already a dangerous situation; the developing countries are replicating the patterns of the West, with all their destructive characteristics. The consequences of this situation have been vividly described as follows:

Major changes are needed in the priorities for transportation policy in the Third World if development is to meet human needs rather than benefit only the current elite groups. The costs of failing to redirect transport policies today will be paid in the decades to come through a sharply reduced quality of life in the world. As cities grow, one can anticipate increased conflict between the mobile elite and the mobility restricted poor, and reduced capacity to solve the problems of capital shortages, not payable debt burdens, toxic air pollution, and global climate change [2].

2.3 TRANSPORTATION PLANNING

The traditional method for transportation planning is a process consisting of four steps, which estimate the number of trips generated in each area, their distribution, the transport mode they use, and the exact routes they follow. Because this method is rather complicated and requires extensive data, many variations of its steps, as well as different procedures, such as disaggregate models, have been developed. Yet the four-step method and its individual steps have generally accepted the most common procedure [7]. Knowledge of this methodology and its major models will be briefly explained in the following sections.

2.3.1 Trip Generation

The goal in trip generation is to estimate for the present and the future planning target year the number of trips generated and attracted by each zone in a given time period, not considering their destinations. This includes both trips generated internally within a zone and trips generated between zones [8]. The basic form of the modals used in the trip-generation phase can be simply written as [9]:

$$T_i = f\left(S_i\right) \text{ and } T_j = f\left(S_j\right) \tag{2.1}$$

where, T_i and T_j represent, respectively the numbers of trips generated by zone i and trips attracted by zone j, and S_i and S_j are the socioeconomic characteristics of zone i and j, respectively.

The socioeconomic and land use characteristics used to estimate trip generation vary with types of zones and activities in them, available data, and possibilities, of collecting local information. Generally, based on Stopher and Meyburg [10] and Bureau of Transportation Economics [9], socioeconomic variables may include household size, household income, car ownership, number of drivers and type of residence structure.

Land use variables include types of activities, such as offices, industry, retail outfits, medical centers, educational and public buildings, and recreational and open space.

These characteristics expected in the planning target year are employed to estimate the number of trips. The basic assumption is that the relationships between influencing factors and trip production in individual zones will be stable over time and that future land uses can be predicted with reasonable accuracy. Moreover, it is implied that the demand for transport is inelastic with respect to the total amount of activities and the quality of the transportation system. When these assumptions are not accurate because major construction of buildings, upgrading of the transportation system, or similar changes are planned and the influences of those changes on trip generation may be different than the basic models predict, it may be necessary to adjust the models.
Several types of techniques developed for computations of trip generation are briefly described here.

Multiple linear regression models are most commonly used for trip-generation forecasting. There are two types of this model: the aggregate zonal version and household level regression models. The general form is:

$$Y_i = a_0 + a_1 X_{1i} + ... + a_n x_{ni} + \varepsilon \qquad (2.2)$$

where,
Y_i : Total number of trips generated by the inhabitants of zone i
X_{1i}, $X_{2i,}$ …, X_{ni} : Explanatory variables for zone i, such as its population, auto ownership, ect.
a_0, a_1, …, a_n : Regression coefficients (estimated by least squares techniques)
ε : Error term, assumed to be independently and normally distributed with an expected value of 0

The planner inserts the historical data for the region in the X and Y values (to estimate the coefficients, one must also know the Y values) and determines the coefficients a_0, a_1,

…, a_n. Using the coefficients determined from the historical data, future trip generation is predicted by substituting the predicted values of the X variables into the formulae.

There are a number of problems with this model. The aggregate values may not be sufficiently precise. Also, maintaining the statistical validity of regression is difficult, and if the stringent assumptions are not met, accuracy of the results is affected. Sometimes, even if the model is statistically valid, the planner may obtain a result that is not logical or physically possible. Both linear regression models, zonal and socio-economic, are not spatially transferable, and they may be affected by a change in cultural values and attitudes of the population.

Cross-classification analysis is aimed at construction of a multidimensional matrix with each dimension representing an independent variable, stratified into a number of discrete classes and categories. Examples of variables for trip production are automobile ownership, household size, and income, and for trip attraction employment type and employment density are often used.

This method makes it easy to understand the impact of different factors on and their relationship with trip generation. Also, it avoids the linear assumption of the regression models. Its drawbacks are suppression of variances among households in a specific zone, sensitivity of the results to grouping, and lack of a statistical measure to assess reliability of the results [9, 10].

Direct estimation of transit trips can be used in areas with a considerable degree of transit use. Since most of the travel-forecasting models described here have been developed for metropolitan regions with high auto ownership, they are heavily oriented to auto trips with less attention to transit and often complete neglect of walking and other modes. In urban areas with high-quality transit systems where most households generate some transit trips, planning of transit systems can use models that directly compute transit trips as a function of household characteristics, employment, and closeness to transit stations. For example, surveys of areas served by metro lines can produce trip-generation rates that can be applied to the areas a planned metro line will serve.

This procedure can be much more practical and less expensive than comprehensive area transportation studies and yet yield results with accuracy that is sufficient for planning many types of transit services in large cities with high-quality transit, such as Boston, New York and Philadelphia, many cities of other industrialized countries, and, even more efficiently, in most developed countries, where bypassing the modal split analysis is not a problem because of dominance of transit, bicycle, and walking trips over auto trips [7].

2.3.2 Trip Distribution

Following the estimation of the number of trips produced by each zone or attracted to it, the next step is to predict how are the generated trips from each zone *i* distributed to each zone *j* as its attracted trip. In the other words, this phase links the produced trips with attracted ones. Generally, trip distribution is considered to be a function of three major groups of factors: the type and extent of transportation facilities connecting zones; the land use patterns; and socioeconomic characteristics of the population.

Models that have been used to forecast trip distribution can be classified into three types:

- The *growth factor model*, which applies a constant growth rate to existing traffic flows. It assumes that travel patterns will not change in the future.
- The *gravity model*, based on the presumption that the number of trips between each pair of zones is proportional to the activities (or trip generation) of those zones but inversely proportional to the distance and other resistances among the trips to potential destinations.
- The *intervening opportunity model*, which bases on traffic flows between zones on the relative opportunities in each area for shopping, entertainment, and employment.

The growth factor modal simply applies a constant growth rate to the current traffic flows. This growth factor is determined empirically from past data. The growth model however has two problems. First, assumes that either there will not be any changes to the highway and transit systems or that those changes will not have any impact on the number of trips individual systems or facilities attract. More importantly, the model assumes that the rate at which traffic has grown in the past will be the rate at which it will grow at in the future, i.e., it is based on extrapolation of past trends.

The gravity model, with many variations in its exact form, is by far the most commonly used model for forecasting trip distribution. The law, when it was first used for analysis of intercity railway trips by Lill in the nineteenth century [11], had the exact form of Newton's law of gravity:

$$T_{ij} = K \frac{M_i M_j}{d_{ij}^2} \tag{2.3}$$

where,

T_{ij} : Number of trips between zones i and j per unit time

K : A constant reflecting local conditions which must be empirically determined

M_i, M_j : Populations of zones i and j, respectively

d_{ij} : Euclidean distance between zones i and j

With extensive applications of this basic modal to trip distribution in urban areas during the 1950s and 1960s, it was noticed that travel behavior of people does not follow this law as precisely as physical bodies relate to gravity. To achieve a better fit, two adjustments were made:

- The form of the equation was modified. For example, each of the *M*'s is either changed in definition (e.g., to include employment in the zone) or is multiplied by a constant factor.
- One or more coefficients in the model are computed from the data obtained for the specific city. This calibration step actually fits the model to a given area at a given time.

After various modifications, the gravity model used most commonly in planning studies has the following basic form:

$$T_{ij} = T_i \frac{A_j \, F_{ij} \, K_{ij}}{\sum_{j=1}^{n} A_j \, F_{ij} \, K_{ij}} \qquad (2.4)$$

where,

n : number of zones

T_i : Total number of trips generated in zone i

A_j : A measure of the attractiveness of zone j (e.g., available employment)

F_{ij} : Friction factor, or impedance to travel between zones i and j, usually computed as inverse function of the costs of travel consisting of travel time, distance, and direct cost.

K_{ij} : Specific zone-to-zone relationship factor, which is empirically computed

Thus, the equation expresses the number of trips from zone i to zone j as proportionate to the relative number of attractions in zone j to the sum of attractions of all zones. A good review of different distribution models is given in Papacostas and Prevedouros [8].

The main limitation of this model is that after modification of the initial equation and calibration of its coefficients, the equation represents a mathematical model that has the main flaws of the constant growth model: it is basic empirical, fitted to a specific situation and time. Its use for predicting at a different time, i.e., 10-20 years in the future, is therefore only as reliable as the assumption that the basic behavior of people in the study area will remain the same as it is at present.

The *intervening opportunities model* is an attempt to correct the deficiencies of the two previous models. It states that number of trips between zone *i* and zone *j*, T_{ij}, is:

$$T_{ij} = \frac{p_i\left(e^{-LV_j} - e^{-LV_{j+1}}\right)}{1 - e^{-LV_n}} \qquad (2.5)$$

where,

L : Probability of accepting any particular destination/opportunity (e.g., shop, accept employment, ect.)

V_j, V_{j+1} : Number of opportunities passed up to the zones *j* and *j+1*, respectively

V_n : The total number of opportunities

p_i : The population in zone *i*

It is important to note that as the total number of opportunities V_n goes to infinity, the number of interchanges becomes a function of the relative number of opportunities in the respective zones and the population of the zone under study.

This method of estimation is more complicated and prone to computational errors, but if used correctly, it is more powerful a useful to the planner than the models based on the present conditions only. If the planner is concerned about values 10-20 years in the future, he/she can adjust population and the number of opportunities in each zone. Although the number of current opportunities may be available, the number being planned may be more difficult for the planner to obtain. Thus, if the data are available, the planner can adjust traffic flows for future changes in the structural environment outside the transportation system, and can even project changes in development caused by changes in the transportation system [7].

2.3.3 Modal Split

Estimation of the distribution of travel among different modes is one of the most important steps in multimodal transportation planning. It produces the basic information on the demand for each mode for given transportation networks. Most commonly, modal split refers to the distribution between transit and automobile travel, but it may sometimes encompass more mode than these basic two. Estimates of the distribution among different modes, such as walking, bus, bicycle, kiss-and-ride (K+R), and park-and-ride (P+R), for access to a major mode, usually a rail transit station, are referred to as *sub-modal split*.

Factors Determining Modal Split: Since each urban traveler decides which mode to use on the basis of various factors concerning him/her and his trip, the modal split estimate is based on the evaluation of various factors that can be defined and estimated in some quantitative manner. These factors can be classified into four major categories:

- Trip maker characteristics: auto ownership, family size and composition, age and income
- Trip characteristics: purpose, length and orientation (direction)
- Transportation system characteristics: travel time (ratio or difference among modes); travel cost (including parking restrictions) and accessibility ratio
- Zone characteristics: residential density, employment density

In practice, each study can incorporate only a few of these factors since the derivation of relationships and complexity of models increases with the number of factors. Moreover, many of the factors are mutually correlated so that using several of them would introduce either unnecessary complexity or a bias. For example, auto ownership is usually closely related to income and residential density, so that when automobile ownership is used, the latter two factors are indirectly also considered. On the other hand, some factors may have a different correlation to modal split under different conditions. For example, most surveys of U.S. cities show that higher income causes lower transit riding, since automobile ownership increases. However, this is generally true only for low-quality transit service, primarily buses. High-quality transit sometimes has the inverse correlation. For example, regional rail or metro lines serving a suburban area often attract riders with higher income than automobile drivers travelling in the same corridor. The planner must therefore be extremely careful which factors are used and what generalizations are made from individual surveys.

Modal Split Models: several mathematical methods have been used for mode choice models and travel forecasting. They can be grouped into two basic categories: aggregate and disaggregate. Most of the aggregate variations are of the trip-interchange type, which use multiple regression, cross-classification, or diversion curves to estimate the division of trips between modes. By contrast, the disaggregate type models, also known as individual mode-choice models use probabilistic methods to estimate behavior of individuals. They are based on utility theory. All these models include some of the factors listed in the four categories of characteristics of trip maker, trip, transportation system, and zone.

Among aggregate models, the trip-interchange models in various forms are most commonly used. Trip-end models were used in a number of cities, but they have been largely abandoned because of their inherent weakness and flawed underlying logic.
The simplest type of trip-interchange model uses the diversion curve method, which utilizes a diagram of trip distribution between transit and automobile travel as a function of the travel characteristics on the two modes. The independent variable is usually the travel time ratio or the travel cost difference. Some studies have used an accessibility index which incorporates both travel time and cost or some other relevant factors. One of the commonly used definitions of the accessibility index for zone *i*, κ_i, is:

$$\kappa_i = \sum_{j=1}^{n} A_j \left(F_{ij}\right) \tag{2.6}$$

where,
A_j : The number of trip attractions in zone *j*
F_{ij} : A travel time friction factor associated with travel from zone *i* to zone *j* over the considered transportation system

This index is computed for trips on both modes, transit and automobile. Then their ratio is obtained, trip with the same ratios are grouped together, and the composite percentage of transit usage is computed for each group. When this percentage is plotted against the accessibility ratio, the diversion curve is obtained. A conceptual form of such a diversion curve is shown in Figure 2.1. The curve shows the percentage of trips divided between modes A and B, automobile and transit, as a function of the ratio of service quality, usually measured by travel times, costs, or some other elements. It must be borne in mind that this diversion curve depends only on the used parameters, such as travel time ratio or difference, disregarding such factors as quality of service, and individual preferences. The curve does not go from 0 to 100 because some travelers use one of the modes regardless of travel time or cost. These travelers, including non-drivers using transit and persons carrying special equipment using cars, are designated as transit captives and automobile captives, respectively.

One drawback of a single diversion curve is that it is very crude and does not incorporate any effects of the trip and trip-maker characteristics. This can be remedied by developing different diversion curves for different trip purposes, car ownership, the economic status of trip maker, or the characteristics affecting travel. Another shortcoming of diversion curve method is that it cannot deal with an entire transit and highway network at one time.

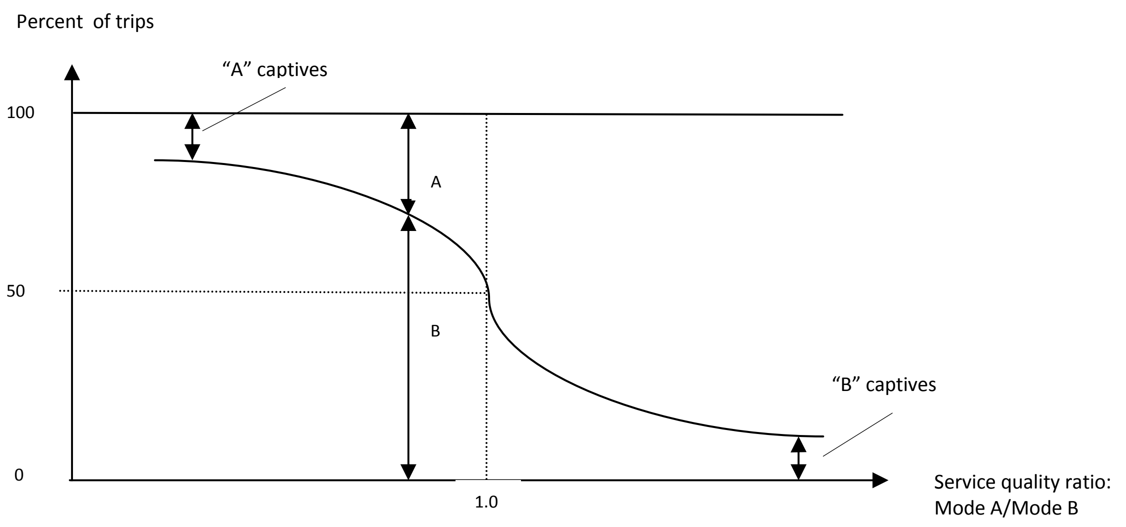

Figure 2.1 Modal distribution curves for two alternative modes.

Yet despite these limitations and deficiencies, trip interchange models, of which diversion curve methods are best-known representatives, are based on realistic relationships and intuitively clear. Although their computational techniques and factors vary widely, most of trip-interchange models originate from the same basic assumptions about relationships in mode choice behavior.

Evaluation of modal split forecast: Extensive analysis of modal choice and development of techniques for its forecast have been done in recent decades. As a result, there is now a wealth of data on the behavior of urban travelers and the relationships among different factors and the usage of the two basic modes, transit and automobile. Numerous models have been developed to mimic *present* behavior and attitudes of people towards *existing* modes. The insights into these problems represent a valuable contribution for analysis and planning of urban transportation systems.

Despite this progress, however, the state-of-the-art in this area needs further improvement. Major deficiencies exist in the underlying orientation in modeling and forecasting methodology, as well as models themselves. Modal split models were developed for studies heavily oriented toward highways and automobile traffic while giving little attention to transit. If the models are calibrated on the conditions where transit service is inferior to the standards that it should ideally meet, they tend to be inadequate for planning improved or new systems.

The modal split models also have technical deficiencies based on quantitative factor, such as travel time, fare, and service headway. Another problem has been that modal split analysis is often limited to two modes, auto and transit. In many cities, particularly large ones with strong centers, other modes often play a significant role. For example, in many Western European and Asian cities, walking trips may represent as many as 25-35 of all trips.

In spite of these shortcomings, modal split models and demand-estimation procedures represent a valuable tool in planning if they are developed and applied correctly. When forecasting models are used for certain quantitative changes of services on existing system, they are adequate. However, when they applied to forecasting patronage on a qualitatively different system (e.g., express service, new mode, modern information system), it is important that a predictive model be used that includes attitudinal variables based on studies of passenger behavior, values, ect. If such models are not available, the planner should complement formal models with personal experience, knowledge about system, and judgment [7].

2.3.4 Trip Assignment

Following modal split estimation, the forecasted amount of travel by each mode among zones is known, but the exact routings of trips must be determined. There are usually several alternative paths that a single trip could take. The purpose of traffic assignment is to allocate all trips to specific paths, thus deriving traffic volume forecasts for each section in street and transit networks.

The trip assignment models are calibrated on the present network then used to estimate travel volumes in the future network. Thus, they provide a tool for testing the adequacy of alternative transportation networks to serve traffic volumes generated by different land use plans and zoning ordinances at present and in the future. An important role for these models is to check whether traffic volumes reach or exceed capacity of individual links and to compute the equilibrium states of flows under different network modifications and travel conditions.

To perform traffic assignment, the planner decides which criteria best represent the actual decision making behavior of the trip maker and what data are available to him/her. Usually, the most important criteria for route selection are, in sequence:

- Shortest travel time
- Shortest travel distance
- Minimum trip cost

There are three basic methods for traffic-assignment procedure. The *all-or-nothing method* assigns all traffic to one route based on the selected criterion (e.g., minimum cost). The *assignment curves method* assigns a portion of the traffic to each route based on the comparative values of the criteria between the best and the next-best routes. The *capacity restraint method* assigns traffic based on the travel times and capacities of available routes and assigns a portion of the traffic to alternative routes as the primary route nears capacity. The two capacity restraint models that are used most frequently are the stochastic models and the user-equilibrium models.

In the all-or-nothing method, the best route gets the entire load. Although this method is the simplest, it is also the least accurate and the worst representation of the decision-making process of the trip makers of all the mentioned models. As traffic is assigned to individual links, some of them may become loaded so much that their volume exceeds its capacity and level of service decreases. Thus, the initially assumed travel time on such facility cannot be achieved, making the results of the assignment unrealistic and physically infeasible.

The assignment curves method assigns traffic between the best and the next-best routes. Based on how the two routes compare quantitatively in regards to assignment criteria, the planner determines the percentage of trip makers who will opt for one route or another. The number of trips assigned for given alternate routes is based on past data and the planner's own experience. This method has been shown to have good results for urban and quasi-urban situations, but it has been found inadequate for recreational trips in rural areas.

The capacity restraint models take into account the fact that travel times on each link change with assigned traffic volumes. The assignment is therefore made gradually, and assumed travel times on each link are adjusted, i.e., lengthened as the assigned volumes increase. The closer the assigned traffic comes to capacity on a given route, the more additional volume must be diverted to the routes that now may have shorter times than on the heavily loaded route or link. This process is iterative and requires a number of traffic assignments. In practice, four assignments are made and the average volume on each link is taken. The Federal Highway Administration recommends the following formulae for the determination of the congested-modified travel time:

$$T(v) = T(0)\left\{1 + \alpha \left(\frac{v}{c}\right)^{\beta}\right\} \tag{2.7}$$

where, *T*(*υ*) represents the travel time on a link, *T*(*0*) denotes the free flow travel time, *C* is the hourly capacity, *υ* is the hourly volume, *α* and *β* are link specific parameters based on the physical characteristics of the link. The formula must be applied for each link and related to the flows determined for the other links in the system. Although the procedure appears complicated, this model approximate closely the behavior of trip makers and therefore is the most realistic trip-assignment method.

Capacity restraint models differ in their assumptions of how trip makers choose paths between their origins and destinations. *Stochastic (dynamic)* models assumed that trip makers choose paths that they *perceive* to have the minimum travel time. However, the travel time of a single path may be perceived differently by each trip maker due to variations in information they have and non-measurable factors (e.g., weather). Therefore, trip makers may choose different paths between the same origin and destination, even though each trip maker believes he/she is using the shortest path. Stochastic models determine the probability that a trip maker will choose a given path, with the underlying assumption that perceived travel times are randomly distributed. Based on these probabilities, trips are assigned to each path in the network. This assignment can called as dynamic traffic assignment too. *Static models* assume all trip makers are valid, know the shortest path in each assignment and never err.

Wardrop [12] identified two criteria that can be used to allocate traffic to competing routes: *user equilibrium* and *system optimization*. *User equilibrium* models assume that trip makers always choose the shortest travel time path between an origin and a destination, this is individual equilibrium, or Wardrop's first principle of traffic distribution in networks. It is implicitly assumed that all trip makers perceive travel time in the same way and that there is no random variation in perceptions. However, this does not imply that all trip makers will choose the same path between each origin and destination. Travel time on each path changes with the volume of traffic (as shown in the equation above), as the shortest path reaches capacity, its travel time may exceed that of alternative paths. A user or individual equilibrium exists when no trip maker can improve his/her travel time by choosing an alternative path. This implies that in equilibrium [7].

System optimal model is based on the Wardrop's second principle where users are assigned to routes so that the total system travel time is minimized. At system optimal, all users are assigned to paths which have equal and minimal marginal costs [13].

Our problem is a traffic assignment problem, so we will realize the last step of transportation planning. Demand in our study is determined, so there is no need for freight generation and trip distribution steps and our problem contains only one mode, road transportation, thus, we do not need model split step too. As we mentioned above, traffic assignment problems can be solved by three approximations (solving methods), all-or-nothing method, assignment curves and capacity restraint methods. We apply capacity restraint methods for it is the most realistic traffic assignment method. Our study assumes traffic flows as average volume counts during peak hours, every trip maker knows the shortest path so it is static assignment. We will try to get equilibrium of travel times among all paths on the same origin-destination pair, we will use user equilibrium model.

In the following section, static assignment and user equilibrium models are explained comprehensively in order to expose our model. Next we will shortly introduce static/system optimal assignment model and dynamic assignment model too.

A) Static Traffic Assignment

The history of traffic assignment studies can be traced back to the works in the 1950s. Early studies assume stationary traffic flows, often regarded as average volume counts during peak hours. Static traffic assignment aims to find a feasible assignment pattern or a loading pattern such that certain route choice conditions are satisfied.

In static assignment, two traffic allocating criteria, namely the user equilibrium condition and the system optimal condition will be analyzed.

- *User Equilibrium*

According to Sheffi [14], the User Equilibrium (UE) condition can be summarized as: *For each O-D pair, the travel cost on all used paths is equal, and (also) less than or equal to the travel cost that would be experienced by a single driver on any unused path*.

UE assignment models are based on Wardrop's first principle which states that at user equilibrium no user can decrease his experienced travel disutility by unilaterally shifting routes. All used routes connecting every origin-destination pair, have equal and minimal travel disutility. All unused routes have a higher travel disutility and thus there is no incentive for a user to shift routes. In most transportation studies, travel time usually determined from link flows is used as a proxy for travel disutility. Depending on the functional form of the relationship used to determine the travel time from the link flows, the equilibrium link flow solutions can vary. The most common functional form adopted to infer travel time from link flows is The Federal Highway Administration formula in equation (2.7).

This formula called as BPR, Bureau of Public Records function in many studies. One should note that in the BPR function, travel time on a link is a function of the flow on that link only and does not depend on the flow on other links. The link interactions are termed “symmetric" as the Jacobian of the travel cost function with respect to the flow variable is a diagonal matrix. Under this symmetric link interaction assumption, the user equilibrium traffic assignment problem can be formulated as a mathematical program [14]. The BPR cost function is continuous, differentiable, strictly increasing as a function of the flow, strictly convex and has a symmetric Jacobian. The objective of the UE formulation has a positive definite Hessian. As the feasible region is convex and bounded, the UE formulation has a unique solution in terms of link flows.

$$\begin{aligned}&Minimize \sum_{ij} \int_{x=0}^{v_{ij}} T_{ij}(x)dx \\ &s.t. \\ &\quad v = Ah \\ &\quad t = Bh \\ &\quad h \geq 0\end{aligned} \tag{2.8}$$

where, υ is the vector of link flows, h is the vector of path flows, A the link-path incidence matrix, t origin-destination trip vector, B trip-path incidence matrix, and T_{ij} denotes the arc cost function for arc (i,j).

The above formulation can be solved using the Frank-Wolfe algorithm [12] which is a method for solving nonlinear mathematical programs through successive linearization. By iteration, the mathematical program is linearized at the current solution and the resulting linear program is solved to determine the descent direction. In the traffic equilibrium problem, the descent direction step reduces to finding the shortest path between every origin destination pair with the costs fixed at the flows from the previous iteration. The step length is then determined using line search techniques to determine the optimal distance to traverse along the steepest descent direction. Fukushima [15] improved the speed of convergence of the Frank-Wolfe method by utilizing the linearization solution from the previous iteration to obtain a better search direction. Lawphongpanich and Hearn [16] present a simplified decomposition method that alternates between two steps: Step 1 involves determining current equilibrium solution assuming users choose only a given set of paths. This solution is obtained as a linear combination of extreme points corresponding to the current set of paths. Step 2 involves determining the new path sets to be added to the current path set by obtaining the minimum path trees with costs fixed at the current equilibrium solution. As the number of paths can grow significantly the number of paths to be contained in the current path sets is restricted by a pre-specified number. Note that if the size of the current path sets is restricted to be equal to 2 then simplified decomposition reduces to the Frank-Wolfe algorithm.

Other mostly applied methods are reduced gradient algorithm, the gradient projection method, and simplified decomposition and disaggregation methods. Although these methods give solutions of higher accuracy, they take considerable time for practical test networks. In recent times efficient algorithms have been developed to solve the user equilibrium traffic assignment problem. However, Frank-Wolfe still remains one of the most popular methods due to its ease of implementation and its ability to get near optimal within a few iterations.

When the travel time on a link is function of the flow on other links, an equivalent convex minimization formulation can be obtained, provided for any two pair of links the marginal effect of flow of second link on the travel time of the first link is equal to the marginal effect of the flow on first link on travel time of the second link. The jacobian is symmetric in this case and the Frank-Wolfe algorithm can be used to determine the optimal solution. The solution is unique in terms of link flows as long as the marginal effect of flow on a link on the travel time of that link is greater than the marginal effect of flow on every other links on the travel time of that link.

When the link interactions are asymmetric, there exists no mathematical programming formulation for the user equilibrium problem. The user equilibrium problem with asymmetric link cost interactions is commonly formulated as a variational inequality [17]. The objective of the variational inequality *VIP*(*F*,*X*) is to determine a link flow vector $x^* \epsilon X$ where X is the set of feasible link flows such that:

$$F\left(x^*\right)^T\left(x - x^*\right) \geq 0 \qquad x \in X \tag{2.9}$$

F is a continuous function mapping the vector of link flows to the vector of link costs and the set of feasible link flows is assumed to be non-empty, convex and compact. There is no guarantee of the uniqueness of the solution. Depending on the functional form of the link cost functions and properties like monotonicity numerous algorithms are available. One of the most common and basic algorithm for solving the asymmetric traffic equilibrium involves using a gap function as defined by Smith [17]. For the above problem, the gap function is defined as:

$$V(X) = \sum_i \psi^2\left(-F(X)(P_i - F)\right) \tag{2.10}$$

where, $\psi(x) = max\{0,x\}$. Note that $V(X) = 0$ only if X is in equilibrium and hence the above function gives a measure of how far the solution is away from equilibria. *Pi* represents the extreme points of the flow polyhedron. The variational inequality can be solved using an inner outer algorithm. In the inner algorithm, for the current solution the costs are fixed and the shortest path is calculated and an all or nothing assignment is conducted. For the outer algorithm, a linear combination of the current set of all or nothing assignments is determined which gives the equilibrium solution. The procedure is assumed converged when $V(x)$ is below a pre-specified convergence limit [13].

- *System Optimal*

The system optimal model is based on the Wardrop's second principle. At system optimal model, all users are assigned to paths which have equal and minimal marginal costs. The efficiency in system performance is achieved at the cost of the individual user as there exists scope for users to reduce their travel times by shifting paths. Therefore, system optimal assignment is not equilibrium state and is not achieved in reality unless users are forced onto least marginal cost routes. Despite its unrealism, system optimal assignment is useful as it acts as a bound on the system performance. When various congestion management measures are tested, system optimal solution provides a frame of reference to determine how far the system is from maximum efficiency. In recent times numerous studies have explored the potential using intelligent transportation systems to disseminate route information to achieve “near” system optimal state [18]. System optimal routing has also been applied in developing effective evacuation strategies. The system optimal assignment problem can be formulated as a nonlinear min cost flow problem with BPR functions used to determine the link costs from the link flows.

$$\begin{aligned} &Minimize \sum_{ij} T_{ij}\left(v_{ij}\right)v_{ij} \\ &s.t. \\ &\quad v = Ah \\ &\quad t = Bh \\ &\quad h \geq 0 \end{aligned} \tag{2.11}$$

The Frank-Wolfe algorithm can be used to determine the system optimal flows. Uniqueness is guaranteed under suitable symmetry assumptions on the jacobian of the link cost functions. One should note that in this case when the objective function is linearized, steepest descent direction corresponds to conducting all or nothing assignment on the marginal cost shortest paths between every origin-destination pair [13].

B) Dynamic Traffic Assignment

Static traffic assignment is, of course, that aspect of the transportation planning process that determines traffic loadings (expressed as flows, i.e., volumes per unit time) on arcs and paths of the road network of interest in a steady state setting. Dynamic Traffic Assignment (DTA) is concerned with the same problem in a dynamic setting. Four types of dynamics used as the foundation of dynamic network models are:

1- Dynamics based on arc exit-flow functions,
2- Dynamics for which both exit and entrance flow rates are controlled,
3- Dynamics based on arc exit-time functions,
4- Tatonnement and projective dynamics.

DTA models may be either equilibrium or disequilibrium in nature. When the solution of DTA model is a dynamic equilibrium, the flow pattern is time varying, but the trajectories through the time of arc and path flows are such that an appropriate dynamic generalization of Wardrop's [12] first principle of user optimality is enforced at each instant of time.

DTA models may be used to generate forecasts of traffic that illustrate how congestion levels will vary with time; these forecasts are intrinsically useful for traffic control and management in both the near-real time and deliberate planning contexts.

The data requirements for DTA models are, on the surface, quite similar to those of static traffic assignments models; however, on closer examination, and as we make clear here, there is one very significant difference. That difference is that DTA models require path-delay functions familiar from static assignment. Path delay operators express the delay on a given path in light of the time of departure from the origin of the path and the traffic conditions encountered along the path. This accounts for the fact that path traversal is not instantaneous and a platoon departing now will encounter traffic that may have departed subsequently from the same or other origins. Thus, there is the potential for path delay operators to depend on the complete history (past, present and future) of flows on the network. Such delay operators are, except in certain special cases, not knowable in closed form; that is, delay operators for DTA are known only numerically for the general case and require a simulation model to determine.

DTA models have two categories based on employing method: rule-based simulation, and based entirely on equations and inequalities [19].

2.4 BI-LEVEL PROGRAMMING

Bi-level programming is a branch of hierarchical mathematical optimization. In this programming method, the model has two levels; the upper level and the lower level. The model seeks to maximize or minimize the upper level objective function while simultaneously optimizing the lower level problem. Bi-level programming is the adequate framework for modeling asymmetric games that has a “leader” who integrates the optimal reaction of a rational “follower” to his decisions within the optimization process. The mathematical model expresses the general formulation of a bi-level programming problem:

$$
\begin{aligned}
&\min_{x,y} F(x,y) \\
&s.t. \\
&\quad G(x,y) \le 0 \\
&\quad \min_y f(x,y) \\
&\quad s.t. \\
&\qquad g(x,y) \le 0
\end{aligned}
\tag{2.12}
$$

where, $x \in R^n$ is the upper level variable and $y \in R^n$ is the lower level variable. The functions F and f are the upper-level and lower-level objective functions respectively. Similarly, the functions G and g are the upper-level and lower-level constraints respectively.

The bi-level programming structure is suitable for many real-world problems that have a hierarchical relationship between two decision levels. Among the fields that the concept can be applied are management (facility location, environmental regulation, credit allocation, energy policy, hazardous materials), economic planning (social and agricultural policies, electric power pricing, oil production), engineering (optimal design, structures and shape), chemistry, environmental sciences, and optimal control. In these cases the upper level may represent decision-makers who set policies that lead to some reaction within a particular market or group of system users. The reaction of the market or system users constitutes the lower level of the system under study.

A sustainable urban transportation model may also have a two level structure. The government, transportation system manager or another responsible institution determines pricing schemes, traffic flow control measures, policy to reach some objectives including the minimization of congestion or emission. According to determined price levels and other variables, drivers aim to maximize their utilities, which mostly include the monetary and time cost of the route chosen. Therefore bi-level programming is a suitable structure for modeling sustainability in transportation networks. For that reason, we give a view of bi-level programming here.

Despite the fact that a wide range of applications fit the bi-level programming framework, real-life implementations of the concepts are scarce. The main reason is the lack of efficient algorithms for dealing with large-scale problems. Bi-level programming problems are NP-Hard problems. Even the simplest instance, the linear bi-level programming problem was shown to be NP-hard. Therefore in the literature global optimization techniques such as implicit enumeration, cutting planes or meta-heuristics have been proposed for its solution. Despite the problem being NP-Hard, some specific cases enable us to solve the problem in polynomial time. Many researchers proposed several optimality conditions for bi-level programming problems. Some of these conditions are used in various solution methods and algorithms. Among the proposed methods are descent methods, penalty function methods and trust region methods [20].

3 MODEL FORMULATION

3.1 IMPACTS OF TRANSPORTATION SYSTEM STIMULI

Transportation is an essential social and economic activity that also results in a number of negative externalities, which include: i) air pollution; ii) noise pollution; iii) accidents; iv) energy use; v) congestion; vi) depletion of oil and other natural resources; vii) social disruption; and viii) damage of landscape and soil. These negative externalities are associated with all facets of the transportation lifecycle that include the production of vehicles, their use, and ultimately their disposal. The fact that the rate of the world's motor vehicle growth is projected to outpace the world's population growth is, therefore, a major concern [21].

Methodologies for assessing such impacts generally depend on the types of impacts under investigation, the scope and the project type and size; and a variety of disciplines typically are involved, including operation resources, engineering, environmental science and economics [2].

3.1.1 Types of Transportation System Stimuli

Synonymous with the words change and intervention, a stimulus may be defined as "an agent that directly influences the operation of a system or part thereof" and may be due to deliberate physical or policy intervention by an agency or to the external environment. External stimuli may be natural or human-made. Natural stimuli include severe weather events and earthquakes; human-made stimuli include facility overloads, interventions (facility repair by the owner or agency), and disruptions (terrorist attacks). Also, in the context of transportation decision making, stimuli may be categorized as physical stimuli (change in the physical structure) and regulatory stimuli (institutional policy or regulation of transportation infrastructure use). An example of a change in physical structure is the construction of a new road or the addition of new lanes. Examples of institutional policy and regulation are speed limit and seat belt laws, respectively [2].

3.1.2 Impact Categories and Types

Identification of the various types and levels of impacts arising from a stimulus is a key aspect of transportation system evaluation and decision making. The various categories and types of impacts expected to occur in response to transportation system changes need to be identified prior to detailed analysis of the impacts. For example, the construction of a new transit line may affect (1) travelers (by decreasing their travel time), (2) transit agency (by introducing a need for the agency to maintain the system after it has been constructed), (3) persons living the transit line (by creating a noise pollution source) and (4) travelers on the network (by offering them new travel choices a possibly changing their origin-destination patterns).

In Table 3.1, we present briefly various categories and types of impacts of transportation system stimuli [2].

A) Technical Impacts

These impacts typically constitute the primary motive for undertaking improvements in a transportation system. The secondary impacts are the consequences or side effects of the stimulus. Technical impacts are described below [2].

- *Facility condition*

An improvement in the condition of a facility leads to a host of impacts, such as increased service life, reduction in vehicle operating costs, and decreased vulnerability to natural or human-made threats. There are established standards of facility characteristics and conditions that must be met, failing which a facility owner may suffer increased operational or safety liability risks.

Table 3.1 Impact Categories and Types

Categories of Impact	Impact Types
Technical	Facility condition
	Travel time
	Vehicle operating cost
	Accessibility, mobility and congestion
	Safety
	Intermodal movement efficiency
	Land-use patterns
	Risk and vulnerability
Environmental	Air quality
	Water resources
	Noise
	Wetlands and ecology
	Aesthetics
Economic efficiency	Initial costs
	Life-cycle costs and benefits
	Benefit-cost ratio
	Net present value
Economic development	Employment
	Number of business establishments
	Gross domestic product
	Regional economy
	International trade
Legal	Tort liability exposure
Socio-cultural	Quality of life

Vehicle operating costs: In the course of using transportation facilities, vehicles consume fuel, lubricants, and other fluids; “soft” replacements such as wiper blades and tires; “hard” replacements such as alternators and batteries; and experience general vehicle depreciation due to accumulated weather and usage effects. VOCs are categorized as running costs (whose values are typically a function of vehicle speed) and non-running costs (whose values are largely independent of speed). In a network level estimation of VOCs, it is important to recognize that networks having only new and small vehicles would incur far lower average vehicle operating costs than would a network having only old and large trucks. As such, the changing composition of the network level vehicle fleets, as well as the relationship between running cost and age, are important [22]. The changing fleet composition is best tracked using cohort analysis.

- *Travel Time Impacts*

For a given project, the travel time impact is the product of the reduction in travel time and the value of travel time per unit vehicle and per unit hour. If vehicle occupancies are known, the analysis can be done in terms of persons rather than vehicles.
Accessibility, Mobility and Congestion: For already developed transportation networks, a desired impact of system improvements (lane addition, High Occupancy Vehicle (HOV) and Bus Rapid Transit (BRT) facilities, Intelligent Transportation System (ITS) implementation, ramp metering, signal timing revisions) may be the mitigation of traffic congestion. On the other hand, in rural areas developing countries, system improvement may be expected to provide accessibility to markets, health centers, agricultural extention facilities, and so on. In both cases, system improvements can lead to enhanced mobility of people, goods and services.

- *Safety*

Increased transportation system safety is typically due to diverse safety enhancement efforts including physical changes to a system and institutional changes such as educating the facility users and enforcing the operating laws and regulations. Safety enhancement may be due to direct implementation of such changes to address safety concerns or may be a secondary benefit of a larger project scope (pavement resurfacing).

- *Intermodalism*

Physical or institutional changes in a transportation system can have profound effects on the efficiency or effectiveness of the overall intermodal transportation network in a region. For example, provision of additional links for a mode, or imposing or relaxing restrictions on the types and quantities of loads, can profoundly change the overall economics of freight delivery.

- *Land-use Patterns*

It is well known that changes in a transportation system cause shifts in land-use patterns and vice-versa. For example, highway construction and transit line extensions have been linked to changes in the extent and distribution of residential, commercial and industrial developments.

- *Risk and Vulnerability*

Recent world event have led to increase awareness of the need to assess the risk and vulnerability of existing transportation facilities or changes thereto. Thus, there are increasing calls to evaluate the impacts of system improvement based not only on traditional impact criteria but also on the vulnerability of the facility to failure in the event of human-made or natural disasters.

B) Environmental Impacts

Environmental impacts are as follows [2]:

- *Air Quality*

Transportation-related legislation passed over the past three decades has consistently emphasized the need to consider air quality as a criterion in the evaluation of transportation systems.

- *Water Resources*

Construction and operations of a transportation system can cause a significant reduction in both the quantity and quality of water resources, and it is necessary to evaluate the extent of this impact prior and subsequent to project implementation. Construction and expansion of airport runway and highway pavements and other surface transportation facilities lead to reduction in the permeable land cover, reduced percolation of surface water, and consequent reduced recharge of underground aquifers. Surface runoff from such facilities often results in increased soil erosion, flooding, and degraded water quality.

- *Noise*

The noise associated with transportation system construction and operation has been linked to health problems, especially in urban areas, and often merits analysis at the stages of pre-implementation and post-implementation evaluation and monitoring.

- *Ecology*

The construction and operation of transportation facilities may lead to the destruction of flora and fauna and their habitat, such as wetlands. For a comprehensive evaluation of ecological impacts, a basic knowledge of ecological science, at a minimum, is needed.

- *Aesthetics*

Transportation projects typically have a profound visual impact on the surrounding built or natural environment. Such impacts may be in the form of a good or bad blend with the surrounding environment, or obscuring an aesthetic natural or human-made feature.

C) Project Economic Efficiency Impact

Project economic efficiency impacts are as follows [2]:

- *Initial costs*

The cost of designing, constructing, preserving, and operating a transportation facility is an important "impact" of the facility. Of these, the construction cost is typically dominant, particularly for a new project. The definition of construction and preservation costs can be expanded to include the cost of associated activities, such as administrative work, work-zone traffic control, work-zone impacts to facility users (such as safety and delay), and diversions.

- *Life-Cycle Costs and Benefits*

The life-cycle approach involves the use of economic analysis methods to account for different cost and benefit streams over time. The life-cycle approach makes it possible to consider the fact that an alternative with high initial cost may have a lower overall life-cycle cost.

D) Economic Development Impacts

Economic development benefits of transportation projects are increasingly being recognized as a criterion for consideration in the evaluation of such projects. The impacts of transportation facilities in a regional economy may be viewed by examining their specific roles at each stage of the economic production process [2].

E) Legal Impacts

The operation of transportation facilities is associated with certain risk of harm to operators, users, and nonusers. With the removal of sovereign immunity in most states, agencies, are now generally liable to lawsuits arising from death, injury or property damage resulting from negligent design, construction or maintenance of their transportation facilities. The growing problem of transportation tort liability costs is considered even more critical at the present time, due to increasing demand and higher user expectations with severe resource constraints. It is therefore useful to evaluate the impact of a change in a transportation system on exposure of an agency to possible tort [2].

3.1.3 Dimensions of Evaluation of Impacts

It is important to identify the dimensions of the evaluation of impacts, as doing would help guide the scope of the impact and to identify the appropriate evaluation discipline or technique to be considered in the evaluation. The categories of dimensions are presented in Table 3.2. Possible levels of each dimension are also shown [2].

Table 3.2 Evaluation scopes of impacts

Dimensions (Scopes)	Levels
Entities effected	Users
	Nonusers (Community)
	Agency
	Facility Operator
	Government
Geographical scope of impacts	Project
	Corridor
	Regional
	National and global
Temporal scope of impacts	Short term
	Medium term
	Long term

A) Entities Effected

In carrying out impact evaluation, it is essential to consider not only the types of impacts but also the various entities that are affected, as discussed below [2].

- *Users*

User impacts include the ways in which persons using a transportation system (vehicle operators and passengers) are directly affected by a change in the system. User impacts typically include vehicle operating costs, travel time and safety.

- *Nonusers (Community)*

Consideration of the effect of transportation systems on nonusers is necessary to ensure equity of system benefits and costs to the society at large. These impacts often include noise and air pollution, other environmental degradation, dislocation of farms, homes and businesses, land-use shifts, and social and cultural impacts.

- *Facility operator*

Operators of transportation systems, such as shippers, truckers, highway agencies, and air, rail, water and land carriers may be affected by physical changes (e.g., improvements) and institutional changes (e.g., deregulation, speed limits). This typically occurs through increased or decreased resources for operations (and in the case of rail operators for facility preservation).

- *Agency*

The impacts on a transportation agency are typically long term in nature and are related to the costs of subsequent agency activities. For example, system improvements may lead to lower costs of maintenance and tort liability in the long run.

- *Government*

These impacts concern the change in the nature or level of the functioning of the city, county, state or national government due to change in transportation system. For example, a new type of infrastructure, policy or regulation for the system may lead to the establishment of a new position, office or department to implement or monitor implementation of the change.

B) Geographical Scope

A well-designed study area is critical in transportation impact evaluation studies because the outcome of the analysis may very well be influenced by the geographical scope of the impacts. Spatial scopes for the analysis may range from point (generally a node such as signalized intersection) or segment wide (local, generally a part of transportation link), to facility (a linear network of reasonable length consisting of a combination of nodes) or corridor-wide, to area-wide (city, county, district, state, ect.). As the geographical scope of an evaluation widens, the impact of the transportation project not only diminishes but also becomes more difficult to measure, due to the extenuating effects of other factors. Specific geographical scopes are typically associated with specific impact type and effected entities. For example, in the context of air pollution, carbon monoxide concentration is a local problem, whereas hydrocarbons are a regional problem, and the emissions of greenhouse gases is a global problem. Also, each geographical impact may be short, medium or long-term, in duration but wider geographical scopes are typically more associated with longer terms, as impacts often take time to spread or be felt over a wider area [2].

C) Temporal Scope

A transportation system stimulus may have impacts that last only a relatively short time (e.g., dust pollution during facility construction) or may endure for many decades after implementation (e.g., economic development). Obviously, the temporal scope of the evaluation will depend on the type of impact under investigation and is also sometimes influenced by (or related to) the geographical scope of the evaluation and the entity affected. Temporal distribution of impacts can also be classified by the occurrence in relation to the time of the stimulus: during-implementation impacts vs. post-implementation impacts. For example, construction dust and topsoil disturbance constitute during-implementation impacts, whereas traffic noise during highway operation is a post-implementation impact. For the purpose of grouping impacts form a temporal perspective, the categories used are short, medium or long-term.

3.1.4 Other Ways of Categorizing Transportation System Impacts

Depending on the viewpoint of the decision maker, there are several alternative or additional ways of categorizing the impacts of transportation stimuli as discussed below. [2]

A) Direct Indirect Impacts

Direct benefit and costs are those related directly to the goals and objective of the transportation stimulus and affect the road users and agency directly, whereas indirect impacts are generally by-products of the action and are experienced by society as a whole. For example, a major objective of speed-limit increases may be to enhance mobility (a direct impact) but may result in indirect impacts such as increased fuel use or increased frequency or severity of crashes.

B) Tangible Intangible Impacts

Unlike intangible benefits and costs, tangible benefits and costs can be measured in monetary terms. Examples of tangible impacts are construction cost and increase in business sales due to an improved economy. Examples of intangible impacts are increased security or aesthetic appeal of a rehabilitated urban highway. The intangibility of certain impacts precludes an evaluation of all impacts on the basis of a single criterion such as economic efficiency. Therefore, in evaluating a system that produces both tangible and intangible impacts, the techniques of scaling the multiple criteria are useful. An alternative way is to monetize intangible performance measures using the concept of willingness to pay: for example, how much people would pay to see a specific improvement in the aesthetic appeal of a bridge in their community, and then use economic efficiency to assess and evaluate all impacts.

C) Real Pecuniary Impacts

In assessing the impacts of transportation system, it is important to distinguish between real costs and benefits (i.e., some utility that is completely lost to (or gained from) the world) and pecuniary costs or benefits (i.e., some utility that is related only to the movement of money around the economy). Real costs represent a subtraction from community welfare. An example is the cost of fatal crashes on the streets of a city. Pecuniary costs are costs borne by people or communities that are exactly matched by pecuniary benefits received elsewhere, so that also there is a redistribution of welfare, there is no change in community welfare. The same definitions apply in the case of real and pecuniary benefits. An example is the increase in business relocations to a city due to improved transportation infrastructure. This would be at the expense of competing cities (located in the region) from which the businesses are expected to relocate; thus there is no net welfare gain for the region. Failure to distinguish between real and pecuniary costs can lead to double counting of costs. It has been recommended that strictly pecuniary effects could be excluded from the evaluation. However, such effects could be included in the evaluation if the analyst seeks to investigate the re-distributional impacts of the transportation system among population subgroups or among cities in a region.

D) Internal External Impacts

For jurisdictional and administrative reasons, it may be worthwhile to consider whether system impacts are internal or external to the study area or analysis period defined at the initial stages of the evaluation procedure. Often, the benefits or costs of transportation system actions are felt beyond the study region or analysis period. For example, enhancement in air quality due to transportation improvements in a region may benefit another region located downwind. Also, the economic impacts of transportation system improvement may start to be realized only after the analysis period has expired.

E) Cumulative and Incremental Impacts

Cumulative costs and benefits are the overall costs and benefits from a pre-identified initial time frame and include the impacts of the transportation stimuli. On the other hand, incremental costs and benefits are those impacts associated only with the transportation stimuli and are determined as the total impact after application of the stimuli less the existing costs and benefits before application.

F) Other Categorizations

Heggie [22] grouped transportation impacts from the perspectives of consumption of scarce resources, creation of additional consumption, and generation of non-monetary costs and benefits. Also, Manheim [23] categorized transportation system impacts in two different ways: the party affected and the resource type consumed in constructing, preserving, and operating a transportation system.

3.2 COSTING OF TRANSPORTATION SYSTEM IMPACTS

In these days, the best way for evaluating a transportation system is understand how much sustainable it is. Either system is available or in project step, solutions need to be sustainable. To achieve sustainability in a transportation system, equilibrium of social, environmental and economic impacts must be provided. As mentioned section above, impacts of transportation systems could be categorized in several ways by evaluating entities affected, geographical scope and temporal scope. In our paper, we will dissert impacts as *internal* or *external* whether their benefits or costs are felt beyond the study region or analysis period or not. In this dissertation, impacts will be evaluated as to geographical scopes, temporal scopes and entities affected. We define impact as internal when impact is *during-implementation* of stimulus, felt only in the *stimulus area* and only affects *user*, *facility operator*, *agency* and *government;* external when impact is *post-implementation*, felt in *wider geographical regions* and affects also *nonuser (community)* beside *user, facility operator*, *agency* and *government*.

To achieve equilibrium between these internal and external impacts we benefit from cost functions. Some impacts of all which were mentioned in pervious sections are important impacts which should be included in evaluation. The others will not be included, because they have relatively lower effects or effects that could not be generalized for every region.

Table 3.3 Internal and External Costs

Internal Costs	Vehicle Operating and Ownership	Congestion	Agency				
External Costs	Air Pollution	Accident	Noise	Land Use	Water Pol. and Hydrologic Impact	Traffic Service	Barrier Effect

3.2.1 Internal Costs

These costs are felt by users, facility operators, agency and government directly, only in the study region and only in the analysis period. Vehicle ownership and operating costs, congestion cost and agency costs are internal impacts.

A) Vehicle Operating and Ownership Costs

We launched the study of Özbay, Bartın and Berechman [24] and the study of Özbay, Bartin, Yanmaz-Tuzel and Berechman [25] to obtain a good formulation of vehicle operating and ownership cost. They defined Operating costs as including fuel, oil, tire-wear, parking fees, tolls, and regular and unexpected maintenance; Ownership cost as including vehicle depreciation and insurance costs. The general form of operating and ownership cost function is as follows:

$$C_{opr} = f\left(C_d, C_g, C_o, C_t, C_m, C_i, C_{pt}\right) \tag{3.1}$$

where,

C_{opr} : vehicle operating cost over many years (dollars/ vehicle)

C_d : depreciation cost for a vehicle over many years

C_g : gas cost (dollars/mile)

C_o : oil cost (dollars/mile)

C_t : tire cost (dollars/mile)

C_m : maintenance cost (dollars/mile)

C_i : insurance cost (dollars/year)

C_{pt} : parking fees and tolls (dollars/mile).

They claim depreciation is caused by wear and tear on the vehicle over time and by the change in demand and taste of users. Hence, depreciation cost is assumed to be related to the vehicle's mileage and age. Insurance cost is depending on vehicle's age. So we do not include depreciation and insurance costs in our model.

They claim, maintenance, fuel, oil, and tire-wear costs and parking fees and tolls depend mainly on the distance traveled and obtained cost values per mile. Data on parking fees, and tolls they used, are from C*ost of Owning and Operating Automobiles, Vans, and Light Trucks,* The United States Department of Transportation, Federal Highway Administration [26]. Maintenance, oil, and fuel and tire-wear costs are taken from American Automobile Manufacturers Association [27], in which the cost values are given as national averages defined on a per mile basis. The vehicle operating cost function is developed as follows:

$$C_{opr} = \sum_{r} \sum_{s} \sum_{k} 0.143 \; x_k^{rs} \, d_k^{rs} \tag{3.2}$$

where,

r : origin zone, $r \in R$

s : destination zone, $s \in S$

rs : origin-destination pair, $rs \in K_{rs} = \left\{ rs \,\middle|\, r \in R, \; s \in S \,\middle|\, \right\}$

k : path between origin zone r to destination zone s, $k \in K_{rs}$

R : origin zones set

S : destination zones set

K_{rs} : path set

x_k^{rs} : number of total trips from r to s assigned to path k

d_k^{rs} : length of path k between origin zone r to destination zone s

B) Congestion Cost

Among some studies exploring congestion impact, travel time impact in other words, we find the study of Özbay, *et al.* [24] more appropriate for defining congestion cost. They defined congestion cost as the time-loss due to traffic conditions and drivers' discomfort, both of which are a function of increasing volume to capacity ratios.

Specifically,

- Time loss can be determined through the use of a travel time function. They accepted its value depends on the distance between any OD pairs (d), traffic volume (Q) and roadway capacity (C).
- Users' characteristics: Users traveling in a highway network are not homogeneous with respect to their value of time. In order to calculate congestion costs, an average value of time (*VOT*) ($/h) was employed by Özbay *et al.* [24]. $7.6 per hour, which is the 40% of the average hourly pre-tax wage rate in NJ, was employed as the value of time.

They used the Bureau of Public Roads travel time function was used to calculate time loss. Thus, total cost of congestion between a given OD pair can be calculated by the time loss of one driver along the route, multiplied by total traffic volume and the average value of time. Congestion cost formulation is:

$$\sum_{ij} Q_{ij} \frac{d_{ij}}{V_{0,ij}} \left(1 + 0.15 \left(\frac{Q_{ij}}{C_{ij}} \right)^4 \right) VOT \tag{3.3}$$

where,

ij : points of link, $i, j \in A$

A : link set

Q_{ij} : traffic flow on link connecting points i and j (vehicles/hour)

d_{ij} : length of link (i,j) (mile)

C_{ij} : capacity of link (i,j) (vehicles/hour)

VOT : average value of time (dollars/hour)

$V_{0,ij}$: free flow speed on link (i,j) (miles/hour)

C) Agency Costs

Agency costs refer to the expenditures incurred by the facility owner and operator in providing the transportation service [2]. Agency costs have two dimensions: *capacity* and *durability*. Capacity is needed to accommodate vehicle flow without excessive congestion and is typically increased by adding lanes. Durability -or long-term pavement serviceability- is needed to accommodate a cumulative flow of heavy vehicles without their imposing excessive pavement damage and the concomitant costs to both public agencies and highway users. Durability is typically enhanced by increasing pavement thickness.

Agency costs include both capital cost and non-capital cost. The capital cost is a periodic cost and includes land acquisition and construction costs and rehabilitation costs. The non-capital cost is an annual cost [28].

- ***Capital Costs***

The capital cost of a roadway facility includes *construction* and *periodic reconstruction* cost. All long-term expenditures to construct a facility such as, roadway design, construction material, labor and administration cost, right of way cost, excavation and drainage cost, interest for capital over the lifetime of the facility are included in *construction* cost.

We tried to launch from the study prepared by Cambridge Systematics, Inc. with The Urban Institute Sydec, Inc. for Federal Transit Administration U.S. Department of Transportation [29]. They grouped construction cost in two, right of way and construction of lanes, and made a formulation depending on lane numbers (*L*) and path length (*M*) for three different roadway types. Generalized formulation can be written as follows:

$$C_{cons} = \sigma_i \; M \; L \tag{3.4}$$

where,
σ_i : unit cost of constructing of roadway type *i*
M : roadway length (miles)
L : number of lanes

At the beginning of a network, land is already been occupied, roads and intersections is already been constructed, so this impact is constant. This formulation depends on roadway length and number of lanes and they both are constant not variables. Thus, we do not include construction cost in our model.

Reconstruction (rehabilitation) cost is a periodic improvement cost and usually done every 25 years. For reconstruction cost function, we tried to launch from FHWA's Highway Statistics 2001 study [30]. Report provides improvement costs per lane-mile. FHWA gathers data from several states in the USA. Reconstruction cost parameter is given as 18537 dollars per lane-mile. The generalized function is as follows:

$$C_{recons} = \omega \, M \; L \tag{3.5}$$

where,
ω : reconstructing cost of one mile roadway
M : roadway length (miles)
L : number of lanes

Even though road defection could be related to traffic flow, there are more dominant effects creating rehabilitation need, such as, density of heavy vehicles passing, rain, snow, salting, and ect. It is difficult to generalize these effects and use commonly as they show severity from road to road. On the other hand, as we only include cost functions accepting traffic flow as variables, we do not use this function in our model.

- ***Non-capital Costs***

Non-capital expenditures include routine maintenance, administration, safety and debt service costs. The most expensive category among non-capital expenditures is routine maintenance and operations. It includes regular expenditures required to keep a roadway in usable condition (e.g., patching repairs, pavement marking, snow and ice removing, signals ect.) Non-capital cost is an annual cost [28].

For maintenance cost function, we again tried to benefit from FHWA's records [30]. They lay before us resurfacing cost parameters, it is likely to maintenance cost. This unit cost is 12285 dollars per lane-mile. General form of the function is as follows:

$$C_{main} = \theta\, M\, L \tag{3.6}$$

where,

θ : maintenance cost for one mile roadway

M : roadway length (miles)

L : number of lanes

This function is depending on roadway length and number of lanes. As these are constant, we do no need to include this function in our model.

3.2.2 External Costs

Costs which are also felt outside study area, during and after analysis period, and by community beside users and agency, are external. Calculating external costs of a transportation system is difficult because of uncertainty of area affected and time impact outlasts.

A) Air Pollution Cost

An air pollutant is a gas, liquid droplet or solid particle which, if dispersed in the air with sufficient concentration, poses a hazard to flora, fauna, property and climate. Air pollution is a visible environmental side effect of transportation, has become a public health concern for millions of urban residents worldwide. Transportation vehicles typically emit carbon monoxide, nitrogen oxides, small particulate matter, and other toxic substances that can cause health problems when inhaled. Air pollution also has adverse effects on forests, lakes and rivers. The contribution of transportation vehicle use to global warming remains a cause for much concern as anthropogenic impacts on the upper atmosphere become increasingly evident.

Transportation or “mobile” sources of air pollution, particularly motor vehicles, are a primary source of local carbon monoxide problems and are considered the main cause of excess regional photochemical oxidant concentrations.

Factors affecting pollutant emissions from motor vehicles are [2]:

(a) Travel-related factors: Travel-related factors include vehicle engine operating modes, speeds, and accelerations and decelerations.

(b) Facility-related factors: Certain facility designs can encourage transportation vehicles to operate at low emitting speeds or modes.

(c) Driver-related factors: Driver behavior varies significantly by person and by traffic condition and can influence emission rates. For example, aggressive drivers typically exert more frequent and severe accelerations and decelerations than do their less aggressive counterparts.

(d) Vehicle-related and other factors: Vehicle emissions are influenced by vehicle age, mileage, condition, weight, size, and engine power.

(e) Environmental factors: At low temperatures, more time is required to warm up the engine and the emission control system, thus increasing the level of cold-start emissions.

Air pollution is a typical example of externality. Those who generate air pollution usually do not bear the full cost of the problem. On the other hand, those who reduce air pollution do not receive the full benefit of the air pollution reduction.

To obtain air pollution cost function, we applied the article of Jiefeng Qin, *et.al* [28], titled as "Development of a Full Cost Model-Modecost". They claim that there are two ways to estimate the damage caused by air pollution: One way establishes air pollution standards at an optimal level and requires the polluter to meet those standards, the other way charges the polluter a pollution fee at the level of the difference between the social marginal damage and the private marginal damage of air pollution. They used the latter, damage cost method to estimate the dollar value of damages caused by air pollution. The method involves three steps: (1) identification of emission sources; (2) estimation of emissions; and (3) calculation of monetary values of each pollutant. These three steps are discussed below.

- *Identification of Emissions Sources*

Air pollution, commonly referred to as "smog" is the contamination of the ambient air by chemical compounds or particulated solids in a concentration that adversely affects living organisms. The main air pollutants include carbon monoxides (CO), hydrocarbons (HC), nitrogen oxides (NO_x), sulfur oxides (SO_x), soot-like particulates (PM), and carbon dioxides (CO_2). Vehicles generate a significant portion of the emissions in urban areas. These emissions can vary according to the type of engine, the mode of operation, the fuel consumption, ect. SO_x and PM emissions are mainly generated by stationary sources, and are excluded in our study. CO_2, which is the primary cause of global warming, will be considered in another section.

Carbon monoxide (CO) is formed in the combustion process as a result of the incomplete burning of fuel; it is always present in small quantities in the exhaust regardless of the air/fuel ratio. The greater proportion of fuel there is in the air/fuel mixture, the more CO is produced. This implies that during idling and decelerating, the CO concentration is very high. It decreases during acceleration and high-speed cruising.

Hydrocarbon is incompletely burned or evaporated gasoline or solvents. Its concentration is high during idling and deceleration, as opposed to concentrations associated with cruising and acceleration.

Nitrogen oxide is a product of the burning of surfer-rich fossil fuel, which is formed during the combustion process. It increases with peak combustion temperature. In the other word, a higher level of NO_x is produced during acceleration and high-speed cruising; lower concentrations exist during deceleration and idling.

- *Estimation of Emissions*

To estimate emission amount, Jiefeng Qin and the others [28] were thinking to make a formula based on engine speed and throttle speed which define the power in engine. But in most cases, variables such as engine speed and throttle opening are not available. Thus, they tried to make a formula calculating emission amount as a function of vehicle speed, as follows:

$$m_p = \frac{\beta_1}{v} + \beta_2 v^2 + \beta_3 \eta v \tag{3.7}$$

where,

m_p : emission rate of pollutant p (CO, HC or NO_x)

v : vehicle speed

η : vehicle acceleration rate

β_i : coefficients

The first term on the right side of the equation captures the emission rate during the idle and deceleration period. The second term deals with the emission rate during the vehicle cruising period, which is consistent with the fact that the drag force on the vehicle cruising at a speed v is proportional to the square of the speed, v^2, because of the aerodynamic force. The last term is the emission rate during the acceleration period. There is a strong correlation between the product of acceleration and the speed and the vehicle's accelerating emissions. The product of acceleration and speed is equivalent to power per unit mass. Therefore, the power expended by a vehicle during acceleration is proportional to the product of acceleration rate and speed. As power demand engine capacity, vehicles tend to burn fuel less efficiently, resulting in high emission rates. Acceleration rates drop slowly when vehicle speed is low. However, they drop sharply after the speed exceeds 40 mph. Based on this observation, it is reasonable to assume that vehicle accelerating rates are a function of speed in the form of:

$$\eta = \beta_4 + \beta_5 v^{1/2} \tag{3.8}$$

Hence, equation (3.7) can be rewritten as

$$m_p = \frac{\alpha_1}{v} + \alpha_2\, v + \alpha_3\, v^{1.5} + \alpha_4\, v^2 \tag{3.9}$$

where,

m_p : emission rate of pollutant p (CO, HC, NO_x) (grams/mile)

v : vehicle speed (miles/hour)

α_i : coefficients

They found relations between vehicle speed and emission rates and grouped the relations according to four vehicle classes, namely, light duty gasoline vehicles (LDGV), representing al passenger automobiles; light-duty gasoline trucks (LDGT), which represent pick-ups and minivans; heavy-duty gasoline vehicles (HDGV), which represent most 2-axle single-unit trucks; and heavy-duty diesel trucks (HDDV), which represent the remaining trucks and buses. In our problem, because of we care only passenger car, we took the light duty gasoline vehicles' formula.

$$m_{HC} = \frac{26.29463}{v} - 0.866522 + 0.280275v - 0.067588v^{1.5} + 0.004486v^{2} \quad (3.10)$$

$$m_{CO} = \frac{237.07805}{v} - 7.450332 + 3.093110v - 0.886121v^{1.5} + 0.067083v^{2} \quad (3.11)$$

$$m_{NO_x} = \frac{2.176306}{v} + 0.453768 + 0.162195v - 0.045865v^{1.5} + 0.003436v^{2} \quad (3.12)$$

- *Monetary Values of Pollutants*

Jiefeng Qin and the others [28] applied several past studies calculating monetary emission damage values of pollutants. They benefitted of the estimates based on stationary sources, because they could not find a study basing on mobile sources. Table 3.4 summarizes the damage-based cost estimations of seven studies undertaken in different areas in the U.S.

Table 3.4 Damage values of pollutants ($/kg), 1992 dollars

Area	**Study**	**HC**	**CO**	**NO_x**	**SO_x**	**PM**
Atlanta	Wang	2.433	N/A	4.90	3.078	5.850
Baltimore	Wang	2.501	N/A	5.01	2.964	5.114
Boston	Ottinger	N/A	N/A	2.04	5.069	2.964
California	Small	0.302	0.019	1.00	1.230	0.586
Chicago	Wang	3.055	N/A	6.09	4.073	12.256
Denver	Wang	1.527	N/A	3.21	2.636	3.836
Houston	Wang	4.005	N/A	7.80	3.293	5.872
Iowa	Hauggard	0.367	0.028	1.20	1.482	1.358
LasVegas	NERA	N/A	N/A	0.24	0.326	1.543
Los Angeles	CEC	7.820	0.003	16.39	8.401	53.880
Massachusetts	MDPU	N/A	0.090	8.10	1.867	4.990
Milwaukee	Wang	2.184	N/A	4.40	2.501	3.349
New Orleans	Wang	2.161	N/A	4.39	2.796	4.073
New York	Ottinger	N/A	N/A	2.04	5.069	2.964
Philadelphia	Wang	3.406	N/A	6.72	3.779	9.459
Sacramento	CEC	4.672	0.001	6.89	1.697	2.464
San Diego	CEC	0.111	0.001	6.29	3.028	16.098
S.F.Area	CEC	0.102	0.001	8.42	3.940	27.605
S.J.Valley	Wang	2.534	N/A	5.08	3.953	7.411
Washington, D.C.	Wang	2.772	N/A	5.44	3.474	7.083

Small's study [31] is based on damage costs to health and materials. The costs associated with mortality are based on lost earning as a result of death. Small omits the pollutant costs for damage to agriculture. His argument is that the estimates of agriculture damage costs are so small that including them is unwarranted.

Haugard [32] bases his estimates of pollutant damage costs on damage to human health, material and vegetation. Damage costs to human health are based on medical bills and lost earning as a result of mortality and morbidity. Damage costs to vegetation are based on a study of 77 crops, as well as on shade trees and other ornamental trees and shrubbery.

The purpose of Ottinger's study [33] was to develop a pollutant cost index could be used for electric utilities in estimating the social costs of producing electricity. Damages which are based on impacts to health, materials, vegetation and visibility were estimated individually for each pollutant.

As in Ottinger's study, the Massachusetts Department of Public Utilities (MDPU) [34] estimated the damage cost of each pollutant separately. The estimates tend to be among the highest developed values.

The California Energy Commission (CEC) [35], estimated emission values of power plants in order to justify its decision on power plant sittings in 1992. The estimated values of are based on the Air Quality Valuation Model (AQVM), which includes emission estimation, air quality simulation, estimation of the physical effects of air pollution and a valuation of air pollution effects. The damage estimates include impacts on human mortality and morbidity, visibility, visual aesthetic effects, material effect, forest-related aesthetic damages and agricultural effects.

A study complete by the National Economic Research Associates (NERA) [36] for the Nevada Power Company estimated damage values of pollutants, corresponding to southern Nevada. The study included the air pollution effects of human mortality and morbidity, visibility, material and agricultural damages and acid damages to ecosystems.

The study by Wang [37] uses the emission values estimated in previous original studies (i.e., the ECE study of California air basins, Ottington's Study in Massachusetts and New York, ect.) to establish regression relationships between emission values and air pollutant concentration in the atmosphere and total pollution. With the established regression relationships and the data on air pollutant concentrations and population is seventeen U.S. metropolitan areas obtained from Environmental Protection Agency (EPA), they estimated emission values for these areas.

By using damage values for CO, HC, NO_x in Table 3.4, Jiefeng Qin and others [28] write annual pollution cost formula as follows:

$$A_{pi}(v_i) = \sum_{i=1}^{8} \left(VMT_i \sum_{p} \left(\gamma_p m_p (v_i) \right) \right) \tag{3.13}$$

where,

p : a pollutant

i : ith period

γ_p : damage value for pollutant p (dollars/gram)

VMT_i : annual auto or truck vehicle mile travelled on the corridor(s) during ith period

$m_p(v_i)$: emission rate of pollutant p (CO, HC, NO_x) (grams/mile)

v_i : speed in ith period

With some arrangements, our air pollution function can be written as follows:

$$C_{air} = \sum_{ij} Q_{ij}\ d_{ij} \sum_{p} \gamma_p m_p \left(v_{ij}\right) \tag{3.14}$$

where,

ij : points of link, $i, j \in A$

A : link set

Q_{ij} : traffic volume on link (i,j) (vehicles/day)

d_{ij} : length of link (i,j) (miles)

vij : vehicle speed on link (i,j) (miles/hour)

p : a pollutant

γ_p : damage value for pollutant p, (dollars/gram)

m_p : emission rate of pollutant p, (gram/mile-vehicle)

We calculate pollution only in pick hours, thus, *i* notion is not going to be in our formula. We change *VMT* parameter with $Q_{ij}*d_{ij}$ multiplication because we try to calculate air pollution cost on link basis. We transform *v* parameter on link basis as well. We decided to include Sacremento State's pollutant damage values in our formula, 0.004672 for HC, 0.000001 for CO, 0.00689 for NO_x.

B) Accident Cost

In the period 1992-2002, approximately 40000 to 45000 fatalities per year were experienced on the U.S. transportation system. Of this, 90 to 95% was highway-related.

For people under 65 years of age, the Center for Disease Control has raked transportation accidents as the third-leading cause of death in the United States (after cancer and heart disease) each year from 1991 to 2000. The economic cost of transportation crashes, which is borne by individuals, insurance companies and government, consists of loss of market productivity and workplace costs. Intangible costs include pain and suffering, and loss of life. The costs of crashes can be very high.

For instance, motor vehicle crashes in the United States cost an estimated $230 billion in 2000, representing approximately $820 per person or 2% of the gross domestic product.

Factors affecting transportation crashes can be classified as environmental, engineering, policy, driver characteristics, vehicle or mode characteristics and enforcement factors.

Procedural framework for safety evaluation essentially comprises the product of two elements: change in *crash frequency* after the proposed transportation invention, and unit *crash monetary costs*. Crash frequency or its reduction can be estimated using crash relationships (rates, equations), developed form national data or preferably, recent local data [2].

We launched accident cost function from two studies, one of them belongs to Ozbay, *et al.* [24], the other belongs to Ozbay, Yanmaz-Tuzel, Mudigonda, Bartin, and Berechman [38]. They both used New Jersey's data in their evaluations.
Özbay *et al.* [24] used New Jersey data containing a detailed accident summary for 1995, including the pedestrians affected, grouped by incident types and by county in New Jersey. They decided to find the accident occurrence rate (number of accidents over time) and the unit cost of an accident in order to estimate the cost of accidents over a given period of time. If a function could be developed to estimate the number of accidents occurring over a period of time, accident costs could also be measured by multiplying the number of accidents by their unit cost values. Clearly, costs vary, accident by accident. However, similar accidents have costs that fall more or less in the same range. Thus, they classified accidents as 1) fatal, 2) injury, or 3) property damage.

Özbay *et al.* [24] believed, various geometric design features of a roadway affects the possibility of an accident, such as number of lanes, horizontal and vertical alignment, super-elevation, sight obstructions, and so forth. However, it was not an easy task to include every variable in the accident occurrence rate function. Thus, they correlated the accident occurrence rate with highway functional type, average traffic volume, and the length of the highway. For this purpose, they classified highways as three categories according to their functional properties. These are interstate, freeway-expressway, and arterial-collector-local. They wrote the generalized form of the total accident cost function as follows:

$$C_{acc} = \sum_{i=1}^{3} \left(C_f P_{fi} + C_h P_{hi} + C_d P_{di} \right) \qquad (3.15)$$

where,

C_{acc} : total accident cost per year (dollars/year)

C_f : unit cost of a fatal accident per crash (dollars)

C_d : unit cost of a property damage accident per crash (dollars)

C_h : unit cost of an injury accident per crash (dollars)

p_{fi} : number of fatal accidents per year for highway type i

p_{hi} : number of personal injury accidents per year for highway type i

p_{di} : number of property damage accidents per year for highway type i.

They took C_f, C_h, and C_d values from Miller and Moffet [39]. These values cover both direct and indirect costs caused by an incident.

In order to utilize the equation (3.15), Özbay *et al.* [24] developed p_{fi}, p_{hi}, and p_{di} functions using the available accident data. As mentioned above, the number of accidents is assumed to be correlated with roadway length (M), as a measure of network properties, and average traffic volume (Q), as an output measure. The general form of the accident occurrence rate (the number of accidents over a given time period) function is given as follows in their article:

$$\rho = \alpha_1 \, M^{\alpha_2} \, Q^{\alpha_3} \qquad (3.16)$$

where,

α_1, α_2, α_3 : estimated coefficients

Özbay *et al.* [24] run nine regression analyses to estimate accident occurance rate as a function of average traffic volume and the roadway length for each highway category. Hence, they obtained nine different functions. Seven of them were statistically significant but two of them were not.

Özbay *et al.* [38] studied on accident occurrence rate again with a new accident database consisting of a detailed accident summary for the years 1991–1995 in New Jersey. They wrote nine functions and made regression analysis. They changed functions from depending on traffic volume and roadway length, to depending on number of lanes, beside traffic volume and roadway length. The unit accident costs employed in these functions were adopted from a recent study by FHWA [40].

Here in our study we are using the later functions which are in the study of Ozbay, *et al.* [38]:

$$C_{acc} = \left[\sum_{ij} \left(178.5\, Q_{ij}^{\ 0.58} d_{ij}^{\ 0.69} L_{ij}^{\ 0.43} + 18359\, Q_{ij}^{\ 0.45} d_{ij}^{\ 0.63} L_{ij}^{\ 0.47} \right) \right] / 365 \qquad (3.17)$$

where,

ij : points of link, $i, j \in A$

A : link set

Q_{ij} : traffic volume on link (i,j) (vehicles/day)

d_{ij} : length of link (i,j) (miles)

L_{ij} : number of lanes of link (i,j)

C) Noise Cost

Noise, defined as unwanted or excessive sound, is one of the most widely experienced environmental externalities associated with transportation systems. Excessive noise can adversely affect real estate value and, more importantly, can cause general nuisance and health problems.

An important feature of noise pollution is that noise generated at a particular time is not affected by previous activity, nor does it affect future activities; unlike other pollutants, noise leaves no residual effects that are evidential of its unpleasantness. For this reason, there may be a tendency to overlook or to underestimate the problem of noise pollution.

Noise is described more completely when combined with descriptions of loudness and frequency. Loudness can be defined as, noise intensity or it is related to the pressure fluctuations amplitude transmitted through the air. Frequency can be defined as a change in the rate of pressure fluctuations in the air measured in terms of pressure changes per second.

A collision between two vehicles is typically loud, but it lasts only a fraction of a second. At the other extreme, noise due to continuous traffic operation may not be intense, but it is continual. Variations of traffic noise with time is considered important for assessing such noise and some effective descriptors of the temporal variation of sound have been developed as follows: maximum sound level, $L_{max}(t)$; statistical sound levels, $L_{xx}(t)$; equivalent sound level, $L_{eq}(t)$; and day/night level, $L_{dn}(t)$. But one of them, L_{eq} has become the metric of choise and is being used in most of noise functions. L_{eq} means the equivalent sound level, is a steady state sound level that contains the same amount of acoustic energy as a time-varying sound level in a given time period [2].

Factors affecting noise propagation can be said as (i) nature of source, distance and ground effects, and (ii) effect of noise barriers. And generally in whole formulas created to calculate noise level or noise impact, these factors are included as variables.

When we were investigating past studies to understand noise impact, we realized it is studied in two categories: *residential depreciation* and *community health*. Residential depreciation impact could be evaluated easily, by a function agreed on generally. Nevertheless, community health impact could not be evaluated as numerical, and also all studies in this field are spatial and could not be generalized. So we only write a formula for residential depreciation impact. To put into our model, we used noise cost function in study of Özbay *et al.* [24]. Their function is calculating the depreciation in the value of residential units.

While there are other factors that cause depreciation in housing values, *closeness* is most often utilized as the major variable explaining the effect of noise externality. Thus, they created a function based on closeness factor. They claim, the closer a house is to a highway, the higher social costs are. In general it is accepted that a sound becomes annoying after 50 dB(A) (A-weighted decibels). Any sound level above this limit definitely imposes a cost on society. Their function assumes this value as lower limit. They use the Noise Depreciation Sensitivity Index (NDSI) as given in Nelson's study [41]. NDSI is defined as the ratio of the percentage reduction in the house value and the change in the noise level. Nelson suggests a value of 0.40% for the NDSI. The house value depreciation function is formed as follows:

$$ND = N_h \left(L_{eq} - L_{\max}\right) DW_{avg} \tag{3.18}$$

$$L_{eq} = 10\log(Q) - 10\log(r) + 20\log(v) + 20 \tag{3.19}$$

where,

ND : depreciation due to noise (dollars)

L_{eq} : equivalent sound level (dB(A)) (This function is only valid for the vehicle flows above 1,000 vehicles/hour.)

Q : traffic flow (vehicles/hour)

r : distance to the highway (feet)

v : average speed of the traffic (miles per hour)

N_h : number of houses affected (number of houses per mile square) (calculated by multiplying the average residential density (*RD*, number of houses per mile square) around a highway by the distance to that highway in feet (r) and the length of the relevant highway section in miles (d). The multiplication by 2 is used to calculate the number of housing units on each side of the way.)

$$N_h = 2\left(RD\right) r\, d \tag{3.20}$$

where,

L_{max} : maximum acceptable noise level

D : percentage discount in value per an increase in the ambient noise level (0.4%)

W_{avg} : average house value (dollars)

Based on equations (3.18), (3.19), (3.20), the noise cost function can be developed as follows:

$$C_{noise} = \left[\sum_{ij} 2 \int_{r_1 = r_{\min}}^{r_2 = r_{\max}} \left(L_{eq} - L_{\max} \right) D\, W_{avg} \frac{RD}{5280}\, dr \right] d_{ij} \frac{i\,(1+i)^N}{\left[(1+i)^N - 1\right] 365} \tag{3.21}$$

$$L_{eq} = 10 \log\left(Q_{ij}\right) - 10 \log\left(r_{ij}\right) + 20 \log\left(v_{ij}\right) + 20 \tag{3.22}$$

where,

ij : points of link, $i, j \in A$

A : link set

Q_{ij} : traffic volume on link (i,j) (vehicles/day)

L_{eq} : equivalent sound level (dB(A))

r_{ij} : distance to link (i,j) (feet)

v_{ij} : vehicle speed on link (i,j) (miles/hour)

RD : number of houses per mile square

d_{ij} : length of link (i,j) (miles)

L_{max} : maximum acceptable noise level (dB(A))

D : percentage discount in value per an increase in the ambient noise level

W_{avg} : average house value (dollars)

N : average lifetime of a house (years)

Minimum distance to highway (r_{min}) is assumed to be 50 feet in our study. L_{max} is taken as 50 dB(A). For the average house value (W_{avg}), we launched the values given in the study of Özbay *et al.* [24] again, we take the “median hausing value (228,940$)”. For residential density (*RD*), we launched from the study of Richardson, Bruton and Roddis [42]. We use the Brisbane city’s data, 723 houses/mile square.

Cost function defines noise cost around a one-mile long roadway segment over so many years. Thus, we multiply cost function with d_{ij} to obtain noise cost for whole roadway. We assume average lifetime of a house (*N*) is 50 years, depreciate the function over 50 years and obtained a daily cost dividing by 365.
Representing maximum distance to highway, r_{max} is calculated by equating *Leq* (equation (3.19)) to 50 dB(A), where the traffic noise is above dB(A).

In equation for L_{eq}, we change traffic flow (*Q*) parameter with Q_{ij} referring the flow on *ij*, speed for traffic *v* with v_{ij} referring speed on link *ij*, distance to highway *r* parameter with r_{ij} referring distance to link *ij*.

D) Land Use Costs

Land use impacts of transportation have two major factors to consider. The first factor concerns how specific policies and planning decisions affect land use, including both direct and indirect land use impacts. Direct impacts involve the land used for transport facilities, such as paths, roads, parking and terminals. Indirect impacts involve changes in the type, density, design and location of development. These impacts vary by mode since automobile transport requires more space than other modes for travel and parking, and tends to encourage more dispersed land use patterns.

The second factor concerns the economic, social and environmental impacts of these different land use patterns. Increased pavement and more dispersed land use development patterns impose various economic, social and environmental costs on society that are often not recognized in conventional transportation planning [43].

We launched from Victoria Transport Policy Institute’s Transportation Cost and Benefit Analysis II, Land Use Impacts study [43] and Roadway Land Value study [44] for all cost types.

- ***Direct Land Use Impact Cost***

This impact refers the value of land devoted to roads and how this cost can be allocated to road users. Most roads have two to four lanes, each 10-14 feet wide, plus shoulders, sidewalks, drainage ditches and landscaping area. Road rights-of-way (the land that is legally devoted to the road) usually range from 24 to 100 feet wide. Most roads in developed countries are paved. In high density urban areas road pavement often fills the entire right-of-way, but in other areas there is often an unpaved shoulder area. The amount of land devoted to roads is affected by:

- projected vehicle traffic demand (which determine the number of traffic lanes)
- road design standards (which determine lane and shoulder widths)
- on street parking practices (which determine the number of parking lanes)
- additional design features, such as shoulders, sidewalks, ditches and landscaping

Roadway land value (direct land use impact) is often considered a sunk cost, except where land acquisition costs are incorporated into roadway user fees. However, there is considerable agreement among economists that such assets should be valued as they would be in a competitive market, that is, at their current replacement cost.

At a minimum, value of land devoted roads is the value of urban periphery land. It bases on the assumption that, each acre used for roads represents one less acre available for other purposes for urban. And especially in urban areas, land of more developed cities values a bit more.

Direct land use costs are based on vehicle use (which creates demand for roads) and varies depending on location, with higher land market values in urban areas, and higher non-market values in areas with high environmental worth [44].

In the "Transportation Cost and Benefit Analysis II – Roadway Land Value" study of Victoria Transport Policy Institute [44], direct land use costs are given for several vehicle types in several time periods. They launched the studies of Delucchi [45], KPMG, [46] and Douglass Lee [47]. They wrote a formulation based on vehicle mile travelled. We use average car-urban peak cost parameter and write the formulation as follows:

$$C_{L.direct} = \sum_{r}\sum_{s}\sum_{k} 0.034\, x_k^{rs}\, d_k^{rs} \qquad (3.23)$$

where,

r : origin zone, $r \in R$

s : destination zone, $s \in S$

k : path between origin zone r to destination zone s, $k \in K_{rs}$

R : origin zones set

S : destination zones set

K_{rs} : path set

x_k^{rs} : number of total trips from r to s assigned to path k

d_k^{rs} : length of path k between origin zone r to destination zone s

- ***Indirect Land Use Impact, Sprawl Cost***

Incremental increases in the amount of land devoted to roads create a more dispersed, automobile dependent land use pattern, known as sprawl. Sprawl tends to increase a number of costs to society, including public service costs, transportation costs and environmental impacts.

Actually there is an argument about treating sprawl as a land use issue, not a transport issue. Transportation decisions affect land use pattern, the two issues cannot be separated. However, without constructing roadways, transportation mode or automobile dependency can't cause sprawl, we believe sprawl is a land use cost.

Benefits of sprawl are mostly private (internal). On the other hand, costs of sprawl are more clear and external. The economically optimal level of sprawl consists of what consumers would choose in an efficient market.

Costs resulting from sprawl can be defined as extra land use costs. Sprawl has extra land use costs as socially, environmentally and aestheticly. Beside these extra costs, sprawl causes increased public service costs and user transportation costs.
There is no study about monetizing extra social and environmental impact of sprawl, so we do not include these extra costs when we form functions of social, environmental and aesthetic costs of land use. Nevertheless we write cost functions for incremental public service and transportation costs below.

Increased public service costs resulting from sprawl: Sprawl tends to increase the costs of public services such as policing and emergency response, school busing, roads, water and sewage. The relationship between land use patterns and public service costs are shown in Figure 3.1.

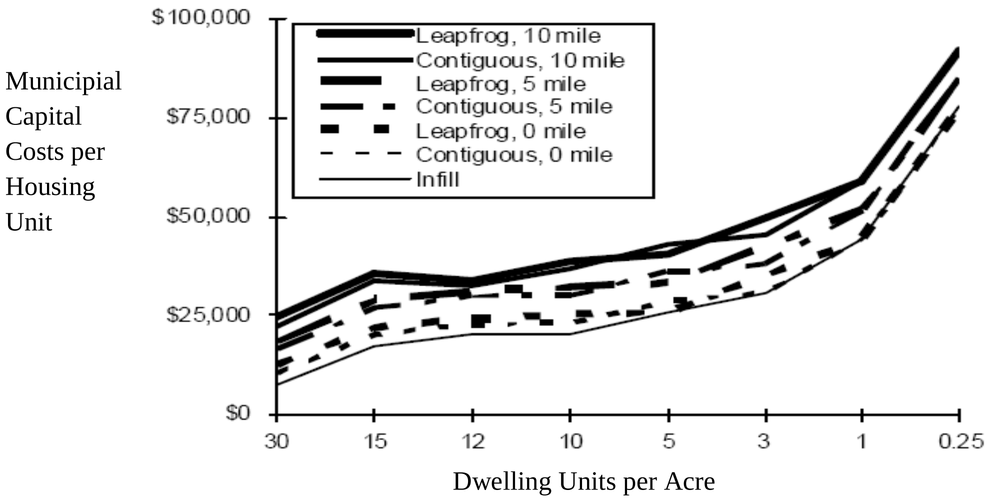

Figure 3.1 Relationship between land use patterns and public service costs

Some costs increase at very high densities due to congestion and high land costs, and decrease in rural areas where governments provide few services. But, sprawl encourages new residents with higher expectations to move to exurban areas, so local governments face pressure to provide urban services to low-density sites despite high unit costs.

Total costs of sprawl are probably greater when commercial development costs are also included:
"Because the home and the workplace are entirely separated from each other, often by a long auto trip, suburban living has grown to mean a complete, well-serviced, self-contained residential or bedroom community and a complete, well-serviced place of work such as an office park. In a sense we are building two communities where we used to have one, known as a town or city. Two communities cost more than one; there is not only the duplication of infrastructure but also of services, institutions and retail, not to mention parking and garaging large numbers of cars in both places."

We launch from the land use value study of Victoria Transportation Policy Institute [43] again to monetize increased public cost resulting from transportation land use policy. They used the outputs of Robert Smythe's study [48], as shown in Table 3.5.

Table 3.5 Household annual municipal costs by residential densities

Costs	**Rural sprawl**	**Rural Cluster**	**Medium density**	**High density**
Units/Acre	1:5	1:1	2.67:1	4.5:1
Schools	4526	4478	3252	3204
Roads	154	77	53	36
Utilities	992	497	364	336
Totals	5672	5052	3669	3576

They assumed that sprawl induces 50% of households to choose one step lower density in Table 3.5 Half the average incremental annual municipal cost increased ([($5,672-$5,052)+ ($5,052-$3,669)+($3,669-$3,576)] x 0.5 = $350), divided by 15,100 annual vehicle miles per household [49], indicated this external cost averages $0.023 per mile, or about $0.03 in 2007 dollars. In our study, we assume cost as 3¢ per vehicle mile and write increased public cost function as follows:

$$C_{L.public} = \sum_{r}\sum_{s}\sum_{k} 0.03\, x_k^{rs}\, d_k^{rs} \tag{3.24}$$

where,

r : origin zone, $r \in R$

s : destination zone, $s \in S$

k : path between origin zone *r* to destination zone *s*, $k \in K_{rs}$

R : origin zones set

S : destination zones set

K_{rs} : path set

x_k^{rs} : number of total trips from *r* to *s* assigned to path *k*

d_k^{rs} : length of path *k* between origin zone *r* to destination zone *s*

Increased transportation costs / reduced access resulting from sprawl: Sprawl creates less accessible land use patterns, which increases mobility requirements to reach common destinations, and reduces transportation options. This increases per capita vehicle ownership and use, increasing total transportation costs [43].

Sprawl induces these impacts more. Sprawl causes:

- more, bigger and longer roads not suitable for walking or cycling,
- changing of social, commercial centers that poor people could not reach easily,
- more vehicle hours and spending more money for households living in low-density suburbs
- few transportation mode choices comparable households in traditional cities/towns

We launch from Victoria Transportation Policy Institute's study [43] to monetize this group of cost. They explained few studies had attempted to quantify increased transportation cost of sprawled land use. They made a correlation between density values and vehicle ownership and operating costs using data from some studies done on their own and by other researchers.

They assumed sprawl causes 50% of households to choose a residence one step lower density in Table 3.5, averaged three incremental increases in vehicle costs and divided by two. By dividing by 15,100 average annual miles, they reached a cost averaged as 12¢ per vehicle mile. We can write cost function as follows:

$$C_{L.trans} = \sum_{r}\sum_{s}\sum_{k} 0.12\, x_k^{rs} d_k^{rs} \tag{3.25}$$

where,

r : origin zone, $r \in R$

s : destination zone, $s \in S$

k : path between origin zone r to destination zone s, $k \in K_{rs}$

R : origin zones set

S : destination zones set

K_{rs} : path set

x_k^{rs} : number of total trips from r to s assigned to path k

d_k^{rs} : length of path k between origin zone r to destination zone s

- ***Environmental Degradation Impact of Land Use***

Roads degrade environmental amenities and agricultural production directly by paving and clearing land, indirectly by encouraging increased development, sprawl and other disturbances, by severing and fragmenting habitat, and by introducing new species that compete with native plants and animals. Sprawl tends to increase air pollution emissions compared with less automobile oriented communities. If just 5% of a watershed is covered with impervious surfaces, such as roads and parking facilities, the water quality of streams is seriously degraded. Paved surfaces have a “heat island” effect (increased local temperatures) which increases urban temperatures by 2-8° F in sunny conditions, increasing energy demand, smog and human discomfort [43].

Banzhaf and Jawahar identify the following benefits from preserving undeveloped urban fringe lands [50]:

1. Protecting groundwater.
2. Protecting wildlife habitat.
3. Preserving natural places.
4. Providing local food.
5. Keeping farming as a way of life.
6. Preserving rural character.
7. Preserving scenic quality.
8. Slowing development.
9. Providing public access.

Ecological damage from roads and traffic is well documented. Many studies could be easily reached in literature.

W. Roley states [51]:

“The net effect on wildlife of automobile-dependent urban sprawl is the fragmentation of habitat and the isolation of these fragments and their wildlife populations from one another. The gravest threat to the survival of wildlife in developed areas around the world is the reduction of both habitat and mobility of wildlife. The automobile, in other words, has become the greatest predator of wildlife.”

Roads cause various types of ecological damage, particularly when introduced to wilderness or semi-wilderness areas. These impacts tend to be complementary and cumulative; although individually they may be minimized through mitigation efforts, their overall effects are still significant. Roads produce the following impacts [43]:

- *Roadkills*: Animals killed directly by motor vehicles. The Humane Society and Urban Wildlife Research Center estimate that more than 1 million large animals are killed annually on U.S. highways. Road kills are a major cause of death for many large mammals including several threatened species. Roadkills increase with traffic speeds and volumes.
- *Road Aversion and other Behavioral Modifications*: Roads affect animals' behavior and movement patterns. For example, black bears cannot cross highways with guardrails. Some species, on the other hand, become accustomed to roads, and are therefore more vulnerable to harmful interactions with humans.
- *Population Fragmentation and Isolation*: By forming a barrier to species movement, roads prevent interaction and cross breeding between population groups of the same species. This reduces population health and genetic viability.
- *Exotic Species Introduction:* Roads spread exotic species of plants and animals that compete with native species. Some introduced plants thrive in disturbed habitats along new roads, and spread into native habitat. Preventing this spreading is expensive.
- *Pollution*: Road construction and use introduce noise, air and water pollutants. (This cost is separately included in our study)
- *Habitat Impacts*: Roads displace and disrupt habitat.
- *Impacts on Hydrology and Aquatic Habitats*: Road construction changes water quality and water quantity, stream channels, and groundwater. (This cost is separately included in our study)
- *Access to Humans*: This includes hunters, poachers, and irresponsible visitors.
- *Sprawl:* Increased road accessible stimulates development, stimulates demand for urban services, which stimulates more development, leading to a cycle of urbanization.

We launched from Land Use Impacts study of Victoria Transport Policy Institute [43] to write a formulation for environmental impact of land use. They launched the study of Maibach, Schreyer, Sutter, Essen, Boon, Smokers, Schroten, Doll, Pawlowska, and Bak [52]. They made a calculation as follows: 3.9 million miles of U.S. public roads carry about 2,300 million vehicle miles of travel, about 600,000 annual VMT per road mile, or about 200,000 VMT per lane mile, assuming 3 average lanes per road. They formed a function based on vehicle mile travelled. Function includes environmental impacts of land devoted roadways bur not quantified the extra environmental cost caused form induced sprawl. Thus, this function formed by the institute, does not include environmental cost of sprawl. The cost is as follows:

$$C_{L.environment} = \sum_r \sum_s \sum_k 0.03\, x_k^{rs} d_k^{rs} \tag{3.26}$$

where,

r : origin zone, $r \in R$

s : destination zone, $s \in S$

k : path between origin zone r to destination zone s, $k \in K_{rs}$

R : origin zones set

S : destination zones set

K_{rs} : path set

x_k^{rs} : number of total trips from r to s assigned to path k

d_k^{rs} : length of path k between origin zone r to destination zone s

- ***Aesthetic Degradation and Loss of Cultural Sites Impact of Land Use***

Roads and parking facilities, vehicle traffic, and low-density development often degrade landscape beauty in various ways. An automobile oriented urban area is inherently ugly because retail businesses must “shout” at passing motorists with raucous signs, because so much of the land must be used for automobile parking, and because the settlement pattern has no clear form.

The value of attractive and healthy landscapes is indicated by their importance in attracting tourism and increasing adjacent property values. Car traffic and roadway expansion is a threat to the cultural heritage and tourist industry of Cairo, Egypt, and probably most other historic cities. Landscape aesthetic degradation can be evaluated using surveys. Visualization techniques can be used to evaluate the esthetic impact of roads and traffic. Ratings generally became less favorable as road size increases.

Transportation aesthetic costs have rarely been monetized. Victoria Transportation Institute uses only the data of Segal's study [53]. They thought that aesthetic degradation from roads probably costs billions of dollars a year in reduced property values and other losses. They evaluated what aesthetic costs could be, and came to a conclusion as this cost can be a minor cost and ranked with other minor environmental costs such as the barrier effect, water pollution. They made a comparable estimate of 0.5¢ per vehicle mile. (They had quantified barrier effect and water pollution resulting from roadways before). The cost function is as follows:

$$C_{L.aesthetic} = \sum_r \sum_s \sum_k 0.005\, x_k^{rs} d_k^{rs} \tag{3.27}$$

where,

r : origin zone, $r \in R$

s : destination zone, $s \in S$

k : path between origin zone r to destination zone s, $k \in K_{rs}$

R : origin zones set

S : destination zones set

K_{rs} : path set

x_k^{rs} : number of total trips from r to s assigned to path k

d_k^{rs} : length of path k between origin zone r to destination zone s

- ***Social Impact of Land Use***

Automobile-oriented transport tends to result in development patterns that are suboptimal for many social goals. Wide roads and heavy traffic tend to degrade the public realm (public spaces where people naturally interact) and in other ways reduce community cohesion [43].

Appleyard [54] reported a negative correlation between vehicle traffic volumes and measures of neighborly interactions and activities, including number of friends and acquaintances residents had on their street, and the area they consider “home territory.” He comments:

“The activities in which people engage or desire to engage in may affect their vulnerability to traffic impact. So many of these activities have been suppressed that we sometimes forget they exist...Children wanting to play, and people talking, sitting, strolling, jogging, cycling, gardening, or working at home and on auto maintenance are all vulnerable to interruption [by traffic]...One of the most significant and discussed aspects of street life is the amount and quality of neighboring. Its interruption or ‘severance’ has been identified as one of the primary measures of transportation impact in Britain.”

Various writers criticize the “placelessness” resulting when urban space is optimized for vehicle traffic. Carlson [55] argues, “Automobile-based development has reduced opportunities for public life and magnified the polarization of our society by aggravating the geographical and time barriers between people with different incomes, and by making it more difficult for those who don’t own cars to participate in life outside their communities”. Sprawl is associated with reduced housing diversity, social alienation, reduced social interaction and exacerbated urban problems. Studies indicate that respondents living in walkable neighborhoods were more likely to know their neighbors, participate politically, trust others, and be socially engaged.

Automobile oriented communities make non-drivers “location disadvantaged” due to their relatively poor access by other modes. Various critics argue that automobile travel, urban scrawl, and middle-class flight to suburbs contribute to racial and income segregation, social conflict and degraded cities. Long commutes increase the physical separation between work and home, leading to reduced sensitivity concerning the impacts of business activities on nearby communities [43].

We have investigated so many publications, articles and other studies to find a monetized definition of social impact of transportation on people, but we could not find. And we decided to launch from Victoria Transport Policy Institute’s study [43]. They had not found any estimates of this group of costs, like us. They thought this cost is probably significant in total, and comparable to environmental impact costs, so they made an estimate of 3¢ per vehicle mile.

$$C_{L.social} = \sum_r \sum_s \sum_k 0.03\, x_k^{rs} d_k^{rs} \qquad (3.28)$$

where,

r : origin zone, $r \in R$

s : destination zone, $s \in S$

k : path between origin zone r to destination zone s, $k \in K_{rs}$

R : origin zones set

S : destination zones set

K_{rs} : path set

x_k^{rs} : number of total trips from r to s assigned to path k

d_k^{rs} : length of path k between origin zone r to destination zone s

E) Water Pollution and Hydrologic Impact Cost

Victoria Transport Policy Institute [56] defines *Water pollution,* as harmful substances released into surface or ground water, either directly or indirectly, and *Hydrologic impact* as changes in surface (streams and rivers) and groundwater flows.

Motor vehicles, roads and parking facilities are a major source of water pollution and hydrologic disruptions. These include:

- *Water Pollution:* Crankcase oil drips and disposal, road de-icing (salt) damage, roadside herbicides, leaking underground storage tanks, air pollution settlement;
- *Hydrologic Impacts:* Increased impervious surfaces, concentrated runoff, increased flooding, loss of wetlands, shoreline modifications, construction activities along shorelines.

These impacts impose various costs including polluted surface and ground water, contaminated drinking water, increased flooding and flood control costs, wildlife habitat damage, reduced fish stocks, loss of unique natural features, and aesthetic losses. An estimated 46% of US vehicles leak hazardous fluids, including crankcase oil, transmission, hydraulic, and brake fluid, and antifreeze, as indicated by oil spots on roads and parking lots, and rainbow sheens of oil in puddles and roadside drainage ditches. An estimated 30-40% of the 1.4 billion gallons of lubricating oils used in automobiles are either burned in the engine or lost in drips and leaks, and another 180 million gallons are disposed of improperly onto the ground or into sewers. Runoff from roads and parking lots has a high concentration of toxic metals, suspended solids, and hydrocarbons, which originate largely from automobiles. Highway runoff is toxic to many aquatic species.

Large quantities of petroleum are released from leaks and spills during extraction, processing, and distribution. Road de-icing salts cause significant environmental and material damage. Roadside vegetation control is a major source of herbicide dispersal. Table 3.6 shows pollution measured in roadway runoff.

Table 3.6 Pollution Levels in Road Runoff Waters (micrograms per liter) [56]

Pollutant	Urban	Rural	Pollutant	Urban	Rural
Total suspended solids	142	41	Nitrate + Nitrite	0.76	0.46
Volatile suspended solids	39	12	Total copper	0.054	0.022
Total organic carbon	25	9	Total lead	0.4	0.08
Chemical Oxygen Demand	114	49	Total zinc	0.329	0.08

Roads and parking facilities have major hydrologic impacts. They concentrate stormwater, causing increased flooding, scouring and siltation, reduce surface and groundwater recharge which lowers dry season flows, and create physical barriers to fish. One survey found that 36% of 726 Washington State highway culverts interfere with fish passage, of which 17% were total blockages [57]. Reduced flows and plant canopy along roads can increase water temperatures. These impacts reduce wetlands and other wildlife habitat, degrade surface water quality, and contaminate drinking water. Hydrologic impacts can be as harmful to natural environments as toxic pollutants. Water pollution emissions are an external cost, and therefore inequitable and inefficient [56].

Victoria Transport Policy Institute's study [56] claims, vehicle maintenance and use are variables of Water quality impact evaluation, and lane miles and parking supply are generally variables of Hydrologic impacts evaluation. They claim, quantifying these costs is challenging. It is difficult to determine how much motor vehicles and roads contribute to water pollution problems since impacts are diffuse and cumulative. Roadway runoff usually meets water quality standards, but some pollutants concentrate in sediments or through the food chain. Even if the quantity of pollutants originating from roads and motor vehicles, and their environmental effects are known, the problem of monetizing impacts such as loss of wildlife, reduced wild fish reproduction, and contaminated groundwater is appeared.

Victoria Transport Policy Institute [56] thinks none of existing estimate incorporates all identified impacts. They claim, WSDOT's [58] cost estimate for meeting water quality standards for state highway runoff is notable because it alone exceeds most other estimates, implying that total water quality and hydrologic costs are substantial. They do the following estimate of *total* water pollution costs from roads and motor vehicles:

1. State highways account for approximately 5% of U.S. road miles, 10% of lane miles, and carry about 50% of VMT. An estimated 300 million off-street parking spaces increase road surface area 30%, and 50% in urban areas. This indicates that *state* highway runoff impacts can be conservatively estimated at one-third of *total* roadway impacts, so the middle value of WSDOT highway runoff mitigation cost estimates ($218) is tripled to include other roads, parking, and residual impacts ($218 x 3 = $655 million), and scaled to the U.S. road system ($655 x 50) for total annual national runoff costs of $33 billion.
2. Add Douglass Lee's [59] estimate of oil spills ($2.7 billion).
3. Add Murray and Ulrich's [60] estimate road salting costs ($6.7 billion).

This totals $42 billion per year; divided by the approximately 3,000 billion miles driven annually in the US gives 1.4¢ per automobile mile. This estimate can be considered a lower-bound value because it excludes costs of residual runoff impacts, shoreline damage, leaking underground storage tanks, reduced groundwater recharge and increased flooding due to pavement. This cost is applied equally to all petroleum powered vehicles. Although it could be argued that buses require more road surface and consume more petroleum per mile, private vehicle owners are more likely to allow their vehicles to drip and to dispose of used fluids incorrectly, so overall impacts are considered equal. Electric cars and trolleys are estimated to cause half the water pollution as an average automobile because they use few petroleum products, but still require roads and parking. Institute [56] concluded their estimations for other types of vehicles in the same way. Table 3.7 shows the estimates of water pollution costs for all vehicle types.

Table 3.7 Estimate-Water Pollution Costs (2007 Dollars per vehicle mile)

Vehicle Class	**Urban Peak**	**Urban Off-Peak**	**Rural**	**Average**
Average car	0.014	0.014	0.014	0.014
Compact car	0.014	0.014	0.014	0.014
Electric car	0.007	0.007	0.007	0.007
Van / Light truck	0.014	0.014	0.0014	0.014
Rideshare passenger	0.000	0.000	0.000	0.000
Diesel bus	0.014	0.014	0.0014	0.014
Electric bus / Trolley	0.007	0.007	0.007	0.007
Motorcycle	0.014	0.014	0.0014	0.014
Bicycle	0.000	0.000	0.000	0.000
Walk	0.000	0.000	0.000	0.000
Telework	0.000	0.000	0.000	0.000

As we assumed all users as passenger cars in our study, and operated the model in peak hours, we use Urban Peak-Average car water pollution cost value ($0.014) in our formulation.

$$C_{water} = \sum_{r}\sum_{s}\sum_{k} 0.014\, x_k^{rs} d_k^{rs} \tag{3.29}$$

where,

r : origin zone, $r \in R$

s : destination zone, $s \in S$

k : path between origin zone r to destination zone s, $k \in K_{rs}$

R : origin zones set

S : destination zones set

K_{rs} : path set

x_k^{rs} : number of total trips from r to s assigned to path k

d_k^{rs} : length of path k between origin zone r to destination zone s

F) Traffic Services Costs

Traffic services include policing, law enforcement, emergency response, planning, courts, street lighting, parking enforcement, and driver training.

These services serve a wide range of users including pedestrians and cyclists beside motorists. These services are mostly funded through local general taxes. Several studies indicate that a significant portion of municipal government budgets are devoted to traffic services. The need for these services, and therefore their costs, tend to increase with motor vehicle traffic, since motorized travel is more dangerous and so requires more management and emergency response. Since traffic services are mostly funded through general taxes, they can be considered an external cost [61].

We launch from Traffic Services study of Victoria Transportation Policy Institute [61] to write a cost function. They benefitted from several studies, when determining cost parameter. They estimated costs as 2¢ per mile for urban peak hours, 1.3¢ per mile urban for off-peak, 0.7¢ per mile for Rural. They applied these cost equally to all motor vehicles with some assumptions. We take average car-urban peak cost value and write our function as follows:

$$C_{traf.ser.} = \sum_{r}\sum_{s}\sum_{k} 0.020\, x_k^{rs} d_k^{rs} \tag{3.30}$$

where,

r : origin zone, $r \in R$

s : destination zone, $s \in S$

k : path between origin zone r to destination zone s, $k \in K_{rs}$

R : origin zones set

S : destination zones set

K_{rs} : path set

x_k^{rs} : number of total trips from r to s assigned to path k

d_k^{rs} : length of path k between origin zone r to destination zone s

G) Barrier Effect Cost

The *Barrier Effect* (also called *severance*) refers to delays, discomfort and lack of access that vehicle traffic imposes on non-motorized modes (pedestrians and cyclists).

Severance usually focuses on the impacts of new or wider highways, while the barrier effect takes into account the impacts of vehicle traffic. Roads and vehicle traffic tend to create a barrier to pedestrian and cyclist travel. In the study of Victoria Transport Policy Institute [150], it is said that the barrier effect is equivalent to traffic congestion costs. They say, most traffic congestion cost estimates exclude impacts on non-motorized travel. In addition to travel delays, they claim vehicle traffic imposes crash risk and pollution on non-motorized travelers. The barrier effect reflects a degradation of the non-motorized travel environment too. This is not to imply that drivers intentionally cause harm, but rather that such impacts are unavoidable when, heavy and hard vehicles traveling at high speed share space with vulnerable road users.

The barrier effect is an external cost, and so tends to be inequitable and inefficient. Since disadvantaged populations often depend heavily on non-motorized transport, and so bear a disproportionate share of this cost, it tends to be vertically inequitable. This impact depends on [62]:

- road width
- traffic speed
- traffic volume
- quality of pedestrian facilities.

- *Quantifying the Barrier Effect*

Both the Swedish [63] and the Danish [64] roadway investment evaluation models incorporate methods for quantifying barrier effects on specific lengths of roadway. Both involve two steps. First, a barrier factor is calculated based on traffic volumes, average speed, share of trucks, number of pedestrian crossings, and length of roadway under study. Second, the demand for crossing is calculated (assuming no barrier existed) based on residential, commercial, recreation, and municipal destinations within walking and bicycling distance of the road. The Swedish model also adjusts the number of anticipated trips based on whether the road is in a city, suburb, or rural area, and the ages of local residents.

Russell and Hine [65] recommend that the barrier effect be evaluated using “crossing ratios,” which is the number of pedestrians who cross a road as a portion of total pedestrian flow along that segment. This crossing ratio is considered inversely related to the barrier effect, although other factors may also influence such behavior. The barrier effect also applies to animals.

- *Estimates of Barrier Effect*

We give some studies below, which have been done to estimate barrier effect.

- Research by the BC Ministry of Transportation and Highways [66] estimates that barrier effect costs average $1,000-1,500 (Canadian dollars) per affected person per year.
- Rintoul [67] calculates that a 5.3 kilometer stretch of major highway crossing through a medium size city imposes barrier effect costs of $2.4 million Canadian annually, or about 83¢ per capita each day. The highway carries 13,600 average annual daily trips, so this cost averages about 8.7¢ Canadian per vehicle kilometer.
- A Danish publication estimates that the barrier effect represents 15% of roadway costs to be considered in benefit/cost analysis (total costs are 50% economic [travel time, accidents, VOC], 30% noise, 15% barrier effect, 5% air pollution) [68].
- The *Bicycle Compatibility Index* includes a number of factors to evaluate how well a particular road accommodates cycling [69]. Increases road width, traffic volumes, traffic speeds, percentage large trucks, driveways, and parking turnover are all considered to reduce the mobility, safety and comfort of bicycle travel.
- The Swedish National Road and Transport Research Institute [70] developed a method of calculating "encroachments costs," the physical encroachment by a road or a railway on an area of recreational, natural or cultural value. A typical case occurs when a road or a railway constitutes a barrier between a river, a lake, or a bay and a built-up area. Four existing cases have been studied where earlier encroachments have been made in order for the respondents to be able to fully understand the scenario in the questionnaire, and answer the questions in a proper manner. CVM (the Contingent Valuation Method) with binary choice is used to determine willingness to pay (WTP) for replacing the road or railroad with a tunnel.
- The Pedestrian Environmental Factor (PEF) indicates that ease of crossing streets is a major factor in determining the amount of walking that occurs in an area [71].
- Sælensminde [72] estimates that the total cost of the barrier effect in Norway equals $112 per capita annually (averaging about 1¢ per vehicle mile), which is greater than the estimated cost of noise, and almost equal to the cost of air pollution.

- A cost-benefit analyses (CBAs) of walking- and cycling facilities in three Norwegian cities, taking account health impacts, vehicle air-pollution and noise, and parking costs, estimates lost benefits ranging from 3.74-4.33 Norwegian Kroner (46-54¢ U.S.) for each kilometer of urban travel shifted from non-motorized modes to automobile as a result of the barrier effect. This is estimated to represent a cost of 3-6¢ per car-kilometer and 18-40¢ per bus-kilometer of travel in these cities. The report concludes: "*Barrier cost is a large external cost related to motorized traffic. It is therefore important to take the barrier cost into account, in the same way as other external costs, when for example the issue is to determine the 'right' level of car taxes or to evaluate different kinds of restrictions on car use.*" [73]
- Tate evaluates various ways to evaluate the barrier effect, and proposes that this can be measured by asking parents whether they would be willing to allow a child to cross a street unaccompanied, under various road and traffic conditions. [74]
- Land Transport New Zealand [75] includes community severance values in their Project evaluation manual and recommends evaluating these effects based on pedestrian and cyclist travel times.

We benefit from the "Transportation Cost and Benefit Analysis II – Barrier Effect" study of Victoria Transport Policy Institute [62], to write a barrier effect cost function. In this study, The Norwegian estimate of 1.5¢ per vehicle mile is used to estimate automobile and motorcycle barrier cost. Transit vehicles are charged 2.5¢, based on barrier effect cost for trucks in Danish and Swedish models, but reduced to account for the extra pedestrian volumes associated with buses which provide safety in numbers at some road crossings. Bicycling is estimated to incur 5% of an average automobile's barrier cost, and so on.

Although larger urban traffic volumes are balanced to some degree by higher speeds on rural roads, greater populations cause this cost to be highest in urban areas, especially during peak periods when traffic volumes are highest and the greatest demand exists for pedestrian and bicycle travel. For these reasons, they applied the basic cost to Urban Off-Peak driving and which is increased 50% for Urban Peak travel and decreased 50%

for Rural driving. Finally for several class of vehicle they formed barrier cost as in Table 3.8.

Table 3.8 Estimate-barrier effect (2007 U.S. Dollars per vehicle mile)

Vehicle Class	**Urban Peak**	**Urban Off-Peak**	**Rural**	**Average**
Average car	0.023	0.015	0.008	0.014
Compact car	0.023	0.015	0.008	0.014
Electric car	0.023	0.015	0.008	0.014
Van / Light truck	0.023	0.015	0.008	0.014
Rideshare passenger	0.000	0.000	0.000	0.000
Diesel bus	0.038	0.025	0.013	0.023
Electric bus / Trolley	0.038	0.025	0.013	0.023
Motorcycle	0.023	0.015	0.008	0.014
Bicycle	0.001	0.001	0.000	0.001
Walk	0.000	0.000	0.000	0.000
Telework	0.000	0.000	0.000	0.000

As we assumed all users as passenger cars in our study, and operated the model in peak hours, we use Urban Peak-Average car cost value ($0.023) in our formulae.

$$C_{bar} = \sum_{r}\sum_{s}\sum_{k} 0.014\, x_k^{rs} d_k^{rs} \tag{3.31}$$

where,

r : origin zone, $r \in R$

s : destination zone, $s \in S$

k : path between origin zone r to destination zone s, $k \in K_{rs}$

R : origin zones set

S : destination zones set

K_{rs} : path set

x_k^{rs} : number of total trips from r to s assigned to path k

d_k^{rs} : length of path k between origin zone r to destination zone s

3.3 MODELING SUSTAINABLE TRANSPORTATION SYSTEMS

As our problem is a multi-objective hierarchical optimization problem we write our function in the formation of bi-level programming. The upper part seeks to minimize the internal and external costs of transportation, the lower part simultaneously minimizes travel times on links by creating equilibrium among paths of same origin and destination.

In the upper part, we write internal and external cost separately, as two objective functions in accordance with multi-objective optimization. We want to minimize both of them under different weights and obtain several equilibrium points.

$$
\begin{aligned}
&\min\ f1(Q_{ij}) \\
&\min\ f2(Q_{ij}) \\
&s.t. \\
&\quad P_{ij} \le P_{\max} && \forall\ (i,j) \in \overline{A} \\
&\quad P_{ij} \ge P_{\min} && \forall\ (i,j) \in \overline{A} \\
&\quad P_{ij} = 0 && \forall\ (i,j) \in A - \overline{A} \qquad (3.32) \\
&\quad \min \sum_{ij \in A} \int_0^{Q_{ij}} \frac{d_{ij}}{v_{0,ij}} \left(1 + 0.15\left(\frac{Q_{ij}}{C_{ij}}\right)^4\right) dQ \ + \sum_{ij \in \overline{A}} P_{ij}\, Q_{ij} \\
&\quad s.t. \\
&\qquad Q_{ij} = \sum_r \sum_s \sum_k \delta_{ij,k}^{rs}\, x_k^{rs} && \forall\ (i,j) \in A \\
&\qquad \sum_k x_k^{rs} = T^{rs} && \forall\ r \in R, s \in S \\
&\qquad x_k^{rs} \ge 0 && \forall\ k \in K_{rs}
\end{aligned}
$$

where,

$$
f1(Q_{ij}) = \min\left[\sum_r \sum_s \sum_k 0.143\, x_k^{rs}\, d_k^{rs} + \sum_{ij} Q_{ij} \frac{d_{ij}}{V_{0,ij}} \left(1 + 0.15\left(\frac{Q_{ij}}{C_{ij}}\right)^4\right) VOT\right]
$$

$$
f2(Q_{ij}) = \min\left[\begin{array}{l}
\sum_{ij} Q_{ij}\, d_{ij} \sum_p \gamma_p m_p (v_{ij}) + \\
\left[\sum_{ij} \left(178.5\, Q_{ij}^{0.58} d_{ij}^{0.69} L_{ij}^{0.43} + 18359 Q_{ij}^{0.45} d_{ij}^{0.63} L_{ij}^{0.47}\right)\right] / 365 + \\
\left[\sum_{ij} 2 \int_{r_1 = r_{\min}}^{r_2 = r_{\max}} \left(L_{eq} - L_{\max}\right) DW_{avg} \frac{RD}{5280} dr\right] d_{ij} \frac{i(1+i)^N}{\left[(1+i)^N - 1\right] 365} + \\
\sum_r \sum_s \sum_k \left(0.034 + 0.03 + 0.12 + 0.03 + 0.005 + 0.03 + 0.014 + 0.020 + 0.014\right) x_k^{rs} d_k^{rs}
\end{array}\right]
$$

r : origin zone, $r \in R$

s : destination zone, $s \in S$

k : path between origin zone r to destination zone s, $k \in K_{rs}$

ij : points of link, $i, j \in A$

R : origin zones set

S : destination zones set

K_{rs} : path set

A : link set

$\bar{A}$: link set subject to tolling, $\overline{A} \subseteq A$

P_{ij} : toll price of link (i,j)

$P_{\max}$: maximum toll price

$P_{\min}$: minimum toll price

d_{ij} : length of link (i,j) (miles)

$V_{0,ij}$: free flow speed (miles/hour)

Q_{ij} : traffic flow on on link (i,j) (vehicles/hour)

C_{ij} : capacity of link (i,j) (vehicles/hour)

$\delta^{rs}{}_{ij,k}$: 1 if link (i,j) belongs to path k from r to s, 0 otherwise

x_k^{rs} : number of total trips from r to s assigned to path k

T^{rs} : number of trips originated at r to destinated to s

d_k^{rs} : length of path k between origin zone r to destination zone s

VOT : average value of time (dollars/hour)

p : a pollutant

γ_p : damage value for pollutant p, (dollars/gram)

m_p : emission rate of pollutant p, (grams/mile)

v_{ij} : vehicle speed on link (i,j) (miles/hour)

L_{ij} : number of lanes of link (i,j)

L_{eq} : equivalent sound level (dB(A))

r_{ij} : distance to link (i,j) (feet)

RD : number of houses per mile^2 (houses/mile^2)

L_{max} : maximum acceptable noise level

D : percentage discount in value per an increase in the ambient noise level

W_{avg} : average house value (dollars)

N : average lifetime of a house (years)

4 SOLUTION METHODS AND APPLICATION

4.1 MULTI-OBJECTIVE OPTIMIZATION

Multi-objective optimization (also called multi-performance or vector optimization) can be defined as the problem of finding: A vector of decision variables which satisfies constraints and optimizes a vector function whose elements represent the objective functions. These functions form a mathematical description of performance criteria which are usually in conflict with each other. Hence, the term, "optimize" means finding such a solution which would give the values of all objective functions acceptable to the designer. Formally, we can state it as follows [76]:

Find the vector $x^* = [x_1^*, x_2^*, ... x_n^*]^T$ which will satisfy the m inequality constraints

$$g_i(x) \geq 0 \qquad i = 1,2,...,m, \tag{4.1}$$

the p equality constraints

$$h_i(x) = 0 \qquad i = 1,2,..., p, \tag{4.2}$$

and optimizes the vector function

$$f(x) = [f_1(x), f_2(x),..., f_k(x)]^T \tag{4.3}$$

where, $x = [x_1, x_2, ..., x_n]^T$ is the vector of decision variables. In other words, we wish to determine from among the set F of all numbers which satisfy (4.1) and (4.2) the particular set $x_1^*, x_2^*, ..., x_k^*$ which yields the optimum values of all the objective functions.

4.1.1 Pareto Optimum

The concept of *Pareto optimum* was formulated by Vilfredo Pareto in the XIX century [77], and constitutes by itself the origin of research in multi-objective optimization. We say that a point $x^* \in F$ is *Pareto optimal* if for every $x^* \in F$ either,

$$\Lambda_{i \in I}\left(f_i(x) = f_i\left(x^*\right)\right) \tag{4.4}$$

or, there is at least one $i \in I$ such that

$$f_i(x) > f_i\left(x^*\right) \tag{4.5}$$

In words, this definition says that x^* is Pareto optimal if there exists no feasible vector x which would decrease some criterion without causing a simultaneous increase in at least one other criterion. Unfortunately, the Pareto optimum almost always gives not a single solution, but rather a set of solutions called *non-inferior* or *non-dominated* solutions [76].

We can illustrate Pareto optimality as shown in Figure 4.1 [78]:

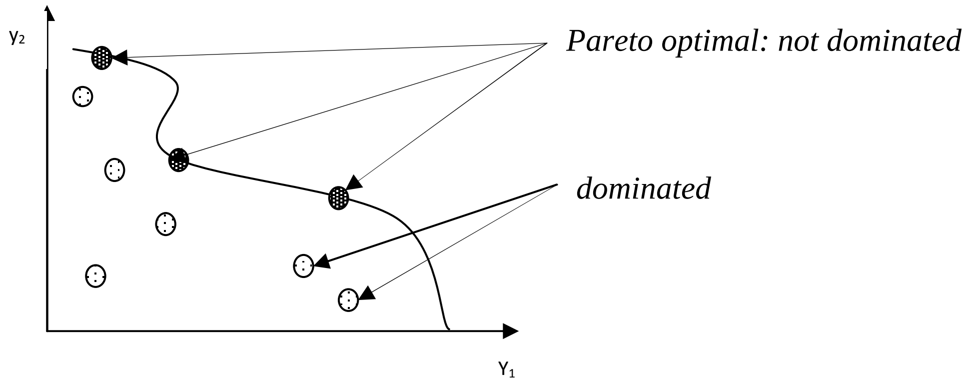

Figure 4.1 One of basic principles of multi-objective optimization: Pareto optimality.

In single objective optimization, decision making is done before search but in multi-objective optimization decision making is done after search [78]. Figure 4.2 shows Pareto optimality and decision maker's selection among all choices.

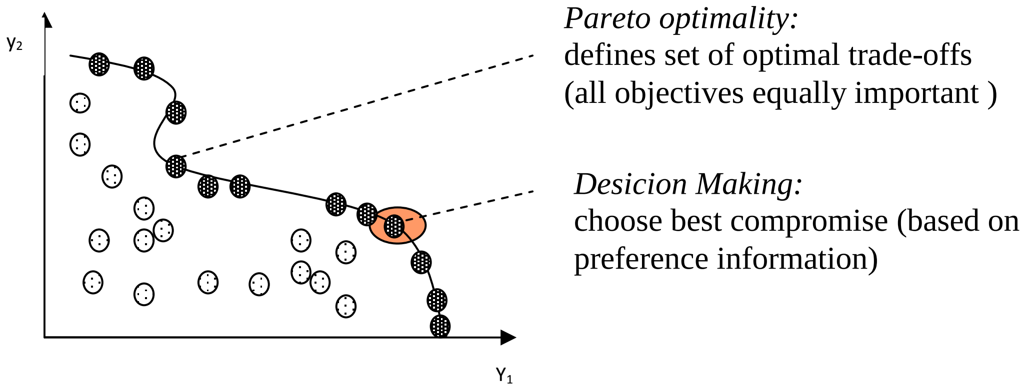

Figure 4.2 Decision making in multi-objective optimization.

4.1.2 Pareto Front

The minima in the Pareto sense are going to be in the boundary of the design region, or in the locus of the tangent points of the objective functions. In Figure 4.3, a bold line is used to mark this boundary for a bi-objective problem. The region of points defined by this bold line is called the *Pareto front*. In general, it is not easy to find an analytical expression of the line or surface that contains these points, and the normal procedure is to compute the points F_k and their corresponding $f(F_k)$. When we have a sufficient amount of these, we may proceed to take the final decision [76].

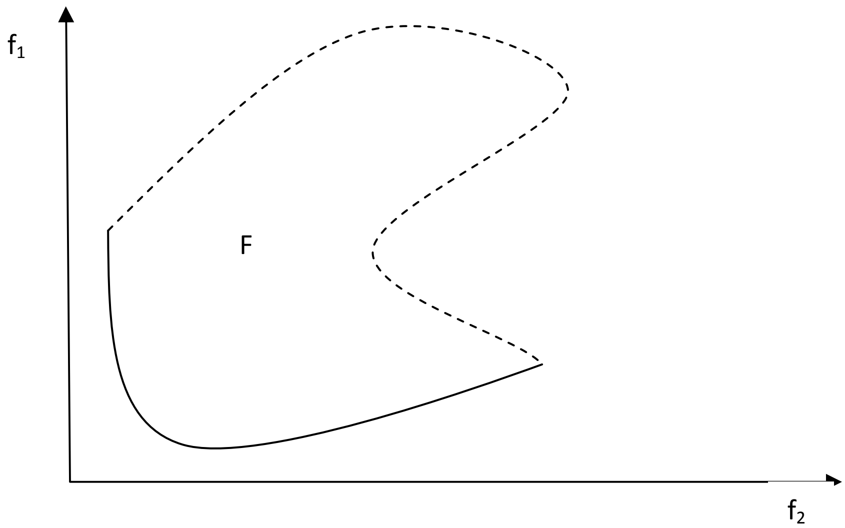

Figure 4.3 Example of a problem with two objective functions. The Pareto front is marked with a bold line.

4.2 FRANK-WOLFE ALGORITHM

The Frank-Wolfe algorithm is effective in solving non-linear optimization problems with pseudo-convex objective functions and linearly constrained feasible solution sets. At each iteration, the algorithm consists of three major steps: (i) linearize the non-linear objective function at the current solution to obtain a linear subproblem; (ii) solve the linear subproblem for an extreme point, which gives the search direction; (iii) do a line search the obtained search direction to find an updated solution. Frank-Wolfe method attempts to solve the following optimization problem:

$$\begin{aligned} &\min\ f(x) \\ &s.t. \\ &\quad Ax = b \\ &\quad x \geq 0 \end{aligned} \tag{4.6}$$

where, $f(x)$ is convex and with a second order derivative exists and continuous.

The main idea of the algorithm is quite simple. The first step is to find a good descent direction. Then, find along the chosen direction the distance to change. The algorithm will iterate until a minimum is reached. Assume that the estimate is x_k after the k^{th} iterations. In the next iteration,

a) Find descent direction. Solve

$$\begin{aligned} &\min \Delta f(x_k)(z - x_k) \\ &s.t. \\ &\quad Az = b \\ &\quad z \geq 0 \end{aligned} \tag{4.7}$$

b) Find distance to change. Let z_k be the solution,

$$r_k = z_k - x_k \tag{4.8}$$

$$x_{k+1} = x_k - t_k r_k \tag{4.9}$$

Perform Taylor series expansion,

$$f(x_k + t_k\, r_k) = f(x_k) + t_k\, \Delta f(x_k) r_k + \frac{1}{2} t^2 \left[r_k^t\, H(w) r_k \right] \tag{4.10}$$

where, *H(.)* is the Hessian of *f* and $w \in [x_k, x_k + t_k\, r_k]$. Let *L* be some bound that $\left\| r_k^t\, H(w) r_k \right\| \leq L$. Thus,

$$\begin{aligned} &f(x_k + t_k\, r_k) \leq f(x_k) + t_k\, \Delta f(x_k) r_k + \frac{1}{2} t^2\, L \mathrel{\hat{=}} \phi \\ &\frac{d\phi}{dt} = 0 \Rightarrow \quad t'_k = -\frac{\Delta f(x_k)}{L} r_k \end{aligned} \tag{4.11}$$

Finally, take $t_k = \min\{t'_k, 1\}$ [79].

4.3 PARETO SIMULATED ANNEALING ALGORITHM

Multi-objective simulated annealing is conceptually identical to a single-objective simulated annealing algorithm. Simulated Annealing analogizes annealing processes of liquids and metals to the minimization of an objective function, basing on first principles of thermodynamics. It is a random search method that avoids getting trapped in local optima by accepting, in addition to solutions that improve on the value of an objective function, also solutions corresponding to a deteriorated objective function value. Accepting bad solutions is done by means of a probabilistic acceptance criterion controlled by annealing cooling schedule (usually Boltzman cooling schedule). In the course of the annealing process, the probability of accepting deteriorated solutions decreases as the temperature drops. The scheme controlling the decreasing probability for accepting deteriorations is called a cooling schedule. A cooling schedule, which starts at a high temperature and decreases toward zero as the search progresses, allows simulated annealing to freely explore the solution space in the beginning of an optimization process and to fully exploit the most promising region in the solution space as temperature drops [80].

Czyzak and Jaszkiewicz [81] modified simulated annealing algorithm for multi-objective optimization problems and developed Pareto simulated annealing. PSA uses several ideas known from simulated annealing:

- concept of neighborhood;
- acceptance of new solutions with some probability;
- dependence of probability on a parameter called temperature;
- scheme of temperature changes.

PSA, however, uses a sample (population) of interacting solutions by iteration. The solutions are called generating solutions. Among meta-heuristic procedures, this concept is used in genetic algorithms. Another new idea used in PSA is to control the objective weights used in the multiple-objective rules for acceptance probability in order to assure dispersion of the generating solutions over the whole set of efficient solutions. Please note that the higher the weight associated with a given objective, the lower is the probability of accepting moves that decrease the value on this objective and the greater is the probability of improving the value of this objective. Thus, by controlling the weights, one can increase or decrease the probability of improving values of the particular objectives [81].

The general scheme of the PSA procedure may be written as follows [81]:

Select a starting sample of generating solutions
$S \in D$
For each $x \in S$ do
Update the set *M* of potentially efficient solutions with *x*
$T := T_0$
Repeat
  For each $x \in S$ do
    Construct $y \in V(x)$
    If *y* is not dominated by *x* then
      Update the set *M* of potentially efficient solutions with *y*
  Select the solution $x' \in S$ closest to x and non-dominated with respect to *x*
    If there is no such solution *x'* or it is the first iteration with *x* then
      Set random weights such that
      $\forall i \lambda_j \geq 0$ and $\sum_j \lambda_j = 1$
    Else
      For each objective f_j

$$\lambda_j = \begin{cases} \alpha \lambda_j^x & \text{if} \quad f_j(x) \geq f_j(x') \\ \lambda_j^x / \alpha & \quad\quad f_j(x) < f_j(x') \end{cases}$$

      Normalize the weights such that $\sum_j \lambda_j = 1$
    Update $x := y$ (accept y) with probability $P(x,y,T,\Lambda)$
  If the conditions of changing the temperature are fulfilled then
    Decrease *T*
Until the stop conditions are fulfilled.

Where $\Delta^x = \left[\lambda_1^x, ..., \lambda_j^x\right]$ is the weighting vector used in the previous iteration for solution $x, \alpha > 1$ is a constant close to one (e.g. $\alpha = 1.05$) and *P(x, y, T, Λ)* is one of the multiple-objective rules for acceptance probability described above.

4.4 COMPUTATIONAL RESULTS AND ANALYSIS

Two algorithms are coded in MATLAB environment. One instance network, namely Sioux-Falls, is used in this study to illustrate the approach. It has 24 nodes, 76 links and 528 OD pairs. Free flow time, capacity, length of arcs, coordinates of nodes and trip data is presented on internet. We accept arc free flow times as in minutes and change them to hour.

First, Frank-Wolfe algorithm is run solely to find the optimal flow. This enabled us to detect most congested arcs of the network. After decreasing sorting the arcs based on the time spent on each, we selected seven of them to be tollable: (6-8), (10-16), (17-19), (11-14), (16-17), (19-20) and (13-24).

As our upper level variables are the toll prices, we initialize PSA algorithm with a population of 10 different toll price vectors. We take initial toll values as 0.05 hour for all arcs. We start with an initial temperature value, 1.0, and decrease it in each iteration by multiplying with a suitable constant, 0.93, until we reach the stopping temperature value, 0.01, and in each *T* value we run program for 35 times to search solution area sufficiently. In each PSA iteration, we create new toll vectors by applying Delete-all technique in which we delete all members of the current vector and replace them with the same number of members that have just been created. We restrict any member to be lower than minimum toll value, 0.015 and higher than maximum toll value, 0.50. In acceptance course of toll candidates, we normalize our objective functions, because they are too large which causes holding back form valid evaluation. As we start with a population of size 10 and let only non-dominated solutions to enter the set M, we may have 10 or less non-dominated solutions after the algorithm terminates. Figure 4.4 and Figure 4.5 show respectively, the change of minimum internal and external cost values by iteration in a sample run. In each iteration, we take the minimum value in population.

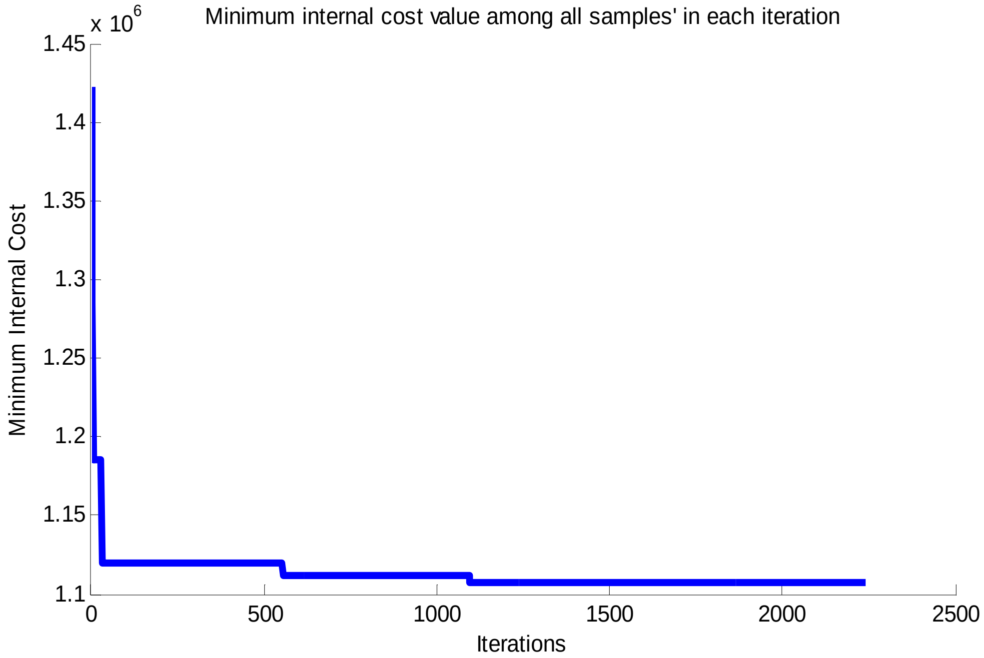

Figure 4.4 Minimum internal cost values of all samples by iterations.

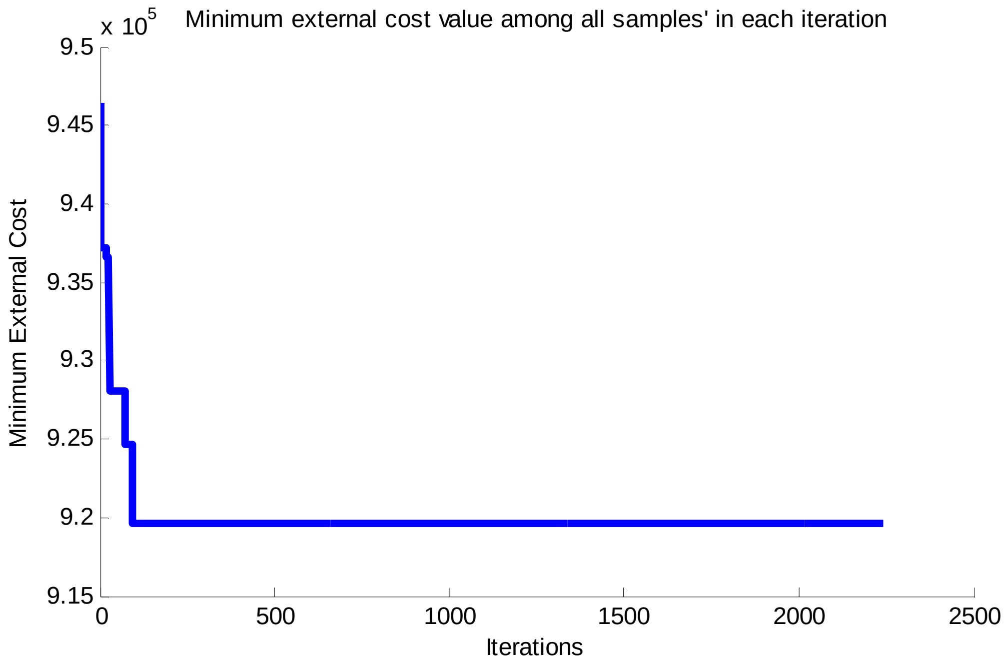

Figure 4.5 Minimum external cost values of all samples by iterations.

These figures show that both of our costs are decreasing in each iteration. It is clear that our algorithm has converged to minimum. In earlier iterations, decrease is larger than later iterations, as expected because of decreasing acceptance probability of bad solutions. We can also mention that our iteration number is enough; not less to stuck on a local optimal point, or no more to spend time without any improvement.

In the Table 4.1, we give internal cost, external cost, weighted cost, geometric mean of congestion, total travel time and toll values of all population members of the same run. In the last iteration, 2400, there are 10 samples in M set in this run, but usually number of solutions arises less than 10 samples when algorithm terminates.

Table 4.1 Cost, congestion and travel time values of all samples in the last iteration

	Internal cost	**External cost**	**Weighted cost**	**Geo. mean of cong.**	**Total travel time**	**Weights of obj. fun.** Int/ Ext	**Toll values** arcs: (8,6),(6,8),(16,10),(10,16),(13,24),(24,13),(19,17),(17,19),(11,14),(14,11),(16,17),(17,16),(19,20), (20,19)
Smp.10	1,107,858.21	1,020,751.17	1,099,652.02	1.31	73.88	0.906 0.094	0.022,0.015,0.021,0.016,0.016, 0.029,0.061,0.066,0.016,0.049, 0.095,0.015,0.015, 0.016
Smp.8	1,121,839.52	991,304.93	1,097,654.56	1.31	74.97	0.815 0.185	0.015,0.033,0.036,0.016,0.016, 0.016,0.062,0.016,0.123,0.108, 0.030,0.016,0.015, 0.036
Smp.7	1,155,265.24	970,764.61	1,148,787.16	1.32	75.61	0.965 0.035	0,016,0.016,0.099,0.031,0.058, 0.016,0.066,0.035,0.026,0.101, 0.022,0.015,0.016, 0.016
Smp.9	1,168,602.26	962,327.67	982,447.77	1.31	76.40	0.098 0.902	0.036,0.028,0.110,0.041,0.019, 0.021,.100,0.015,0.031,0.097,0.018,0.035,0.016, 0.016
Smp.4	1,227,452.83	951,647.27	1,028,458.63	1.32	78.86	0.278 0.722	0.015,0.016,0.203,0.016,0.015, 0.015,0.093,0.079,0.015,0.305, 0.016,0.045,0.015, 0.025
Smp.6	1,239,960.51	939,635.15	1,227,198.73	1.31	79.31	0.958 0.042	0.117,0.016,0.186,0.016,0.016, 0.016,0.155,0.027,0.015,0.016, 0.016,0.015,0.015, 0.015
Smp.2	1,289,597.65	930,357.34	1,223,038.93	1.32	82.83	0.815 0.185	0.016,0.016,0.214,0.015,0.015, 0.015,0.259,0.106,0.098,0.273, 0.349,0.016,0.015, 0.015
Smp.1	1,337,594.22	928,081.40	968,025.45	1.31	82.98	0.098 0.902	0.016,0.016,0.440,0.202,0.015, 0.055,0.441,0.016,0.016,0.015, 0.016,0.015,0.144, 0.016
Smp.5	1,351,459.14	926,247.89	1,044,668.47	1.30	82.89	0.26 0.74	0.016,0.199,0.339,0.015,0.015, 0.016,0.222,0.069,0.016,0.146, 0.015,0.016,0.015, 0.015
Smp.3	1,378,359.67	919,611.03	1,362,252.33	1.35	85.50	0.965 0.035	0.034,0.015,0.415,0.016,0.015, 0.015,0.371,0.373,0.016,0.015, 0.216,0.016,0.015, 0.015

We plot Pareto optimal solutions in Figure 4.6. The solution on that graphic are obtained after polling non-dominated solutions of five PSA runs and then identifying and removing dominated solutions from that poll. It can be easily observed that low external cost levels are reachable as long as high budget is allocated to internal cost items. It now remains to the decision maker or traffic authority to select among the solution that best fit his/her objectives.

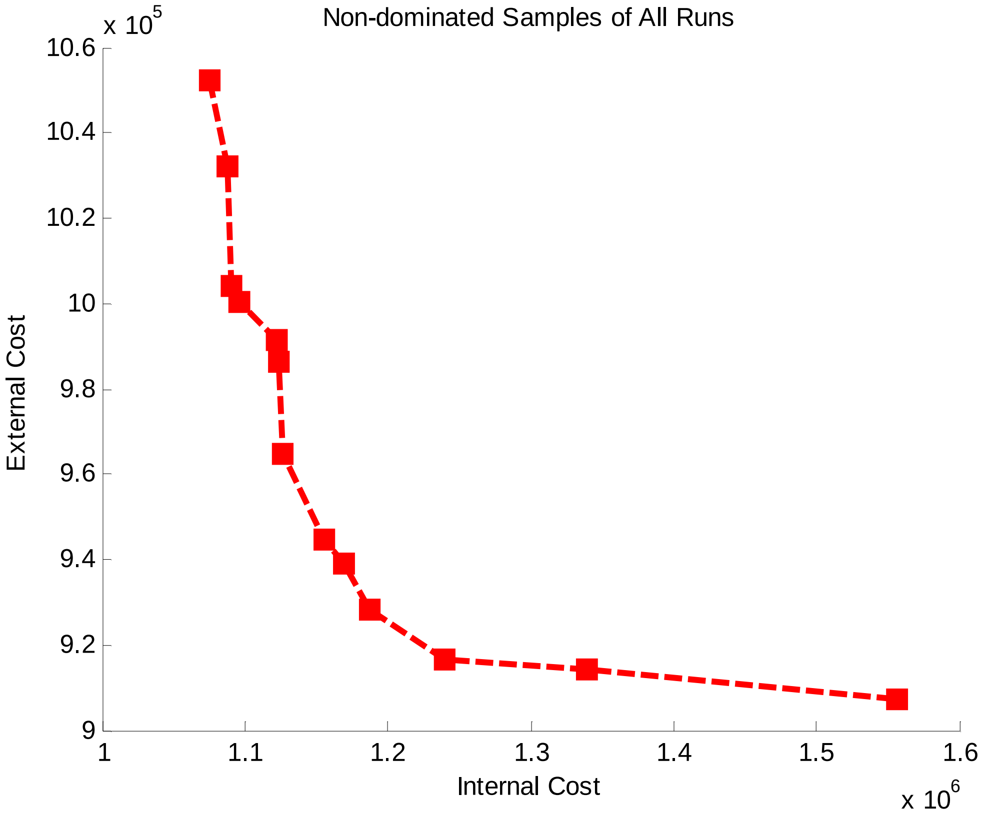

Figure 4.6 Pareto optimal graphic of the samples of five good runs.

5 CONCLUSION

This study shows us taking into account costs of all traffic impacts could be good instruments to manage a city network. Separating user costs which are paid in real world and costs to social and environmental life which are not charged mostly, give us a chance to obtain balancing solutions. As we create more than one solution by applying PSA, we present different weighted solution alternatives. A traffic manager could choose a policy which is less expensive for users but a bit less careful for environment and social life or a politic which is more expensive for users but very much better for environment and social life or a politic which provides equilibrium point between.

As we look into average traffic congestion values without tolling and after PSA run, each solution we obtained after PSA results better than without toll scenario. Even this is not our initial goal, this is an advantage.

Toll pricing helped us to reach good solutions as a traffic management instrument. It has only the effect of increasing travel time on the way it is applied and does not change traffic structure. Toll prices obtained give us the chance to know total external cost and if we decide to charge external costs to users, it also presents a method to apply. On the other hand, by comparing with internal costs we could create some performance measures to evaluate the system in an aggregate unit.

Our methodology is suitable for many studies in this field. When anyone decides to assign traffic on a district or city, he/she can scale the impacts and derive the related functions, or could modify functions presented here. After plugging these functions to our model, it will be then possible to obtain similar results.

Our algorithm makes use of Frank-Wolfe algorithm as a sub procedure. As this algorithm is a steepest descent like algorithm, its convergence to the optimum is slow. The user equilibrium problem investigated in this study is a nonlinear programming problem with a convex nonlinear objective function and linear constraints. Therefore, there are other methods like conjugate gradient that can reach optimum in a less iteration and execution time. There are also variants of Frank-Wolfe algorithm which have more complex data structures yet achieving faster execution times. As our algorithm was faster enough on the subject problem and our main focus was to provide non-dominated solutions to the decision makers, we were not motivated to develop the most efficient algorithm. However, if the dimension of instances becomes large, a more efficient sub procedure would be necessary, since PSA algorithm calls the sub procedure for each solution in the population at every iteration.

Another line of research can be to use another multi-objective meta-heuristics such as genetic algorithms instead of PSA. There exist very efficient elitist genetic algorithms such as NSGA-II or SPEA-II that can be implemented without much complication and that can enable to compare the results obtained with PSA.

For future works, we propose to separate traffic impacts into three groups; economic, environmental, social, to increase solution severity. By this way, sustainability could be evaluated much more effectively. We propose secondly, when a city traffic management is to be done, collecting its own data about impacts and writing its own cost functions could give better solutions. As it is difficult to find generalized impact cost functions, obtained data and functions may not represent the city as well as its own data. In our model, we initially decided the links which to be priced. But someone could apply a slightly differentiated algorithm which can choose links to price by its own. Finally, we only uses toll optimization instrument to manage our network, but district pricing, road widening and road adding are the other traffic management instruments which worth to try.

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