FHWA/NJ-2007-003

# Cost of Transporting People in New Jersey

# Phase 2

## FINAL REPORT

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16. Abstract

This project has developed a state-of-the-art GIS-based interactive tool for calculating network-wide full marginal costs (FMC) of highway transportation in New Jersey. The new tool is used to evaluate the short-term impacts of policy implications on the marginal costs of different trips. The illustration of the proposed FMC calculation methodology on a sample network shows that the "traditional" distance-based approach overestimates the marginal cost of the network, and more importantly it provides marginal cost on the basis of distance rather than trips, which is the most basic way of considering travel behavior of drivers. Results obtained from application of the new tool on the North Jersey network demonstrate that FMC between an Origin-Destination (O-D) pair exhibit differences among various paths that connect any single O-D pair. These results also demonstrate the importance of analyzing trips based on a number of factors in addition to travel times such as volume, capacity, road type, and distance. The analyses conducted to observe the short-term impacts of capacity investments on several route sections (NJ Route 18, NJ Route 17, NJ Route 3, and the Garden State Parkway) demonstrate that even though capacity investments can reduce the marginal cost of users, the amount of savings mainly depends on the characteristics of that region, the excessive demand that needs to be satisfied, and the reduced congestion delays.

This GIS-based tool will help transportation planners to estimate the changes in transportation costs due to a particular transportation demand management measure or supply change such as adding new lanes or improving existing lanes. This is a critical component of transportation planning, because demand patterns experience both spatial and temporal variations due to the changes in demand and supply, and an accurate cost estimation tool based on the new route flows will help planners to better quantify the effects of these variations and thus to better evaluate current and future transportation investment alternatives. Moreover, transportation planners will be able to study the changes in various components of marginal functions, namely operation, environmental, accident and others and evaluate various options based on the individual cost component of interest to them and the decision makers.

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# EXECUTIVE SUMMARY

The extensive and highly developed highway infrastructure of New Jersey, carrying heavy traffic of freight and commuters, plays a pivotal role in ensuring mobility in the area. Yet, given the high-density growth of the region, it will be impossible to meet all current and potential demand even with an expanded highway system. Although new rail investments are expected to divert people from highway to rail, highways will remain the backbone of the overall transportation network. Thus, to keep pace with economic growth in the State, the highway transportation system must continuously evolve to face the challenge of achieving increased efficiency and connectivity. For decades this challenge has been a major objective of the federal and local government investments in transportation improvements.

Central to this objective is the need for new tools for accurate estimation of the full marginal costs of highway travel in the State. This information is essential for allocating resources efficiently, for ensuring equity among users of different transportation modes, and for developing effective pricing mechanism. Full Marginal Costs (FMC) means the overall costs accrued to society (State of NJ) from servicing an additional unit of user. FMC includes capital costs, maintenance costs, highway accident costs, congestions costs and environmental costs.

Full marginal cost (FMC) is an effective measure to determine the true cost of transportation. It is defined as the cost of an additional unit of output. The term “output” is defined as the representation and simplification of the overall utilization of product systems by means of selected units. Intermediate outputs such as vehicle-miles or vehicle-hours are mainly used to evaluate the technical efficiency of a system. On the other hand, final outputs, such as number of trips or number of passengers, are used to analyze the overall efficiency and effectiveness of the system.

The principal motivation of this study lies in the definition of outputs. Due to the considerably extensive scope of the analysis, our primary focus is on the final outputs. In this study, trip is regarded as the major output measure. In other words, FMC is defined and calculated as “cost per trip.” Although “trip”, as a final output of highway transportation, is not a standard measure as vehicle-miles or vehicle-hours, it has several desirable attributes (e.g., trip distance, time of the day, highway functional types on a route, urbanization degree, topography, and climate) that will enable us to better understand the policy implications of additional travelers on the roadway network.

Full transportation costs include both private costs (costs that users directly experience also called internal or direct costs) and social costs (also called external or indirect costs). Determination of full costs is of great interest in transportation economics, since it is the key element in every economic analysis, decision-making steps and policy considerations. This study is mainly concerned with the estimation of the FMC of highway transportation demand in New Jersey.

The four major scopes of our study can be summarized as follows:

- Improve the trip-based FMC methodology developed in the first phase of the project, and develop a novel methodology to estimate trip-based FMC, which considers not only the shortest “travel time” path but a set of feasible paths between each O-D pair attractive to the travelers while calculating the FMC of highway transportation in New Jersey.
- Update the various transportation cost functions developed in the first phase of the project.
- Develop a GIS-based interactive computer tool, which implements the proposed methodology, and estimates the FMC between different origin and destination (O-D) pairs at several levels of detail, including single O-D

pair, and a set of O-D pairs within certain area, county or the entire network.

- Investigate the short-term impacts of policy implications on the FMC of different trips.

Existing literature in the area of “transportation costs” are reviewed and highway transportation cost categories are identified based on the results of this review (Section 3).

Application of marginal cost in transportation network differs from its basic economic definition. This phenomenon creates several interesting research questions that can be summarized as follows:

- While calculating network wide marginal cost, do we have to add an extra trip between every origin-destination (O-D) pair?
- Or do we have to pick one O-D pair and introduce the trip between this O-D pair? If the answer is “yes”, then which pair?
- What is the effect of an additional trip to the overall network flow patterns? In reality, does the extra trip effect flows at the equilibrium?
- What is the effect of policy implications on the cost of an additional trip, in the short-run?

In order to simplify these issues, we propose a new methodology to estimate the system marginal cost within a reasonable accuracy range in a highway network. The methodology presented here estimates trip based FMC by considering a set of feasible paths between each O-D pair. This approach enables the planners to realistically capture the effect of unit increase in demand while considering the traveler’s decisions. This is essential for accurately calculating network-wide marginal costs. Section 5 of our report is dedicated to this particular issue. In order to implement this proposed methodology, we first develop marginal cost functions. Marginal cost functions depend on total cost functions since once total cost functions are developed marginal cost functions can easily be derived with respect to a selected variable. In this study, highway transportation costs are categorized in 3 major groups.

1. User Costs
    a. Vehicle Operating Costs
    b. Congestion Costs
    c. Accident Costs
2. Infrastructure Costs
    a. New Construction Costs
    b. Maintenance and Improvement Costs
    c. Right-of-Way (Land Acquisition) Costs
3. Environmental Costs
    a. Air Pollution Costs
    b. Noise Costs

Each cost category was estimated using the data obtained from NJDOT and from other sources. The overall methodology employed to develop cost functions, and the cost models estimated using the available New Jersey data are presented in Section 4 of the report. It should be noted that each cost model is a product of a long and meticulous data collection manipulation process. Except for congestion and environmental cost categories, we developed our own cost functions specific to New Jersey (NJ). As for congestion and environmental costs, since the development of these cost models requires a more long-term and comprehensive research project than this one, we adopted the most appropriate models found in the literature and used them in our cost calculations.

The proposed trip-based FMC estimation methodology and marginal cost functions estimated for different cost categories are implemented in GIS using C programming language and Visual Basic for Applications (VBA) (Section 6). The proposed GIS-based tool has several advantages as summarized below.

1. With the developed GIS-based tool, the origin and/or destination of a trip can be either
    a. Single nodes, a set of nodes within each Traffic Analysis Zone (TAZ) or counties, or a set of randomly sampled nodes within the entire transportation network. This makes the proposed FMC estimation model a very useful tool for application in a real-world highway transportation improvement scenario.

For county and network level selection, user does not need to specify the location of O-D pairs. With the FMC estimation at the TAZ and county levels, the user can observe the changes in trip-based FMCs among different O-D pairs in a certain area. Moreover, the whole network selection helps the user to observe the distribution of trip-based FMC throughout the entire network.

2. The proposed tool, does not only estimate FMC between a selected O-D pair, but it can also compare two different networks (before and after scenarios), and estimate short-term impacts of network changes (lane and/or link additions, etc.) on the FMC of a trip.

The proposed trip-based FMC methodology is then illustrated on a simple network and on Northern New Jersey, and compared with existing methodologies in the literature (Section 7). The comparison results show that the “traditional” distance-based approach overestimates the marginal cost of the network, and more importantly it provides marginal cost on the basis of distance rather than trip, which is the most basic way of considering travel behavior of drivers. Distance-based measures do not produce useful information regarding the network efficiency and the effectiveness of the transportation system [(2)], because they do not capture the well-established basic mechanism of traveler decision making process (Section 7.1). Results obtained from the application of the new tool on the North Jersey network demonstrate that FMC between an O-D pair exhibit differences among various paths that connect any single O-D pair. These results also demonstrate the importance of analyzing trips based on a number of factors in addition to travel times such as volume, capacity, road type, and distance (Section 7.2).

Section 8 of the report is dedicated to calculation of short-term impacts of policy investments on the FMC of different trips using the GIS-based tool. The analyses are focused on lane improvements imposed on several route sections, namely NJ Route 18, NJ Route 17, NJ Route 3, and the Garden State Parkway. The changes between before and after scenarios demonstrate that even though capacity investments can reduce the marginal cost of users, the amount of savings mainly depends on the characteristics of that region. Particularly, the amount of capacity investment highly depends on the amount of excessive demand that needs to be satisfied, and the reduced congestion delays. In general, the more congested a road is, the more traffic is generated by increased demand. Increased capacity on highly congested urban roads attracts considerable traffic due to high levels of latent demand [(76)]. Thus, if a road section to be improved is in a very congested area, capacity investments may result in overall higher usage of this same road section.

This GIS-based tool will help transportation planners to estimate the changes in transportation costs due to a particular transportation demand management measure or supply change such as adding new lanes or improving existing lanes. This is a critical component of transportation planning, because demand patterns experience both spatial and temporal variations due to the changes in demand and supply, and an accurate cost estimation tool based on the new route flows will help planners to better quantify the effects of these variations, and thus to better evaluate current and future transportation investment alternatives. Moreover, transportation planners will be able to study the changes in various components of marginal functions, namely operation, environmental, accident and others and evaluate various options based on the individual cost component of interest to them and the decision makers.

Finally the readers should be reminded that the results of this study are based on a number of models that include assumptions and approximations. It is clearly stated in the report that every model is highly sensitive to these assumptions. Nevertheless, we believe that our assumptions are fairly accurate and based on the real-world data from.

We genuinely hope that the methodology proposed here, and the results obtained count as a contribution to the research in the field area transportation economics.

## 1. INTRODUCTION

New Jersey has been called the corridor state, an apparent consequence of its role and proximity to the strong markets and population centers in New York City, Philadelphia and the Boston-Washington Northeast Corridor. During the last decade the economy of the State of New Jersey has been growing largely due to its key location and well-developed transportation infrastructure. According to a Northern Jersey Transportation Planning Agency (NJTPA) report [(1)], Northern New Jersey, which is at the heart of the economic activity in the State, is served by a vast multi-modal transportation system that supports nearly every aspect of economic activity in the region. This transportation system, which represents more than a century of public and private investment, includes 35,390-kilometers of road network (285-kilometers of which are toll roads), a comprehensive system of public transportation (comprising 250 public and private bus routes; 628-kilometers of commuter rail network; a 23-kilometer rapid transit network (PATH); and over 40-kilometers of light rail (Newark City subway/ Light Rail, and the Hudson-Bergen Light Rail).

The extensive and highly developed highway infrastructure of New Jersey, carrying heavy traffic of freight and commuters, plays a pivotal role in ensuring mobility in the area. Yet, given the high-density growth of the region, it will be impossible to meet all current and potential demand even with an expanded highway system. Although new rail investments are expected to divert people from highway to rail, highway will remain the backbone of the overall transportation network. Thus, to keep pace with economic growth in the State, the highway transportation system must continuously evolve to face the challenge of achieving increased efficiency and connectivity. For decades this challenge has been a major objective of the federal and local government investments in transportation improvements.

Central to this objective is the need for new tools for accurate estimation of the full marginal costs of highway travel in the State. This information is essential for allocating resources efficiently, for ensuring equity among users of different transportation modes, and for developing effective pricing mechanism. Full Marginal Costs (FMC) means the overall costs accrued to society (State of NJ) from servicing an additional unit of user. FMC includes capital costs, maintenance costs, highway accident costs, congestion costs and environmental costs.

Estimation of full highway transportation costs has long been one of the major concerns of transportation economists and planners due to its importance in decision-making and policy considerations. The main objective of this interest in FMC estimation is to ensure that prices paid by transportation users reflect the true cost of providing transportation services.

Full marginal cost (FMC) is an effective measure to determine the true cost of transportation. It is defined as the cost of an additional unit of output. The term “output” is defined as the representation and simplification of the overall utilization of product systems by means of selected units. In Berechman et al.[(2)], terms **intermediate** and **final outputs** are defined for transportation systems. The usage of these terms in cost calculation depends on the purpose of the analysis. **Intermediate outputs** such as vehicle-miles or vehicle-hours are mainly used to evaluate the technical efficiency of a system. On the other hand, **final outputs** (also called demand-oriented measures in Berechman et al. [(2)]), such as number of trips or number of passengers, are used to analyze the overall efficiency and effectiveness of the system.

The principal motivation of this study lies in the definition of outputs. Due to the considerably extensive scope of the analysis, our primary focus is on the **final outputs**. In this study, **trip** is regarded as the major output measure. In other words, FMC is defined and calculated as “cost per trip.” Although “trip”, as a final output of highway transportation, is not a standard measure as vehicle-miles or vehicle-hours, it has several desirable attributes (e.g., trip distance, time of the day, highway functional types on a route, urbanization degree, topography, and climate) that will enable us to better understand the policy implications of additional travelers on the roadway network.

In transportation, FMC measures the actual increase in costs due to an additional unit of travel (a trip or mile). Hence, FMC represents the additional costs that the State should consider to encourage efficient transportation use. This study is mainly concerned with the estimation of the FMC of highway transportation demand in New Jersey. The analysis of these cost models is then applied to the northern New Jersey network. The study is divided into ten sections:

Sections 2 gives a brief conceptual overview of the new tool for estimating marginal cost (MC) functions on a road network. Section 3 describes and summarizes the different cost categories found in the literature review of the past studies. Section 4 explains the total, average and marginal cost functions developed for each cost category based on New Jersey–specific data used in the analysis. Section 5 deals with different proposed marginal cost estimation methodologies for road networks. Section 6 explains the details of the developed GIS-based FMC estimation tool, while Section 7 illustrates the application of different methodologies. Section 8 and Section 9 focus on the short-term impacts of network changes on the FMC of different trips. Finally, section 10 presents the results of the analysis as well as the conclusions.

## 2. OVERVIEW OF MARGINAL COST ANALYSIS

Marginal cost is defined as the cost of an additional unit of output. While producing an extra unit of this output, the cost associated with it arises. For an isolated roadway segment shown in Figure 1 that connects zones A and B, the travel cost of one user in its simplest form can be given as a function of volume, f(Q). Then the total cost of travel on this roadway segment is Q.f(Q). The marginal cost of travel in this segment can be derived as follows. Suppose there is an extra unit number of trip, $\varepsilon$, between zones A and B. The demand between the zones then becomes Q + $\varepsilon$ and the total marginal cost of traveling on this roadway one extra unit increase in the output can be calculated as shown in equation-2.

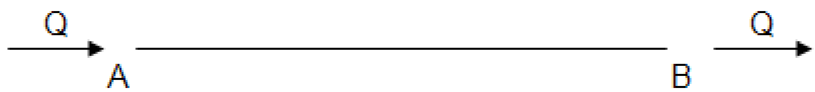


**Figure 1. Highway link**

$$\lim_{\varepsilon \to 0} \frac{(Q+\varepsilon)f(Q+\varepsilon) - Qf(Q)}{\varepsilon} \tag{1}$$

$$MC_{A-B} = \frac{\partial(Qf(Q))}{\partial Q} \tag{2}$$

where,

$Q$ = Total demand from origin point A to destination point B (veh/hour)

$f(Q)$ = Travel cost function for one user ($)

$\varepsilon$ = Additional unit number of trip added to the road segment A-B

$MC_{A\text{-}B}$ = Marginal cost of additional trip ($)

In this formulation, two major points are worth consideration. The first major point is related to estimation of marginal costs when the roadway segment on hand is not composed of only one link, but rather it is a complicated network. The simplest example of this case is shown in Figure 2.

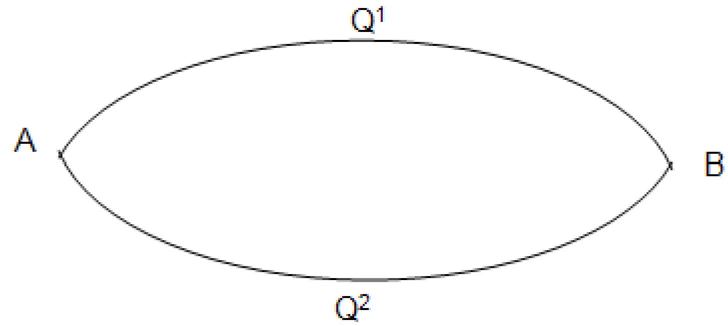


**Figure 2. Sample network**

In the network-wide case, the marginal cost concept presented above is not fully applicable, since user decisions need to be considered. In Figure 1, there is only a single route between an origin-destination (O-D) pair, thus each user must use this route to travel from A to B. However, in the network case, shown in Figure 2, when there is more than one choice, the user is inclined to choose the most attractive route to travel. In other words, the user selects the route that maximizes his/her utility. This decision process is accomplished without corporation of the other users. Drivers individually choose their routes in the network based on the maximum utility criteria (or minimum cost, if it is assumed that all the users are identical), and as a result, the system reaches a point where no user can reduce his/her travel cost by switching routes. This point is called the *user equilibrium*.

In reality, whenever an extra unit of demand is introduced between an O-D pair, the prior equilibrium conditions will no longer be valid. The system becomes, so called, unstable. In other words, users will intuitively realize that the route on which they are traveling is no longer the minimum cost route in terms of travel time. Hence, they will modify their traveling patterns until the system reaches its equilibrium state again, which can be called Equilibrium II. Obviously, flows on each link take on different values and link travel time costs change. Thus, the marginal cost of the system can be calculated as the difference in the total costs of Equilibrium I and Equilibrium II, as shown in equation-3.

$$MC_{A-B} = \frac{\sum_{i=1}^{N} Q_2^i f(Q_2^i) - \sum_{i=1}^{N} Q_1^i f(Q_1^i)}{\varepsilon} \quad (3)$$

where,

$i$ = Link index ($i$ = 1, 2,……N)

$N$ = Total number of links

$Q_1^i$ = Total flow observed at link $i$ at Equilibrium I (veh/hour)

$Q_2^i$ = Total flow observed at link $i$ at Equilibrium II (veh/hour)

$f()$ = Travel cost function for one user ($)

$\varepsilon$ = Additional unit number of trip added to the road segment A-B

$MC_{A-B}$ = Marginal cost of additional trip ($)

When a real network with many O-D pairs and routes is considered, calculation of network-wide marginal cost is not straightforward for several reasons. The most important reason is related to the effect of an extra unit of demand to the overall network. In reality, adding only one trip to a very complicated network may have only a negligible impact on the network, which makes it infeasible to measure the network-wide marginal cost of extra trips. However, extra demands included in the system will have a noticeable impact after some time. Thus, for illustration purposes in this study, extra unit of demand introduced between an O-D pair is defined as the demand equivalent to one percent (1%) of the original demand between that O-D pair. The next section summarizes the various cost categories found in the literature review.

## 3. LITERATURE REVIEW

Various studies in the literature have suggested that road users should be charged for the full costs of travel. In other words, every user should pay for the costs s/he experiences, plus the costs s/he imposes on the rest of the society [1,4,5,6,7, and 8]. Thus, extensive analysis of cost categories may help to identify fair and efficient road pricing. Highway transportation costs can be classified as direct or indirect costs. **Direct costs** (sometimes called private or internal costs) include the costs that auto users directly consider as monetary losses (e.g., as vehicle operating cost, auto depreciation, and time consumed in traffic). **Indirect costs** (also called social or external costs), on the other hand, refer to the costs for which auto users are not held accountable. These include the costs that every user imposes on the remaining traffic (e.g., costs of congestion, accidents, air pollution, and noise). After an extensive literature review, the following costs categories are identified in this study:

1. Vehicle costs (ownership, operational, parking)
2. Travel time and congestion costs
3. Accident costs
4. Air pollution costs
5. Noise costs
6. Roadway costs (maintenance)

### 3.1. Vehicle Costs

Vehicle costs include the costs attributed to the vehicle owner. These costs are internal to the car owner and can be divided into two subcategories: fixed (ownership, insurance, registration, taxes), and variable (maintenance, repair, fuel, parking, and tolls). Variable costs increase with vehicle usage (mileage). The American Automobile Association [19], Canadian Automobile Association (www.caa.ca), Kelley Blue Book (www.kbb.com), Black Book (www.blackbookusa.com), and U.K. Automobile Association (www.theaa.co.uk) publish estimates of vehicle costs (ownership and operating) for various types of vehicles, taking into account model, age, condition, mileage, accessories, and geographic location.

### 3.2. Congestion Costs and Value of Travel Time

Congestion costs refer to the external costs a driver imposes on other motorists. These costs include increased travel time (delay), driver stress, and travel time variability, and can be analyzed in three main categories: (1) time costs experienced by the driver, (2) external costs imposed by the driver on the rest of the drivers, and (3) delay (queue) costs experienced by all users when the demand on the roadway exceeds the road capacity (bottleneck cases).

Since all these cost categories are directly related to travel time, the monetary value of time (VOT) is a crucial aspect of this category. Depending on the mode used by the traveler, travel time costs may include time devoted to waiting, accessing vehicles, and actual travel.

In their study of congestion costs in Boston and Portland areas, Apogee Research estimated congestion costs using VOT values based on 50% of the average wage rate for work trips and 25% for other trip purposes (15). Based on the review of international studies, K. Gwilliam (10) concluded that work travel time should be valued at 100% wage rate, whereas non-work travel time should be valued at 30% of the hourly wage rate, if better local data is unavailable. Similarly, USDOT (11) suggested VOT values between 50% and 100% of the hourly wage rate depending on traveler type (personal, business). In these studies, user characteristics, mode of travel, or time of day choices are not included into the VOT estimation. To overcome this major drawback, stated preference surveys are conducted tin some studies mentioned o estimate VOT values for different modes and trip types (12,13, 14). Table 1 shows a summary of these studies by study area and the estimated VOT values. All values are converted to 2005 dollars using the inflation rates corresponding to estimation years of VOT values [15].

**Table 1. Summary of VOT estimates (in 2005 dollars)**

| Study | Area and comments | VOT |
|---|---|---|
| Apogee [16] | Boston & Portland, MA, peak/off-peak, express way/non-express way, rail/bus/bicycle/walk | 7.6-20.3 ¢/mile |
| U.S. DOT [11] | U.S. general, in-vehicle, out-of-vehicle time, personal/business | 10.64-19.74 $/hour |
| Mayeres et al. [12] | Brussels, peak/off-peak, cur/public/truck | 6.4-40.6 $/hour |
| Booz Allen Hamilton [13] | Brisbane, Australia, peak/off-peak, bus/rail/ferry/car, CBD/NON-CBD | 6.56-11.13 $/hr |
| I.T. Transport [14] | Rural Bangladesh, Men/Women, employment, travel conditions, weekday/weekend | 3.5-26.68 taka/hr (0.064-0.48 $/hr) |

### 3.3. Accident Costs

Accident costs are the economic value of damages caused by vehicle accidents/incidents. These costs can be classified in two major groups: (1) cost of foregone production and consumption, which can be converted into monetary units, and (2) life-injury damages, which cannot be easily converted into monetary units. Costs associated with these two categories are given in Table 2.

If we develop a function that estimates the number of accidents that occurs over a period of time, accident costs can as well be measured by multiplying the number of accidents by their unit cost values. It should be clear that the cost of each accident varies. However, similar accidents have costs that fall more or less in the same range. Thus, we classified accidents as 1) fatal, 2) injury, and 3) property damage accidents. Moreover, accident occurrence rate is assumed to be correlated with the **highway type**, **average traffic volume** and the **length** of the highway. So, in this study highways are grouped into three categories according to their functional properties. These three categories are **interstate**, **freeway–expressway** and **arterial-collector-local**. Detailed description of the accident cost estimation process is provided in Section 4.1.3.

**Table 2. Accident cost categories**

| Pure Economic Costs | |
|---|---|
| Major costs | Description |
| Medically related costs | Hospital, Physician, Rehabilitation, Prescription |
| Emergency services costs | Police, Fire, ambulance, helicopter services, incident management services |
| Administrative and legal costs | Vehicle repair and replacement, damage to the transportation infrastructure |
| **Life Injury Costs** | |
| Employer costs | Wages paid to co-workers and supervisors to recruit and train replacement for disabled workers, repair damaged company vehicles, productivity losses due to inefficient start-up of substitute workers |
| Lost productivity costs | Wages, fringes, household work, earnings lost by family and friends caring for the injured |
| Quality of life costs | Costs due to pain, suffering, death and injury |
| Travel delay costs | Productivity loss by people stuck in crash related traffic jams |

### 3.4. Air Pollution Costs

The contribution of air pollution is either from the direct emission of the pollutants by the vehicles or from the resulting chemical reactions of the emitted pollutants with each other or with the existent materials in the atmosphere. Motor vehicles emit pollutants in two ways: (1) exhaust emissions, and (2) evaporating emissions [(17)]. Some of the major air pollutants emitted from the motor vehicles are carbon monoxide (CO), lead, volatile organic compounds (VOC), nitrogen oxides ($NO_x$), sulphur dioxide ($SO_2$), and particulate matters ($PM_{10}$).

### 3.5. Noise Costs

Noise costs refer to the cost of unwanted sound and vibrations caused by the motor vehicles due to engine acceleration, tire-road contact, braking, and horns.

Type of vehicle, traffic speed, stops, inclines, and pavement condition are some of the factors affecting the noise generated by the motor vehicles [18].

### 3.6. Roadway Costs

Roadway costs cover construction, maintenance, and operation of the roadway facilities. Construction costs, land acquisition, and maintenance costs are relatively easy to estimate since they are mostly provided in government budgets and agency reports.

Table 3 and Table 4 summarize the past studies of full/marginal cost of transportation that were reviewed in the first phase and the second phase of this project, respectively. For each study reviewed, the study area and the cost categories considered by the researchers are provided. An extensive review of literature on the full/marginal cost of motor vehicle use in the United States can be found in [19,20].

**Table 3. Summary of studies that estimate cost of transportation (1$^{st}$ Phase)**

| Study | Area | Cost Category |
|---|---|---|
| Mayeres et al. [12] | Brussels | Vehicle Costs, Congestion, Accident, Noise, Roadway, Air Pollution, Climate Change |
| Jara-Diaz et al. [21] | Chile freight transportation | Vehicle, Congestion, Topography, Distance |
| KPMG [22] | Vancouver Regional District | Vehicle Costs, Congestion, Accident, Noise, Roadway, Water Pollution, Air Pollution |
| Miller et al. [23] | U.S.A. general | Vehicle, Congestion, Accident, Noise, Roadway, Air Pollution |
| Cipriani et al. [24] | Central Puget Sound | Vehicle Costs, Congestion, Accident, Noise, Roadway, Air Pollution |
| TRB [25] | U.S. freight transportation | Vehicle Costs, Congestion, Accident, Noise, Roadway, Air Pollution |
| Levinson [26] | California | Vehicle Costs, Congestion, Accident, Noise, Roadway, Air Pollution |

## Table 4. Summary of studies that estimate cost of transportation (2nd phase)

| Study | Area | Cost Category |
|---|---|---|
| Anderson et al. [1] | Twin Cities Region | Vehicle Costs, Congestion, Accident, Noise, Roadway, Air Pollution, Climate Change |
| Banfi et al. [4] | 17 European Countries | Vehicle Costs, Congestion, Accident, Noise, Roadway, Air Pollution, Climate Change |
| Decorla-Souza et al. [5] | U.S. general | Vehicle Costs, Congestion, Accident, Noise, Roadway, Water Pollution, Air Pollution |
| Verhoef [7] | Theoretical | Congestion, Accident, Noise, Air Pollution |
| Apogee [16] | Boston, Portland | Vehicle Costs, Congestion, Accident, Noise, Roadway, Water Pollution, Air Pollution |
| Keeler et al. [27] | San Francisco Bay Area | Vehicle, Congestion, Noise, Air Pollution, Roadway, Accidents |
| Fuller et al. [28] | U.S. general | Congestion, Accident, Noise, Air Pollution |
| Mackenzie et al. [29] | U.S. general | Vehicle Costs, Accident, Roadway, Air Pollution, Climate Change |
| OTA [30] | U.S. general | Vehicle Costs, Congestion, Accident, Noise, Roadway, Water Pollution, Air Pollution |
| Lee [31] | U.S. general | Accident, Noise, Roadway, Water Pollution, |
| IBI [32] | Ontario, Canada | Vehicle Costs, Congestion, Accident, Roadway, Air Pollution, Climate Change |
| Black et al. [33] | U.S. general | Vehicle Costs, Congestion, Accident, Noise, Roadway, Water Pollution, Air Pollution |
| Madison et al. [34] | U.K. general | Congestion, Accident, Noise, Roadway, Air Pollution |
| Delucchi [35] | U.S. general | Vehicle Costs, Congestion, Accident, Noise, Roadway, Water Pollution, Air Pollution |
| FHWA [36] | U.S. general | Congestion, Accident, Noise, Roadway, Air Pollution |
| Sansom et al. [37] | U.K. | Vehicle Costs, Congestion, Accident, Noise, Roadway, Air Pollution |
| Gibbons et al. [38] | Dublin | Congestion, Accident, Noise, Air Pollution |
| Proost et al. [39] | Europe | Congestion, Accident, Noise, Air Pollution |
| Quinet [40] | Europe | Vehicle Costs, Congestion, Accident, Noise, Roadway, Air Pollution |

## 4. ESTIMATION OF NEW JERSEY–SPECIFIC COST FUNCTIONS

Highway transportation costs can be grouped in three major categories: (1) user costs, (2) infrastructure costs, and (3) environmental costs. In the following sections, the total, average and marginal cost functions are developed/updated using NJ-specific data for each cost category.

### 4.1. User Costs

User costs are composed of three major groups: (1) self-vehicle operating costs, (2) congestion costs, and (3) accident costs.

#### 4.1.1. Vehicle Operating Costs

Self-vehicle operating costs are affected by many factors, such as road design, type of the vehicle, environmental factors, and flow speed of traffic. In this study, vehicle operating costs are estimated considering depreciation cost, cost of fuel, oil, tires, insurance, and parking/tolls. Based on these different cost components, the total, marginal and average vehicle operating cost functions can be developed as shown:

$$C_{opr} = f\left(C_f, C_o, C_t, C_{pt}, C_{ins}, C_d, m, a\right) \tag{4}$$

$$C_d = f\left(m, a\right) \tag{5}$$

$$C_{opr} = \left(C_f + C_o + C_t + C_{pt}\right).m + \left(C_d + C_{ins}\right).a \tag{6}$$

$$MC_{opr} = \frac{\partial C_{opr}}{\partial m} \tag{7}$$

$$AC_{opr} = \frac{C_{opr}}{m} \tag{8}$$

where

$C_{opr}$ = Cumulative user cost over *n* years ($)

$MC_{opr}$ = Marginal user cost ($/mile)

$AC_{opr}$ = Average user cost ($/mile)

$C_d$ = Total depreciation cost over *n* years ($)

$C_f$ = Cost of fuel ($/mile)

$C_o$ = Cost of oil ($/mile)

$C_t$ = Cost of tires ($/mile)

$C_{ins}$ = Cost of insurance ($/year)

$C_{pt}$ = Cost of parking and tolls ($/mile)

$m$ = Mileage over $n$ years (miles)

$a$ = Age of auto (years)

Among all the aforementioned cost components, only the depreciation cost has to be estimated. All other categories are defined by their unit cost values per mile. Depreciation occurs due to wear and tear on the vehicle over the years, and the changing demand and taste of users. There are two parameters in the cost model to represent these factors, namely, mileage ($m$) and auto age ($a$) (26).

Depreciation data required to estimate the depreciation costs are obtained from the official Website of *Kelley Blue Book* available online. The cost data are extracted for three different car models, namely, Honda Civic, Honda Accord, and Ford Taurus, as these are three of the most selling economy cars in the United States. The depreciation cost estimated for each car model is given in Table 5. Various cost functions developed for different car models indicate that the Ford Taurus has the highest fixed depreciation cost over its lifespan, Honda Accord is the car model least sensitive to the mileage, and the depreciation cost of each car model is almost equally sensitive to the vehicle age.

**Table 5. Depreciation cost functions for different car models**

| **Car Model (1995-2005)** | **Depreciation Cost (in *n* years)** | **Goodness of fit** |
|---|---|---|
| *Honda Civic* | $C_d = 3091.55 + 0.11(m/a) + 1888.45a$ | $r^2 = 0.79$ |
| *Honda Accord* | $C_d = 4417.94 + 0.07(m/a) + 1796.92a$ | $r^2 = 0.80$ |
| *Ford Taurus* | $C_d = 7208.73 + 0.12(m/a) + 1495.3a$ | $r^2 = 0.77$ |

The other cost categories, namely, cost of fuel, oil, tires, insurance, parking and tolls are obtained from the AAA report (41) and USDOT report (42). The unit operating costs given in Table 6 are all in 2005 dollars.

**Table 6. Operating costs (in 2005 dollars)**

| Operating Expenses | Unit Costs |
|---|---|
| Gas & oil | 0.082 ($/mile) |
| Maintenance | 0.053 ($/mile) |
| Tires | 0.006 ($/mile) |
| Insurance Cost | 1288 ($/year) |
| Parking and Tolls | 0.02 ($/mile) |

Including all the units cost values for each car model (Table 5 and Table 6) the total, marginal and average vehicle user cost functions are estimated as shown in Table 7.

The change in the marginal vehicle operating cost throughout the life of each car model is shown in Figure 3. As expected, marginal cost value for each car model decreases as the vehicle age increases. Moreover, Honda Accord experiences the lowest marginal cost, whereas the highest marginal cost per mile is observed for Ford Taurus for the first 10 years. However, as the vehicle age increases to more than 10 years, each car model experiences similar marginal costs per each vehicle mile traveled.

**Table 7. Vehicle operating cost functions for different car models**

| Car Model (1995-2005) | Total Cost (in *n* years) | Marginal Cost ($/mile) | Average Cost ($/mile) |
|---|---|---|---|
| *Honda Civic* | $C_{opr} = 3091.55 + 0.11(m/a) + 3176.45a + 0.143m$ | $MC_{opr} = 0.11/a + 0.143$ | $AC_{opr} = 3091.55/m + 0.11/a + 3176.45(a/m) + 0.143$ |
| *Honda Accord* | $C_{opr} = 4417.94 + 0.07(m/a) + 3084.92a + 0.143m$ | $MC_{opr} = 0.07/a + 0.143$ | $AC_{opr} = 4417.94/m + 0.07/a + 3084.92(a/m) + 0.143$ |
| *Ford Taurus* | $C_{opr} = 7208.73 + 0.12(m/a) + 2783.3a + 0.143m$ | $MC_{opr} = 0.12/a + 0.143$ | $AC_{opr} = 7208.73/m + 0.12/a + 2783.3(a/m) + 0.143$ |

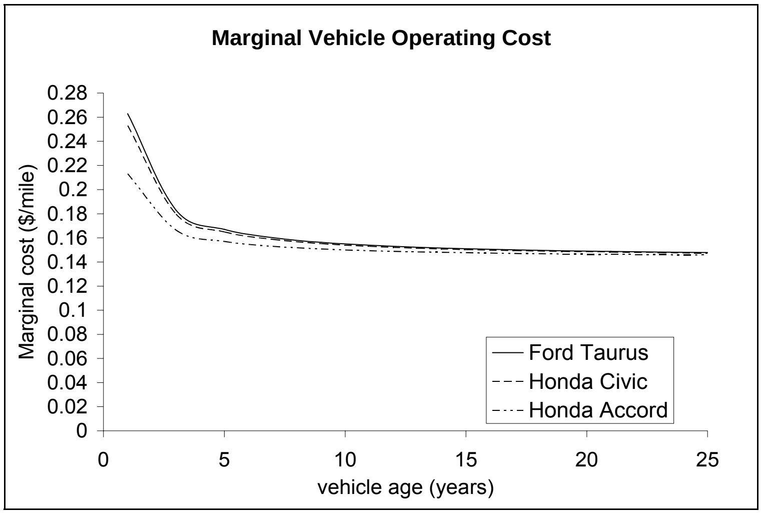


**Figure 3. Marginal operating cost of each car model throughout the car life**

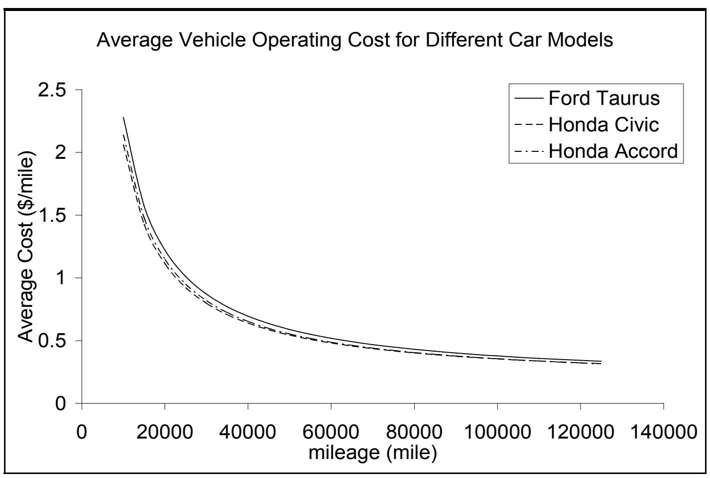


**Figure 4. Average operating cost of each car model throughout the car life**

Similarly, the change in the average operating cost for each car model at a vehicle age of 5 years is shown in Figure 4. The average cost of each car model decreases as the vehicle miles traveled increase. In addition, unlike the marginal costs, Honda Civic has the lowest average cost per mile. Like in the marginal cost case, the highest average cost is observed at Ford Taurus. However, after reducing drastically over the first 60,000 miles, the average cost of each car model becomes almost constant irrespective of any further mileage increase. These results indicate that Ford Taurus has the highest average and marginal cost values per mile compared with other car models. However, after 10 years of vehicle age and 60,000 miles of travel, all cost values become almost the same and insensitive to the further changes in age and/or miles traveled.

### **4.1.2. Congestion Costs**

Congestion costs can be defined as the drivers' time loss and discomfort in the traffic. Its magnitude can be determined in two different cases: regular congestion and hypercongestion.

*Regular Congestion Costs:* Regular congestion refers to the time loss costs experienced when capacity limit is not exceeded. Time loss cost refers to the valuation of time spent on the trip, including actual travel, waiting time, accessing vehicles, delay, and driver discomfort. In this study, only the actual travel time is considered while estimating the time loss costs, which can be determined through the use of a travel time function (Bureau of Public Road's function). This function depends on the distance between the O-D point of the trip, the traffic volume, and the value of time that the users place for their unit of travel time. The total regular congestion cost for all users on a roadway connecting points *a* and *b* can be formulated as follows:

$$TC_{cong}^{R} = Q.T_{a,b}(Q,d).VOT \tag{9}$$

$$TC_{cong}^{R} = Q.\frac{d_{a,b}}{V_o}.\left(1 + 0.15\left(\frac{Q}{C}\right)^4\right)VOT \tag{10}$$

where;

$TC_{cong}^{R}$ = Total regular congestion cost ($)

$Q$ = Traffic volume between nodes *a* and *b* (veh/hr)

$d_{a,b}$ = Distance between nodes *a* and *b* (mile)

$T_{a,b}(Q,d)$ = Travel time between nodes *a* and *b* as a function of $Q$ and $d$

$C$ = Capacity of the roadway segment between nodes *a* and *b* (veh/hr)

$VOT$ = Value of time ($/hr)

$V_o$ = Free flow speed (mile/hr)

*Hypercongestion Costs:* When the capacity limit is exceeded, queuing begins to form, which becomes more severe as the demand increases. Because this condition cannot continue indefinitely, as soon as the demand reduces, the queue starts to dissipate and the system reverts to ordinary congestion. The queue cost category refers to the monetary value of the time spent in the queue until the queue dissipates and normal traffic conditions are observed. Using a bottleneck model, the travel time for a vehicle entering a queue at time *t* can be formulated based on the theory of kinematic waves [43]. The travel time through the bottleneck is formulated as follows:

$$T(t) = T_1(t,Q) + T_2(t,C)$$
$$T(t) = \frac{L - J(t)}{V_1[Q(t)]} + \frac{J(t)}{V_2[C]} \tag{11}$$

where

$T_1(t,Q)$ = Regular travel time when capacity limit is not exceeded

$T_2(t,C)$ = Travel time spent at the physical queue when capacity limit is exceeded

$T(t)$ = Total travel time (hr)

$L$ = Roadway length (mile)

$J(t)$ = Length of the queue (mile)

$V_1[Q(t)]$ = Speed of the traffic for the congested conditions (mph)

$V_2[C]$ = Speed of the traffic for the hyper-congested conditions (mph)

$Q(t)$ = Flow rate (veh/hr)

$C$ = Capacity of the bottleneck (veh/hr)

If it is assumed that the vehicles both enter and leave the roadway segment during the queuing period, equation-11 becomes as follows [44]:

$$T(t) = \frac{Q}{C} \tag{12}$$

The proof of equation-12 is presented in Appendix A. If the time between queue formation and dissipation is taken as 1 hour, the total cost for the hyper-congestion case can be expressed as follows:

$$TC_{cong}^{H} = Q.T_2(Q,C).VOT \tag{13}$$

$$TC_{cong}^{H} = Q.\left(\frac{Q}{C} - 1\right).\frac{VOT}{2} \tag{14}$$

Based on these expressions, the total, marginal and average congestion cost can be estimated for two different cases: (1) capacity limit is not exceeded ($Q \leq C$) and (2) capacity limit exceeded ($Q > C$):

$$C_{cong} = \begin{cases} Q.\dfrac{d_{a,b}}{V_o}.\left(1+0.15\left(\dfrac{Q}{C}\right)^4\right).VOT & \text{if } Q \leq C \\ Q.\dfrac{d_{a,b}}{V_o}.\left(1+0.15\left(\dfrac{Q}{C}\right)^4\right).VOT + Q.\left(\dfrac{Q}{C}-1\right).\dfrac{VOT}{2} & \text{if } Q > C \end{cases} \tag{15}$$

$$AC_{cong} = \frac{C_{cong}}{Q} \begin{cases} \dfrac{d_{a,b}}{V_o}.\left(1+0.15\left(\dfrac{Q}{C}\right)^4\right).VOT & \text{if } Q \leq C \\ \dfrac{d_{a,b}}{V_o}.\left(1+0.15\left(\dfrac{Q}{C}\right)^4\right).VOT + \left(\dfrac{Q}{C}-1\right).\dfrac{VOT}{2} & \text{if } Q > C \end{cases} \tag{16}$$

$$MC_{cong} = \frac{\partial C_{cong}}{\partial Q} = \begin{cases} \dfrac{d_{a,b}}{V_o}.\left(1+0.15\left(\dfrac{Q}{C}\right)^4\right).VOT + 0.6.\dfrac{d_{a,b}}{V_o}\left(\dfrac{Q}{C}\right)^4.VOT & \text{if } Q \leq C \\ \dfrac{d_{a,b}}{V_o}.\left(1+0.15\left(\dfrac{Q}{C}\right)^4\right).VOT + 0.6.\dfrac{d_{a,b}}{V_o}\left(\dfrac{Q}{C}\right)^4.VOT + VOT.\left(\dfrac{Q}{C}-0.5\right) & \text{if } Q > C \end{cases} \tag{17}$$

where

$C_{cong}$: Total Congestion Cost

$AC_{cong}$: Average Congestion Cost

$MC_{cong}$: Marginal Congestion Cost

In the case of hypercongestion, the first term on the right-hand side of equation-17 is the time loss cost experienced by the driver; the second term is the external cost that the driver imposes on the other users on the road; and for the Q > C case, the third term refers to the queue costs due to extensive demand.

### 4.1.3. Accident Costs

Accident costs can be classified into two major groups: (1) foregone production/consumption by individuals, and (2) life-injury damages. In order to estimate the accident costs, the accident occurrence rate and the unit cost of accident should be known. Since costs vary by accident type, accidents can be classified into three categories: fatal, injury, and property damage.

The accident occurrence rate is correlated with the highway type and geometric design of the roadway, such as number of lanes, horizontal and vertical alignment, and sight clearance/obstructions. Since it is not easy to include every variable in the accident rate function, highways were grouped in three categories only according to their functional properties: (1) freeway, expressway, and interstate highway; (2) principal arterial road; and (3) arterial-collector-local road. The generalized total accident cost function can be expressed as follows:

$$C_{acc} = \sum_{r=1}^{3} C_f P_f^r + C_i P_i^r + C_p P_p^r \,, \tag{18}$$

where

$C_{acc}$ = Total accident cost ($/year)

$C_f$ = Unit cost of fatal accident ($)

$C_i$ = Unit cost of injury accident ($)

$C_p$ = Unit cost of property damage accident ($)

$P_f^r$ = Number of fatal accidents per year for highway type *r*

$P_i^r$ = Number of injury accidents per year for highway type *r*

$P_p^r$ = Number of property damage accidents per year for highway type *r*

The general form of the accident rate function (*P*), shown in equation-19, is correlated with highway type, traffic volume (*Q*), number of lanes (*L*), and roadway length (*M*) [45]:

$$P = \alpha_1 Q^{\alpha_2} M^{\alpha_3} L^{\alpha_4} \tag{19}$$

where $\alpha_1, \alpha_2, \alpha_3,$ and $\alpha_4$ are the estimated coefficients.

Using the 2004 crash record data available at the NJDOT Web site [46], the accident rate is estimated for each road type. A total of nine different accident rate functions are developed. Table 8 shows the developed cost functions along with the statistical test results for each parameter.

**Table 8. Accident rate functions**

| Accident type | Freeway/Interstate | Principal Arterial | Arterial/Local |
|---|---|---|---|
| **Property damage** | $P_p^f = 0.05Q^{0.77}.M^{0.76}.L^{0.53}$<br>$r^2 = 0.72$ | $P_p^{pa} = 0.07Q^{0.58}.M^{0.69}.L^{0.43}$<br>$r^2 = 0.62$ | $P_p^a = 0.09Q^{0.58}.M^{0.77}.L^{0.77}$<br>$r^2 = 0.62$ |
| **Injury** | $P_i^f = 5.10^{-4}Q^{0.85}.M^{0.75}.L^{0.49}$<br>$r^2 = 0.63$ | $P_i^{pa} = 0.08Q^{0.45}.M^{0.63}.L^{0.47}$<br>$r^2 = 0.56$ | $P_i^a = 0.04Q^{0.74}.M^{0.81}.L^{0.75}$<br>$r^2 = 0.57$ |
| **Fatality** | $P_f^f = 0.06Q^{0.17}.M^{0.42}.L^{0.45}$<br>$r^2 = 0.45$ | $P_f^{pa} = 0.66Q^{0.04}.M^{0.3}$<br>$r^2 = 0.16$ | $P_f^a = 4.3Q^{-0.14}.M^{0.05}.L^{0.11}$<br>$r^2 = 0.15$ |

The results of the regression analyses indicate that for each road and accident type (except for fatality-type accidents), roadway length, traffic volume, and number of lanes has a statistically significant effect on the accident rate. However, regarding fatality-type accidents, the goodness of fit values are quite low for principal arterial and arterial/local road types. The weakness in these particular results can be explained by the fact that fatality-type accidents are relatively small in number and are not significantly different between each county. Therefore, fatality accident rate functions are excluded for principal arterial and arterial/local road types. The unit cost of accidents, $C_f$, $C_i$, and $C_p$, shown in Table 9, are taken from "Motor Vehicle Accident Costs" study by [47]. All values are converted to 2005 dollars.

**Table 9. Unit accident costs by type [47]**

| Accident Type | Value per Accident ($)* |
|---|---|
| Fatality | 3,315,000 |
| Injury | 229,499,99 |
| Property Damage | 2,550 |

*: in 2005 dollars

As shown in equation-18, to calculate the total accident cost, first the occurrence rate of a particular accident type (Table 8) is multiplied by the unit cost of that accident type (Table 9), and then summed over all accident types. Using the accident rate functions and unit accident costs shown in Table 8 and Table 9 respectively, the total, marginal and average accident cost functions are calculated as shown in Table 10.

**Table 10. Accident cost functions**

| Cost Type | Freeway/Interstate | Principal Arterial | Arterial/Local |
|---|---|---|---|
| **Total Cost** | $C_{acc} = 127.5.Q^{0.77}.M^{0.76}.L^{0.53} + 114.75Q^{0.85}.M^{0.75}.L^{0.49} + 198{,}900.Q^{0.17}.M^{0.42}.L^{0.45}$ | $C_{acc} = 178.5.Q^{0.58}.M^{0.69}.L^{0.43} + 18{,}359Q^{0.45}.M^{0.63}.L^{0.47}$ | $C_{acc} = 229.5Q^{0.58}.M^{0.77}.L^{0.77} + 9179.96Q^{0.74}.M^{0.81}.L^{0.75}$ |
| **Marginal Cost** | $MC_{acc} = 98.175Q^{-0.23}.M^{0.76}.L^{0.53} + 97.53Q^{-0.15}.M^{0.75}.L^{0.49} + 33{,}813Q^{-0.83}.M^{0.42}.L^{0.45}$ | $MC_{acc} = 103.5.Q^{-0.42}.M^{0.69}.L^{0.43} + 8261.55Q^{-0.55}.M^{0.63}.L^{0.47}$ | $MC_{acc} = 133.11Q^{-0.42}.M^{0.77}.L^{0.77} + 6793.17Q^{-0.26}.M^{0.81}.L^{0.75}$ |
| **Average Cost** | $AC_{acc} = 127.5.Q^{-0.23}.M^{0.76}.L^{0.53} + 114.75Q^{-0.15}.M^{0.75}.L^{0.49} + 198{,}900.Q^{-0.83}.M^{0.42}.L^{0.45}$ | $AC_{acc} = 178.5.Q^{-0.42}.M^{0.69}.L^{0.43} + 18{,}359Q^{-0.55}.M^{0.63}.L^{0.47}$ | $C_{acc} = 229.5Q^{-0.45}.M^{0.83}.L^{0.79} + 9179.96Q^{-0.26}.M^{0.81}.L^{0.75}$ |

### 4.2. Air Pollution Costs

Highway transportation accounts for the air pollution due to the release of pollutants during motor vehicle operations. Its contribution is either through the direct emission of the pollutants from the vehicles or the resulting chemical reactions of the emitted pollutants with each other or with the existent materials in the atmosphere. As reported by the Environmental Protection Agency (EPA) [48], the air pollution costs in New Jersey are calculated based on the several pollutants, namely VOC, CO, $NO_x$, and $PM_{10}$.

Estimating costs attributed to highway air pollution is not a straightforward task, since there are no reliable methods to narrow down the origins of the existing air pollution levels. The constraints for estimating the costs attributed to air pollution are listed as follows:

1. Air pollution can be *local*, *trans-boundary* or *global*. As the limits of its influence broaden, the cost generated goes up, and after a certain point it becomes cumbersome to track down.
2. Air pollution effects are not sudden. Namely, unless the pollution level is at intolerable amounts, the damage imposed on the human health, agricultural products and materials can be detected after years.
3. Even if the influence of air pollution could be pinned down, to predict the contribution of highways requires several assumptions. The emission rates depend on several factors, such as topographical and climatic conditions of the region, vehicle properties, vehicle speed, acceleration and deceleration, fuel type and etc. The widely used estimation model is in US federal MOBILE software, which requires the above listed factors. Based on the input values, the program estimates emissions of each pollutant. However, the accuracy of this specific model and the other current models are negotiable (For more information see Small et al [(49)]).
4. Cost values acquainted with air pollution require a detailed investigation and an evaluation of people's preferences and their willingness to pay in order to cover the adverse effects. Any unit value per pollutant can be negotiable to another researcher.

In this study, we first will adopt an emission function to estimate the pollutant quantity generated by motor vehicles. Next, unit cost values of each pollutant are calculated based on the methods presented in the literature. Unit cost calculations will be based on NJ pollutant emission amounts reported by EPA.

First, the emission rate (grams/miles) for the primary pollutants, namely *VOC*, *CO* and $NO_x$ are determined. Then, by multiplying the emission rate with the total miles traveled in the network, the total amount emitted for each pollutant in NJ is calculated. The total cost is, clearly, unit cost values of each pollutant ($/grams) multiplied by the total amount emitted. The proposed cost function includes a fuel consumption function. The proposed emission function was based on the fuel consumption, given in equation-20

[50]. It is seen from the equation that the relationship between speed and fuel consumption is nonlinear. The high percentages of fuel consumption at relatively low speeds can be attributed to the frequent accelerations and decelerations:

$$F = 0.0723 - 0.00312V + 5.403x10^{-5}V^2 \quad (20)$$

where;

$F$ = Fuel consumption at cruising speed (gallons/mile)

$V$ = Average speed (miles/hour)

Specifically,

$$V = V_0\left(1 - \frac{Q}{C}\right)^{0.5} \quad (21)$$

where;

$V_0$ = Free flow speed (miles/hr)

$Q$ = Traffic volume (veh/hr)

$C$= Capacity of the road (veh/hr)

The emission rates of each pollutant (*grams per gallon*) are *69.9* grams for *CO*, *13.6* grams per $NO_x$, and *16.2* grams for *VOC* (SYNCHRO User Manual). So the amounts of pollutants released (*gr*) per mile are calculated as follows:

$$E_{CO} = 69.9F \quad (22)$$

$$E_{NO_x} = 13.6F \quad (23)$$

$$E_{VOC} = 16.2F \quad (24)$$

The cost of air pollutants has long been investigated in the literature (Small [51], Small et al.[49], Mayeres et al. [12]). There are three ways of estimating the costs of air pollution: *Direct estimation of damages*, *hedonic price measurement* (relates the price changes and the air quality) and *preference of policymakers* (pollution costs are inferred from the costs of meeting pollution regulations) (Small et al.[49]).

Small et al. [49] adopt the direct estimation of damages method to measure the unit costs of each pollutant. The study differentiates the resulting damages in three categories:

*mortality from particulates*, *morbidity from particulates* and *morbidity from ozone*. It is assumed that human health costs are the dominant portion of costs due to air pollution rather than the damage to agriculture or materials. *Particulate Matter* ($PM_{10}$) which is both directly emitted and indirectly generated by the chemical reaction of *VOC*, $NO_x$, and $SO_x$, is assumed to be the major cause of health damage costs. Ozone ($O_3$) formation is attributed to the chemical reaction between *VOC* and $NO_x$.

Using the fuel consumption function based on EPA analysis and the unit costs of air pollutants, total, marginal and average air pollution costs per mile are calculated as follows [4545]:

$$TC_{air} = Q(0.01094 + 0.2155F) \tag{25}$$

$$AC_{air} = (0.01094 + 0.2155F) \tag{26}$$

$$MC_{air} = 0.01094 + 0.2155\left(F + \frac{\partial F}{\partial Q}\right) \tag{27}$$

where;

$TC_{air}$ = Total air pollution cost (\$/mile)

$MC_{air}$ = Marginal air pollution cost (\$/mile)

$AC_{air}$ = Average air pollution cost (\$/mile)

$Q$ = Traffic volume (veh/hr)

### 4.3. Noise Costs

There are several methods used to define noise in a numerical range such that any noise source can be examined by the human ear. In general, it is accepted that a sound after 50 dB(A) becomes annoying and imposes a cost on society.

The social cost of noise is usually estimated by calculating the depreciation in the value of residential units alongside highways (i.e., the closer a house is to a highway, the higher the noise cost). In this study, the Noise Depreciation Sensitivity Index is taken as 0.85% as suggested by Delucchi et al. [52]. The house depreciation function is defined as follows:

$$ND = N_h(L_{eq} - L_{max})DW_{avg} \quad (28)$$

where;

$ND$ = Depreciation value ($)

$N_h$ = Number of houses affected (houses/mile$^2$)

$L_{eq}$ = Equivalent noise level (dB(A))

$L_{max}$ = Maximum acceptable noise level (50 dB(A))

$D$ = Percentage discount in value per increase in the ambient noise level

$W_{avg}$ = Average housing value ($246,628, U.S. Census Bureau, 2005)

The number of houses affected from the noise can be calculated by multiplying the average residential density (*RD*, housing units/square mile) around a highway by the distance to that highway (*r*, mile) and the length of relevant highway section (*d*, miles), as shown below:

$$N_h = 2(RD)rd\ . \quad (29)$$

The formula for the equivalent noise level, $L_{eq}$, is obtained from the FHWA's recently developed Traffic Noise Level Model [(52)]. This model is based on recent measurements of noise from different motor vehicles (autos, light trucks, medium trucks, heavy trucks, buses), and has parameters related to intermediate obstructions, road surface type, and noise emitted by accelerating vehicles. The expression for $L_{eq}$ is as follows:

$$L_{eq} = 10\log(Q) + 10\log(K) - 10\log(r) + 1.14 \quad (30)$$

where;

$Q$ = traffic volume (veh/day)

$r$ = distance to the highway (ft)

$K$ = Total noise-energy emission from different vehicle classes

For cars and trucks, the expression for noise-energy emission is as follows [(52)]:

$$K = K_{car} + K_{truck}$$

$$K = \frac{F_c}{V_c}\left(V_c^{4.174}.10^{0.115} + 10^{5.03F_{ac}+(1-F_{ac})6.7}\right) + \frac{F_{tr}}{V_{tr}}\left(V_{tr}^{3.588}.10^{2.102} + 10^{7.43F_{atr}+(1-F_{atr})7.4}\right) \quad (31)$$

where;

$K_c$ = Noise-energy emission from autos

$K_{truck}$ = Noise-energy emission from trucks

$F_c$ = Percent of autos in the traffic

$F_{tr}$ = Percent of trucks in the traffic

$F_{ac}$ = Percent of constant speed autos in the traffic

$F_{atr}$ = Percent of constant speed trucks in the traffic

$V_c$ = Speed of autos in the traffic (mph)

$V_{tr}$ = Speed of trucks in the traffic (mph)

Based on equations above the total, marginal and average noise cost functions are developed as follows:

$$C_{noise} = 2\int_{r_1=50}^{r_2=r_{max}} \left(L_{eq} - 50\right) DW_{avg} \frac{RD}{5280} dr \tag{32}$$

$$MC_{noise} = \frac{\partial C_{noise}}{\partial Q} = \frac{DW_{avg}RD}{264}\left[\frac{\partial r_2}{\partial Q}\left(log\,Q + log\,K - ln\,r_2 - 4.89\right) + \frac{\left(r_2 - r_1\right)}{ln10}\left(\frac{1}{Q} + \frac{\partial K/\partial Q}{K}\right)\right] \tag{33}$$

$$AC_{noise} = \frac{C_{noise}}{Q} = \frac{DW_{avg}RD}{2640.Q}\int_{r_1=50}^{r_2=r_{max}} \left(L_{eq} - 50\right) dr \tag{34}$$

## 4.4. Infrastructure and Maintenance Costs

Infrastructure costs include all long-term expenditures, such as facility construction, material, labor, administration, right of way costs, regular maintenance expenditures for keeping the facility in a state of good repair, and occasional capital expenditures for traffic-flow improvement. Highway investment and its costs can be best described by defining input prices, output, and network properties [53]. Input includes the cost of all phases of construction, such as roadway design, land acquisition, labor, construction material, and equipment. Network properties represent the physical capabilities of the constructed highway facility, which include the number of lanes, lane width, pavement durability, intersections, ramps, overpasses, and so forth. In addition, environmental factors are important elements in highway construction. Highway location, demographics of the district, soil properties, topography, weather conditions, and other factors have an effect on infrastructure and maintenance costs.

In the computation of marginal infrastructure cost, new construction and land-acquisition costs cancel out since these costs are not a function of traffic volume, *Q*. Thus, maintenance and improvement constitute the only cost category that remains in our marginal infrastructure cost function. We attempt to express the maintenance cost in terms of input and output. Input in this context includes all components of maintenance work, such as equipment usage, earthwork, grading, material, and labor. Output implies the traffic volume on the roadway. The data employed include completed or ongoing resurfacing works between 2004 and 2006 in New Jersey [54, 55, 56]. The estimated cost function is given below:

$$C_M = \frac{796.32(M)^{0.40}(L)^{0.39}}{P} \tag{35}$$

where;

$C_M$: Cost of maintenance per lane width (1000$/year)

*M*: Roadway length (miles)

*L*: Number of lanes

*P*: Design cycle period

*P* factor given in equation-35 represents the time period (in years) between two consecutive resurfacing improvement works. The time period is calculated from the formulation given by: [57]

$$P = \frac{N}{ESAL} \tag{36}$$

where;

*ESAL*: Equivalent single axle load

*N*: Number of allowable repetitions (1,500,000)

*ESAL* converts the axle loads of various magnitudes and repetitions to an equivalent number of "standard" of "equivalent" loads based on the amount of damage they do the pavement [57]. *ESAL* factor is calculated as follows:

$$ESAL = Q * 365 * P_t * T_f \quad (37)$$

where;

$Q$: Traffic volume (veh/day)

$P_t$: Percentage of trucks in traffic

$T_f$: Truck factor

Truck factor changes with respect to different road types. Values for various road types are provided in Table 11.

**Table 11. Truck factor values**

| **Road Type** | **Area Type** | |
|---|---|---|
| | **Rural** | **Urban** |
| **Interstate** | 0.52 | 0.39 |
| **Freeway** | - | 0.23 |
| **Principal** | 0.38 | 0.21 |
| **Minor Arterial** | 0.21 | 0.07 |
| **Major Collector** | 0.3 | 0.24 |
| **Minor Collector** | 0.12 | |

Based on the estimated total maintenance cost and the design cycle period functions the marginal cost function is calculated as follows:

$$MC_M = \frac{796.32(M)^{0.40}(L)^{0.39}}{P.365.24.Q}.t \quad (38)$$

where;

$MC_M$: Marginal maintenance cost in year 2005 ($/trip)

$Q$: Traffic volume (vehicles/hr)

$t$: trip duration (hr)

## 4.5. Issues While Updating the Cost Functions

Table 12 shows the data sources and the type of data used while estimating the cost functions. In order to compute FMC of a trip realistically, re-calibration and update of the databases are crucial.

**Table 12. Data sources and type of data used in marginal cost estimation**

| Cost Category | Data Sources and Type of Data |
|---|---|
| **Vehicle Operating** | AAA [41], USDOT [42]: cost of fuel, cost of oil, cost of tires, cost of insurance, cost of parking and tolls – format: pdf documents<br>Kelly Blue Book: Depreciation cost, mileage over "n" years, vehicle age – format: text files |
| **Congestion** | TP + Output: Link volume, capacity, and free flow speed – format: dbf files compatible with Viper software |
| **Accident** | NJDOT[46]: length of the road section, number of fatal accidents per year for each highway type, number of injury accidents per year for each highway type, number of property damage accidents per year for each highway type – format: excel sheets<br>NJDOT[46]: Volume, capacity and number of lanes for the corresponding road section – format: pdf documents obtained from Straight line diagrams<br>TP + Output: Link volume, capacity, and road length – format: dbf files compatible with Viper software |
| **Air Pollution** | EPA [48]: Current air pollution cost function (not specific to network, but universal)<br>TP + Output: Fuel consumption at cruising speed, average speed, volume, capacity and free flow speed – format: dbf files compatible with Viper software |
| **Noise** | US Census Bureau: Depreciation value and current housing prices – pdf document<br>FHWA Traffic Noise Level Model[52]: Current noise function<br>TP + Output: % of autos and trucks on the road, % of constant speed autos, % of constant speed trucks, speed of autos, speed of trucks – format: dbf files compatible with Viper software |
| **Maintenance** | NJDOT Fiscal year reports [54, 55, 56]: Cost of maintenance, type of project, length and number of lanes of the corresponding road section – format: pdf documents<br>TP + Output: Volume, roadway length, number of lanes – format: dbf files compatible with Viper software |

The documents obtained from NJDOT regarding CPM data included cost of the project, but information regarding the road section (length or number of lanes), type of the project were not provided.

# 5. MARGINAL COST ESTIMATION METHODOLOGIES

As stated in the Section 1 and Section 2, marginal cost is the cost of an additional unit of output. However, in transportation facilities, there is no unique or precise way of representing the output. Depending on the output definition, two main approaches can be followed: (1) distance-based marginal cost estimation, and (2) trip-based marginal cost estimation.

## 5.1. Distance-Based Marginal Cost Estimation

In the distance-based approach, marginal cost between an O-D pair is estimated on a per distance basis using a cost function specific to a segment of roadway. Then, the summation of this quantity for the entire network is used as the total marginal cost of the system [53,58,59]. Distance-based marginal cost of a network can be displayed mathematically as follows:

$$MC_1 = \sum_{i=1}^{N} d_i MC_i \tag{39}$$

$i$ = Index for the links in the network

$N$ = Total number of links in the network

$MC_i$ = Marginal cost of one additional unit of demand on the link $i$ (\$/mile)

$d_i$ = Length of the link $i$ (miles)

$MC_1$ = Distance-based marginal cost of the entire network (\$)

This approach assumes that each link is loaded with the same amount of unit demand irrespective of its location or origin and destination. Thus, in this case, network-wide marginal cost represents the overall effect of all the demand changes in all the links on the network. This methodology does not realistically capture the effect of unit increase in demand required to estimate marginal costs. As Safirova et al. [60] point out; it is not possible "to uncouple the individual effects of changes in one link on the other links by this method". To obtain more accurate results using the distance-based approach, it would be necessary to add one unit of demand only to one link while keeping the flow at all other links the same. However, since travel demand, in general, is defined by the origin and destination, it is impossible to accomplish this. To overcome this drawback, Safirova et al. [60] proposed reducing the capacity of a link of the network by one mile instead of increasing the demand on that link, and then reassigning the O-D demands to the network and estimating the marginal cost per mile for the new network.

Even with this new approach to the distance-based estimation proposed by Safirova et al. [60] the ultimate output of the network-wide marginal costs is still expressed in the unit of $/mile. However, intermediate outputs such as vehicle-miles and vehicle-hours usually represent the technical efficiency of a network, whereas final outputs such as number of trips or number of passengers represent the overall efficiency and effectiveness of the system [2]. Since the main purpose of this project is to investigate the overall efficiency of the New Jersey highway network, marginal cost per mile does not provide the required information in terms of network efficiency. Moreover, there are several possible route choices within a network. In the distance-based approach, however, user decisions are not considered. Therefore, this approach estimates the marginal cost of the network irrespective of the origins, destinations, and route choices of the users.

## 5.2. Trip-Based Marginal Cost Estimation

Unlike the distance-based approach, in the trip-based approach [21], marginal costs are estimated on a trip basis for each O-D pair. Hence, the output of the transportation network is defined as trip instead of distance, and for each O-D pair, the road network is represented as routes instead of links. The users choose the most attractive route from a set of possible routes on which to travel. Therefore, the extra unit added to the system appears in terms of number of trips, not number of vehicles traveling on each link, and the cost of adding one extra trip to the system can therefore be estimated in $/trip. Depending on the impacts of one additional unit of demand on the overall network, two different methodologies can be used to estimate the network-wide marginal cost between an O-D pair.

### 5.2.1. Trip-Based Marginal Cost Estimation Methodology A

Methodology A is proposed by Ozbay et al. [61], in the first phase of the *Cost of Transporting People in NJ Project*, to estimate the FMC of transportation between various O-D pairs of the North Jersey network.

In this methodology, it is assumed that one additional unit of demand between an O-D pair does not disturb the overall network equilibrium. Based on this assumption, in order to find the marginal cost of a given trip, the following steps are implemented:

1. The shortest route between a given O-D pair and the links corresponding to that route are determined.
2. The marginal cost of each link on the shortest route is estimated using the derivative of the total cost function of that link.
3. The marginal cost of one additional unit of demand between an O-D pair to the whole network is estimated as the sum of the marginal costs of the links on the shortest route.

Trip-based marginal cost for an O-D pair A-B estimated by Methodology A can be represented mathematically as follows.

$$MC_{2A} = \sum_{i=1}^{N} MC_i \qquad (40)$$

$i$ = Index for the links of the shortest path between A-B

$N$ = Total number of links in the shortest path between A-B

$MC_i$ = Marginal cost of link $i$ ($)

$MC_{2A}$ = Trip-based marginal cost of an additional trip between A-B ($/trip)

Under this methodology, when one unit of demand is introduced to the network, each route/link shares this additional unit proportionally, and the marginal cost of a trip can be estimated on a trip basis. However, this methodology has two main drawbacks:

1. Only the shortest travel time path is considered. In reality, parameters other than travel-time, such as volume, highway-type, and trip-distance, also affect users' route choice between a particular O-D pair and, consequently, the calculation of FMC.
2. It assumes that one additional unit of demand does not disturb the network equilibrium. In reality, even though small increases in the demand may not disturb the system, after some threshold value, the additional demand included in the

system will disturb the system. Thus, this method does not accurately consider system disturbance due to additional demands.

### 5.2.2. Trip-Based Marginal Cost Estimation Methodology B

Methodology B is proposed to overcome the first drawback of Methodology A, which determines not only the shortest "travel time" path but also a set of feasible paths between each O-D pair attractive to the travelers while calculating the FMC. Several different approaches can be employed to determine multiple paths between O-D pairs, mainly based on the determination of k-shortest paths that satisfy user-defined constraints. In Dial [(62)] and Sherali et al [(63)], a labeling approach is adapted, which includes all paths that are optimal with respect to a label (e.g., time, cost, or distance). Alternatively, heuristic methods are deployed by many researchers (see for example [(64)] and [(65)]). These methods are mainly based on link elimination and penalty rules, where the network is modified after finding the shortest path.

Existing k-shortest path algorithms may be divided into the two categories: (1) those that allow paths to have repeated links (see for example [(66)] and [(67)]), and (2) those that only consider acyclic paths, where link repetition is not allowed (see for example [(68)] and [(69)]). A comparative numerical study by Brander and Sinclair [(70)] shows that within the class of algorithms considering only acyclic paths that are applicable to directed graphs (such as transportation networks); the method proposed by Lawler [(68)] offers the best performance. Lawler provides an exact algorithm for finding the k-shortest paths between a single origin and a single destination. This algorithm first defines the set of all paths in a network and determines the shortest path of this set. Then the remaining paths are divided into mutually exclusive subsets, and the shortest path for each of these subsets is determined. This approach is later extended by Van der Zijpp, and Catalano [(71)], by adding constraints related to detour and overlap.

The method proposed in this study provides an alternative to the algorithms mentioned above. The main advantage of the proposed method is that it finds the constrained shortest paths directly, instead of selecting the paths from a large set of overall paths. In addition, it allows for defining a path choice set on the basis of objective constraints such as limitation of travel time, minimum required disjoint links, and limitation on total number of links.

The algorithm, adapted in this study to find k-shortest paths from an origin to a particular destination in a directed acyclic transportation network, (i.e., links on the transportation are all directed, and no link cannot be used more than once in the shortest path) is based on iterative application of the modified version of Dijkstra's algorithm. The basic idea in Dijkstra's algorithm is to find the shortest path from one origin to all destinations. However, in our case, the main focus is to find O-D specific shortest paths. Thus, to reduce the complexity of the algorithm, Dijkstra's approach is modified such that it terminates as soon as a path from the selected origin to the specified destination is found. As soon as the shortest path between the particular O-D pair is found, the network is modified by randomly deleting two links from the shortest path while keeping the network connected. The modified Dijkstra's algorithm is then reapplied to the modified network to find the next candidate path. The iteration continues until a user-defined number of paths have been found, or no more paths that satisfy the required constraints can be found.

The main idea of the multiple-path approach is to find the set of a predefined number of *feasible* paths that are attractive to the travelers between the selected O-D pair. Therefore, several constraints are introduced into the proposed algorithm. These constraints can be summarized as follows:

**Constraint (1)**—*Travel Time Constraint*: Let $t_i$ be the travel time of the candidate path $i$ and $t_1$ be the travel time of the first shortest path. Path $i$ is feasible if the following condition holds:

$$t_i \leq \phi_{max} t_1 \qquad (41)$$

Path *i* is infeasible if constraint (1) is not satisfied. The variable $\phi_{max}$ is a user-defined limitation factor on travel time. For illustration purposes, a value of $\phi_{max} = 1.3$ is selected.

**Constraint (2)**—*Rate of Disjointedness Constraint*: Let $A_i = \{a_{1i}, a_{2i}, ...a_{Mi}\}$ denote the links of the $i^{th}$ candidate path where *M* is the number of links of the candidate path, and $A_1 = \{a_{11}, a_{21}, ...a_{N1}\}$ denote the links of the first shortest path, where *N* is the total number of links of the first shortest path. Then, path *i* is feasible if a sequence of links within path *i* cannot be found for which the following conditions hold:

(i) $$s_n = \begin{cases} 0 & \text{if } a_{n1} = a_{mi} \quad \forall n \in N, \forall m \in M \\ 1 & \text{otherwise} \end{cases} \tag{42}$$

(ii) $$S = \frac{\sum_n s_n}{N} \tag{43}$$

(iii) $$S \geq \delta_{min} \tag{44}$$

The variable $\delta_{min}$ is a user-defined limitation factor on disjoint rate. For illustration purposes, a value of $\delta_{min} = 0.35$ is selected. Path *i* is infeasible if constraint (2) does not hold.

**Constraint (3)**—*Link constraint*: Using the variables defined earlier, path *i* is feasible if the following condition holds:

$$M \leq \theta_{max} N \tag{45}$$

The variable $\theta_{max}$ is a user-defined limitation factor on the total number of links. For illustration purposes, a value of $\theta_{max} = 1.35$ is selected if *M* is larger than 8, and $\theta_{max} = 1.5$ is selected otherwise. Path *i* is infeasible if no such constraint (3) is not satisfied.

A summary of the steps of the proposed algorithm is given below:

*Step 1*: Find the shortest path between a given O-D pair using the link travel times and link flows (Dijkstra's Algorithm).

*Step 2*: Store the number of links and the total travel time of the shortest path.

*Step 3*: Randomly select two links on the shortest path and set the travel time of these links to infinity while keeping the network connected.

*Step 4*: Find the next shortest path between the O-D pair using the modified link travel times and determine the number of links of that path (modified Dijkstra's algorithm).

*Step 5*: If the candidate path satisfies all three constraints, store that path as an alternative shortest path; if not, ignore that path.

*Step 6*: Repeat steps 4 and 5 until the user-defined number of different paths is determined.

After finding all the feasible paths and the links on each feasible path that can be realized between each O-D pair, the marginal cost of each possible path will be calculated as the summation of the marginal costs of the links on that path. Then, the marginal cost of the trip between each O-D pair will be estimated as the *weighted* average of marginal cost of all the possible paths. Mathematically trip-based marginal cost of an O-D pair A-B estimated by Methodology B can be represented as follows.

$$MC_{2B} = \frac{1}{K}\left( \frac{\sum_{j=1}^{K}\sum_{i=1}^{N} Q_{ij} MC_{ij}}{\sum_{j=1}^{K}\sum_{i=1}^{N} Q_{ij}} \right) \tag{46}$$

$j$ = Index for the shortest path between A-B ($j$: 1,…..,$K$)

$K$ = Total number of feasible shortest paths between A-B

$i$ = Index for the links of the $j^{th}$ shortest path between A-B ($i$: 1,…..,$N$)

$N$ = Total number of links in the $j^{th}$ shortest path between A-B

$MC_{ij}$ = Marginal cost of the link $i$ in the $i^{th}$ shortest path (\$)

$Q_{ij}$ = Volume observed at link $i$ of the $i^{th}$ shortest path (veh/hr)

$MC_{2B}$ = Trip-based marginal cost of additional trip between A-B (\$/trip)

### 5.2.3. Trip-Based Marginal Cost Estimation Methodology C

In Methodology C, it is assumed that additional demand between an O-D pair disturbs the network equilibrium. Therefore, in order to estimate the marginal cost of additional one unit demand the following steps are completed:

1. The total demand between the given O-D pair is assigned to the network by user equilibrium traffic assignment approach.
2. The total network cost for the before condition is estimated based on the resulting travel times and traffic flows obtained from the traffic assignment.
3. The demand between the O-D pair is increased by one unit, which is 1% of the original demand between that O-D pair.
4. This increased O-D demand is reassigned to the network, and total network cost for the after condition is re-estimated.
5. Marginal cost of the additional one unit of trip to the entire network is estimated by calculating the total cost difference between the two networks and by dividing by the extra O-D demand included into network.

Mathematically, this methodology can be represented as follows:

$$MC_{2C} = \frac{TC_{after} - TC_{before}}{\varepsilon} \tag{47}$$

where,

$TC_{after}$ = Total network cost after the additional one unit of demand between an O-D pair is introduced ($)

$TC_{before}$ = Total network cost for the original network ($)

$\varepsilon$ = The additional unit of demand included to the network (veh/hour)

$MC_{2C}$ = Trip-based marginal cost of additional trip between A-B ($/trip)

## 6. GIS-BASED MULTIPLE-PATH FMC ESTIMATION TOOL

This section focuses on the proposed GIS-based FMC estimation tool. The proposed tool implements the constrained k-shortest path algorithm (Methodology B) using C programming language and Visual Basic for Applications (VBA), and calculates the FMC of a trip between a selected O-D pair. In the developed GIS-based tool, the origin and/or destination of trip can be:

a. Single node
b. User-defined set of nodes within Traffic Analysis Zones (TAZ) or one TAZ for each origin and destination
c. County-to-County selection, i.e. user-defined set of nodes within each county (one county for each origin and destination)
d. Intra-County selection i.e. user-defined set of nodes within a county (same county for the origin and destination)
e. Network-wide selection - user-defined set of nodes within the whole network at hand

The proposed tool has the following advantages:

1. With the FMC estimation on TAZ and county level, the user can observe the changes in trip-based FMCs among different O-D pairs in a certain area. Moreover, the network-wide selection helps the user to observe the distribution of trip-based FMC throughout the whole network.
2. The proposed tool, not only estimates FMC between selected O-D pairs, but it also compares two different networks, and estimates the short-term impacts of network changes (lane and/or link additions, etc.) on the FMC of a trip.

Figure 5 shows the flow chart of the proposed GIS-based Multiple-path FMC estimation tool. In the first step of this tool, the user is prompted to select whether s/he wants to estimate FMC between two O-D locations, or to observe the short-term impacts of network changes on the FMC of different trips. Then, the user selects the origin and destination of the trip for which s/he is wants to calculate FMC (as shown in Figure 6).
If the user wishes to select a single node for the origin and destination, the following steps are completed:

1. The user visually selects the origin node and the destination node from the network interested.
2. C-program finds all feasible paths between that particular O-D pair.
3. For each of the paths, the total, marginal and average costs are calculated, and stored permanently to a folder.
4. Each of the costs and their weighted average for the O-D pair are displayed on a Visual Basic form on the ArcView map of the network (as shown in Figure 7).

If the user wishes to conduct multiple O-D pair analysis depending on the selection the following steps are completed:

- For TAZ selection, the user visually selects two different TAZs for origin and destination locations. The program automatically saves the whole origin and destination nodes located within the selected TAZs.
- For county-to-county selection, the user selects two different counties for origin and destination locations from the dropdown list. The program automatically saves the whole origin and destination nodes located within the selected counties.
- For intra-county selection, the user selects only one county for both origin and destination locations from the dropdown list. The program automatically saves the whole origin and destination nodes located within the selected county.

For network-wide selection, the user does not need to specify any O-D location. Instead, the program automatically saves the whole origin and destination nodes located within the entire network. After specifying the type of the multiple O-D pair selection, the following steps are conducted:

1. The user is prompted to specify the number of O-D pairs to be analyzed.
2. Then, the C-program randomly samples the user-defined number of O-D pairs between the selected TAZs, counties, or the network.
3. For each O-D pair, all the feasible paths are calculated in the C-Program, and the weighted average of the total, marginal and average of each cost category is calculated.
4. After the calculations are completed for each O-D pair, the sampled O-D pair ID numbers, and corresponding cost values are displayed on a Visual Basic form on the ArcView map of the network.
5. By selecting the row of a path in the cost output form, the shortest path of that particular O-D pair is highlighted on the map.

If the user does not wish to conduct any comparison analysis, after displaying the cost values for the selected O-D pair, the tool is ready to rerun the estimation process for different O-D pairs. On the other hand, if the user wishes to compare two different networks (e.g. before and after scenario), then after displaying the results for the first network, the user specifies the second network. Then, the C-program reruns for this new modified network, and displays the cost values for the same set of O-D pairs. And finally, in another table, the changes in the cost values of each O-D pair are displayed. The details of the installation and operation of the software are provided in Appendix B.

The developed GIS-based cost estimation tool enables planners to efficiently identify areas of interest, to observe the short-term impacts of network changes, and to visualize results on the study network by taking advantage of powerful graphical capabilities of ArcGIS combined with the algorithm developed in this study.

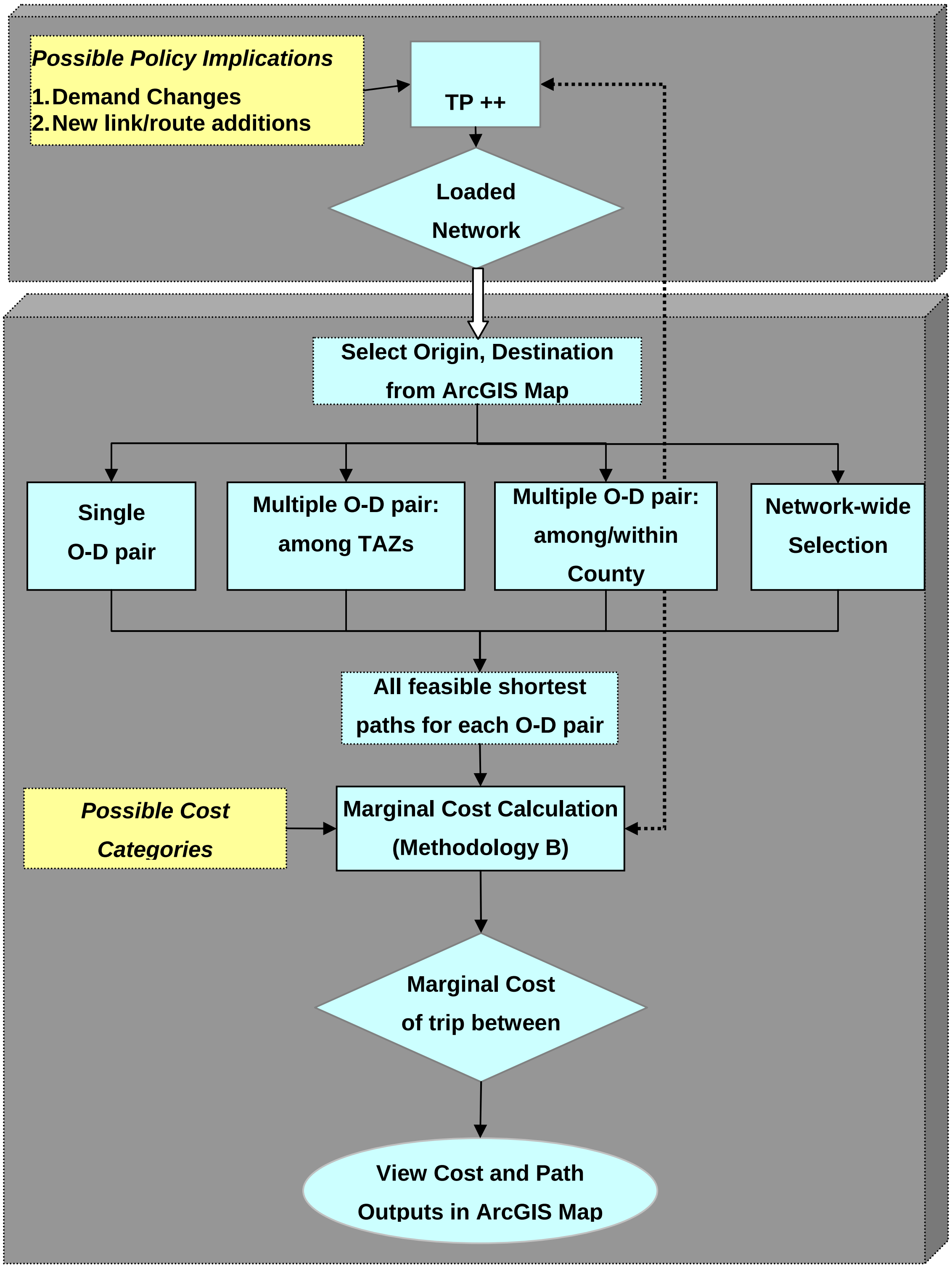


**Figure 5. Flow chart of the proposed model improvements for the second phase of the project**

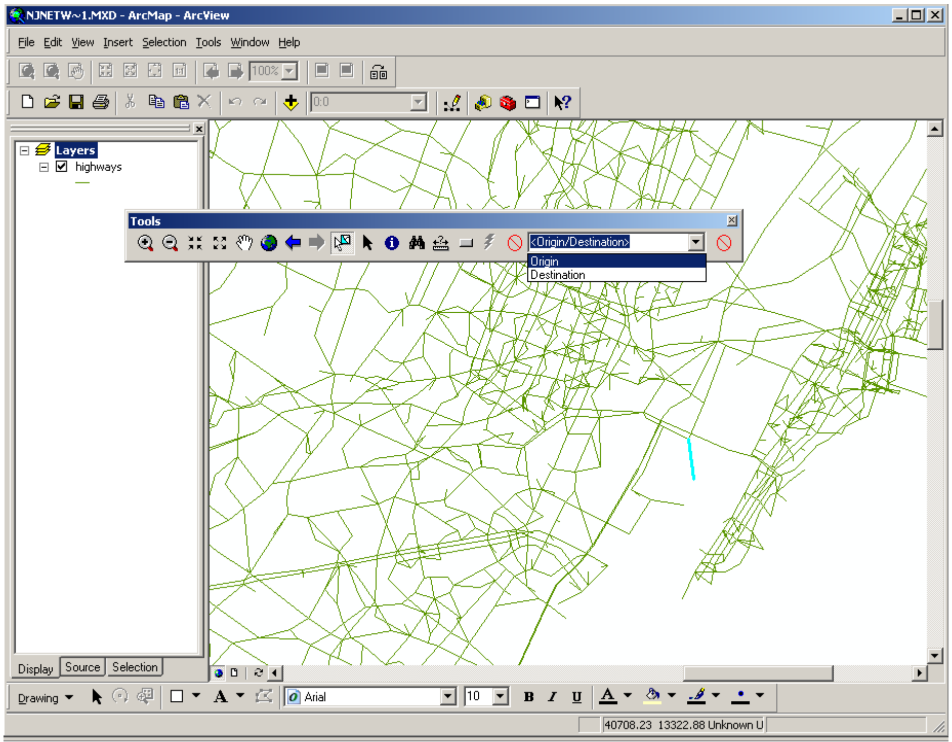


**Figure 6. Selection of the origin and destination**

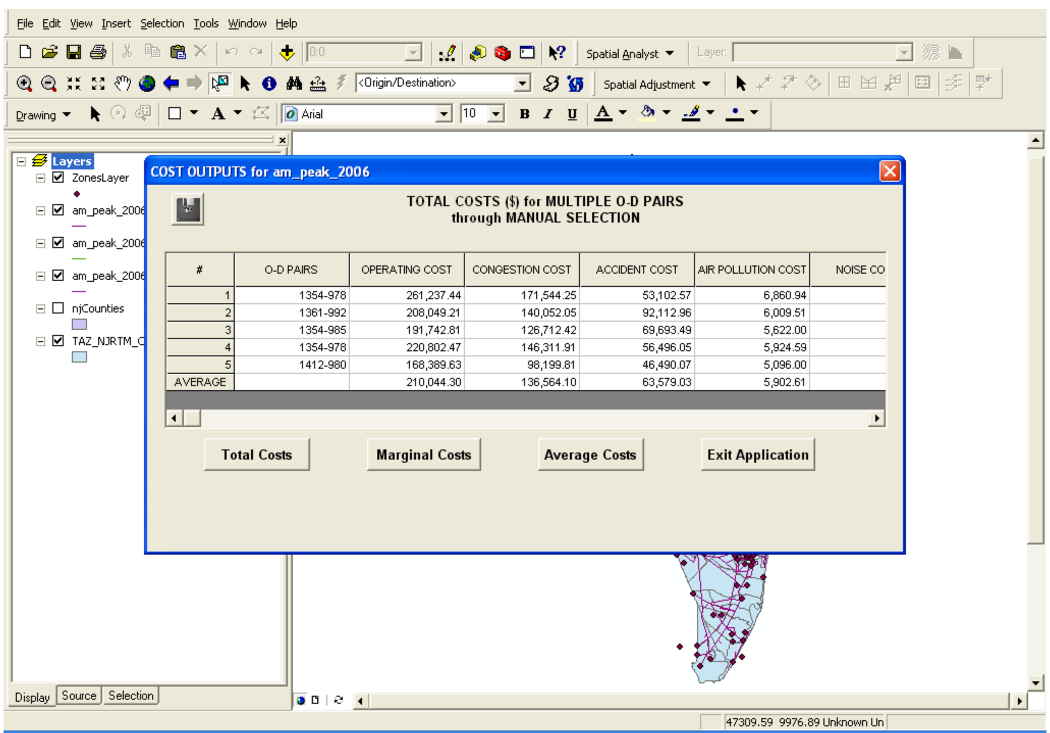


**Figure 7. Output shown as various costs for each path**

## 7. NUMERICAL ILLUSTRATION OF PROPOSED IMPROVEMENTS

### 7.1. A Simple Sample Network

In this section, proposed improvements to the current methodology are illustrated using a sample network (Figure 8) with 4 nodes and 5 links. For simplicity it is assumed that the demand is generated only from Node A to Node B, and other nodes are just transient nodes that users bypass along their travel route. The travel times of each link as a function demand (Q) and the distance of each link are shown in Table 13.

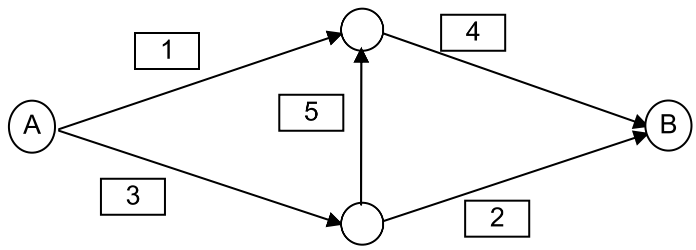


**Figure 8. Graphic representation of the sample network**

**Table 13. Travel time function of each link**

| Link No | Travel time Function (min) | Distance |
|---|---|---|
| 1 | 21 + 0.001*Q | 16 |
| 2 | 19 + 0.001*Q | 14 |
| 3 | 8 + 0.01*Q | 12 |
| 4 | 6 + 0.01*Q | 11 |
| 5 | 4 + 0.002Q | 10 |

For simplicity, it is assumed that the hourly demand between O-D pair A-B is constant during each time of the day at a level of 900 veh/hr, the capacity limit is not exceeded, and the value of time of each user is the same, namely, $0.2/min. It is also assumed that the total cost of each user is composed of only congestion cost. Based on these assumptions, marginal cost is calculated using equation-17.

To assign the 900 veh/hr demand between O-D pair A-B, user equilibrium traffic assignment is implemented. In this type of assignment the total demand is assigned to the links such that, at the equilibrium each used path between A-B has the same travel time. In the following sections marginal cost estimation results for distance-based approach and Methodologies B and C of the trip-based approach are presented.

### 7.1.1. Distance-Based Marginal Cost Estimation

In this section, marginal cost of the sample network illustrated in Figure 8 is estimated using distance-based approach. To accomplish this task, first the total demand between O-D pair A-B is assigned using user equilibrium traffic assignment. Then, marginal cost of each link is calculated based on the resulting travel times and traffic flows at each link. Finally, the total network marginal cost is calculated as the sum of the marginal cost of all links in the network, as shown in equation-17. Table 14 shows the traffic flow, travel time, marginal cost of each link, and the corresponding network marginal cost.

**Table 14. Distance-based approach analysis results**

| link | volume | Travel time (min) | Marginal congestion Cost |
|---|---|---|---|
| 1 | 120 | 21.12 | $4.25/link |
| 2 | 120 | 19.12 | $3.85/link |
| 3 | 780 | 15.8 | $4.72/link |
| 4 | 780 | 13.8 | $4.32/link |
| 5 | 660 | 5.32 | $1.33/link |
| **Marginal Cost of the Network** | | | **$18.46, $0.40/mile** |

In the distance-based marginal cost estimation approach, it is assumed that one additional unit of demand is added to each link of the entire network, instead of one additional unit of demand to one link. Thus, the network-wide marginal cost calculated as the sum of the individual link marginal costs indicate a very high value of $18.46 for the total miles traveled, and a value of $0.40/mile.

### 7.1.2. Trip-Based Marginal Cost Estimation, Methodology B

In this section the marginal cost of the entire network is calculated using Methodology B of the trip-based approach. As stated before in this method, first using user equilibrium assignment traffic flows and corresponding travel times of each link are determined. Then, all feasible paths are found using the proposed k-shortest path algorithm and for each possible path the marginal cost is estimated. Finally network-wide marginal cost of one additional unit of demand is calculated as the *weighted* average of marginal cost of all possible paths. It should be mentioned that in this methodology it is assumed that adding one unit of demand does not disturb the network equilibrium, thus the O-D demand increased by one unit is not reassigned to the network. Table 15 shows all the possible paths between O-D pair A-B, corresponding marginal cost of each path and the network wide marginal cost of additional trip.

**Table 15. Marginal cost of each trip, trip-based approach, Methodology B**

| Route | Links | Marginal Cost of Additional Trip ($MC_{2B}$) |
|---|---|---|
| 1 | 1,4 | $8.57/route |
| 2 | 3,2 | $8.57/route |
| 3 | 3,5,4 | $10.37/route |
| **Average MC/trip** | | **$9.89/trip** |

As shown in Table 15, when trip based approach is used to estimate the marginal cost of additional unit to the network and when all the possible paths are included in the estimation process, it is observed that the resulting marginal cost per trip is $9.89. If the marginal cost estimation is performed by considering only one shortest path, ignoring the other feasible paths, as done in the first phase of the project, the marginal cost of trip would be $8.57 which is lower than the actual marginal cost of the additional trip. These results indicate that since marginal cost is a function of many parameters other than travel time, ignoring alternative paths may result in the underestimation of the marginal costs. Moreover, when this methodology is compared with the distance-based approach, it can be observed that trip-based approach results in marginal cost values almost half of the distance-based approach for the total miles traveled in the network. This methodology provides marginal cost on a trip basis, whereas the distance-based approach provides marginal cost in terms of total miles traveled, which does not provide accurate information regarding the final output of the network, “trip”.

### 7.1.3. Trip-Based Marginal Cost Estimation, Methodology C

This section estimates the marginal cost of the entire network using methodology C of the trip-based approach. After assigning the O-D demand to the network, resulting travel times and link flows are used to calculate the total network cost of the original network. Then, the demand between the O-D pair A-B is increased by 90 units (1% of the original O-D demand), the increased demand is reassigned to the network, and total network costs of the modified network are calculated. Finally network-wide marginal cost of additional one unit demand is calculated as the difference between the before and after total costs divided by the additional demand. Table 16 shows the traffic flow, travel time, total cost of the original and the new network, and the corresponding marginal cost of trip.

**Table 16. Marginal cost of each trip, trip-based approach, Methodology C**

| Link No | Original Network | | | New Network | | |
|---|---|---|---|---|---|---|
| | Demand (veh/hr) | Travel Time (min) | Total Cost ($) | Demand (veh/hr) | Travel Time (min) | Total Cost ($) |
| 1 | 120 | 21.12 | 506.88 | 192 | 21.19 | 813.77 |
| 2 | 120 | 19.12 | 458.88 | 192 | 19.19 | 736.97 |
| 3 | 780 | 15.8 | 2464.8 | 798 | 15.98 | 2550.41 |
| 4 | 780 | 13.8 | 2152.8 | 798 | 13.98 | 2231.21 |
| 5 | 660 | 5.32 | 702.24 | 606 | 5.21 | 631.69 |
| | | | **Marginal Cost of the Network** | | **$7.54/trip** | |

As shown in Table 16, in Methodology C, as extra demand is added between the O-D pair A-B, the system is disturbed and the new network reaches a new equilibrium point. The marginal cost of an additional trip to the network based on the Methodology C is found to be $7.54 per trip. This estimated marginal cost is lower than the marginal cost estimated by link-based approach and the Methodology B of the trip based approach. However, it should be mentioned that in the distance-based approach and the Methodology B, the additional demand was 1 veh/hr, while in Methodology C the additional demand was 90 veh/hr (1% of the original demand). Since marginal cost is the cost imposed to the rest of the commuters imposed by the additional unit of demand, definition of demand "unit" is important. Therefore, comparing these methodologies may not be reasonable.

## 7.2. Application to Northern New Jersey Network

In this section different marginal cost estimation methodologies are applied to the North Jersey network. For illustration purposes two O-D pairs with different characteristics were considered in order to observe the change in the marginal costs among different trips. The first O-D trip is from New Brunswick to Princeton Junction in Central New Jersey. This is a relatively long trip through a very congested area. The second O-D pair selected is from Ocean County to Monmouth County. This is a shorter trip through a less congested area. Since Methodology C requires assignment of demand to the network before and after increasing the O-D demand, only Methodology A and Methodology B are compared for the NJ network. While estimating the cost functions the following cost categories are considered: (1) vehicle operating costs (VOC), (2) congestion costs (CC), (3) accident costs (AC), (4) air pollution costs (APC), (5) noise costs (NC), and (6) maintenance costs (maint). For illustration purposes, only the afternoon peak of the 2006 network is presented. The following sections provide the details of each cost category, required assumptions and cost estimation methodologies.

### 7.2.1. Cost Estimation for O-D Pair New Brunswick and Princeton:

***Methodology A:***

In this section, trip-based marginal cost from New Brunswick to Princeton is estimated using Methodology A. Figure 9 shows the shortest path between New Brunswick and Princeton during pm peak hours. As shown in Figure 9, the shortest path follows Route

1. The shortest path has 53.17 minutes of travel time, with 19.72 miles of distance, and 15,903 veh/hr of traffic volume.

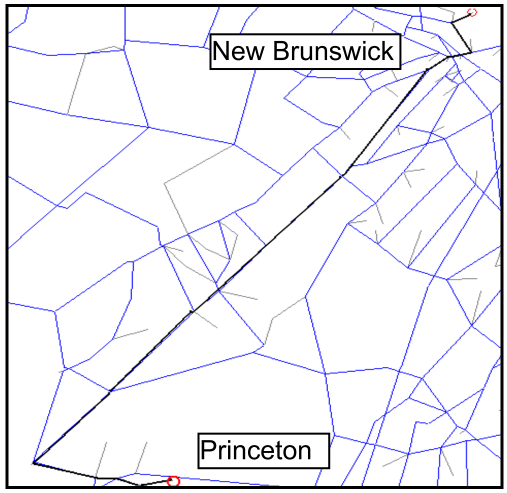


**Figure 9. Shortest path between New Brunswick and Princeton**

Table 17 provides marginal cost of trip for each cost category estimated from the shortest path between the selected O-D pair. The marginal cost of this particular trip is \$62.69/trip when queue costs are included, and \$17.24/trip when queue costs are excluded, indicating that most part of the marginal cost come from congestion and maintenance costs. On the other hand noise costs have no significant contribution to the marginal cost of the trip between New Brunswick and Princeton. The reason for very small noise costs could be due to the fact that the shortest path is very congested because of volumes exceeding the capacity. These high volumes result in very low speeds, which reduces the noise costs.

**Table 17. Marginal cost of each cost category – Methodology A**

| Cost Category | $MC_{opr}$ (\$/trip) | Congestion | | | $MC_{acc}$ (\$/trip) | $MC_{air}$ (\$/trip) | $MC_{noise}$ (\$/trip) | $MC_{maint}$ (\$/trip) | Sum (\$/trip) |
|---|---|---|---|---|---|---|---|---|---|
| | | $MC_{time}$ (\$/trip) | $MC_{ext}$ (\$/trip) | $MC_{queue}$ (\$/trip) | | | | | |
| **Marginal** | 2.87 | 7.79 | 5.42 | 45.45 | 0.69 | 0.45 | 0.006 | 0.011 | 62.69*<br>17.24** |

*: Marginal Queue Cost Included, **: Marginal Queue Cost Excluded

***Methodology B:***

In this section, trip-based marginal cost between New Brunswick and Princeton Junction is estimated using Methodology B. Table 18 provides the total travel time, distance, and total hourly volume observed at each shortest path. As shown in Table 18 travel time and distance values for each path are very close to each other; while total volume shows differences among different shortest paths.

**Table 18. Travel time and volume information for each path – Methodology B**

| Shortest Path | Travel time (min) | Distance (mile) | Volume (veh/hr) |
|---|---|---|---|
| **First** | 53.17 | 19.72 | 19,930 |
| **Second** | 54.3 | 21.61 | 33,061 |
| **Third** | 55.62 | 22 | 42,661 |
| **Fourth** | 55.87 | 20.88 | 24,711 |
| **Fifth** | 57.37 | 22.63 | 36,584 |
| **Sixth** | 58.11 | 20.71 | 21,953 |
| **Seventh** | 60.1 | 21.44 | 27,270 |

Figure 10 shows seven different used paths between New Brunswick and Princeton Junction during pm peak hours. The shortest paths mainly follow Route 1 and the NJ Turnpike. The only difference between different paths is the arterial roads used to connect to Route 1 or the NJ Turnpike. Table 19 shows the marginal cost of each path, as well as the average cost values. The results indicate that when costs are estimated considering seven different paths, trip-based marginal cost between the selected O-D pair is $66.98/trip when queue costs are included and $19.67/trip when queue costs are excluded. These findings show that marginal cost values between the selected O-D pair, show differences between different paths, and none of the cost category follows a particular pattern according to different paths. The reason behind different cost values for different paths may be due to the fact that shortest paths are determined only considering the travel times between O-D pairs. However, apart from travel time there are other path properties like volume, distance, road type, area type, and vehicle speed affecting the marginal cost between an O-D pair. Therefore, ignoring the other paths between the O-D pairs may result in under/over estimated cost values. Moreover, comparison of different cost categories show that for a congested area, the major part of the marginal cost comes from queue costs, followed time, operating, and accident costs.

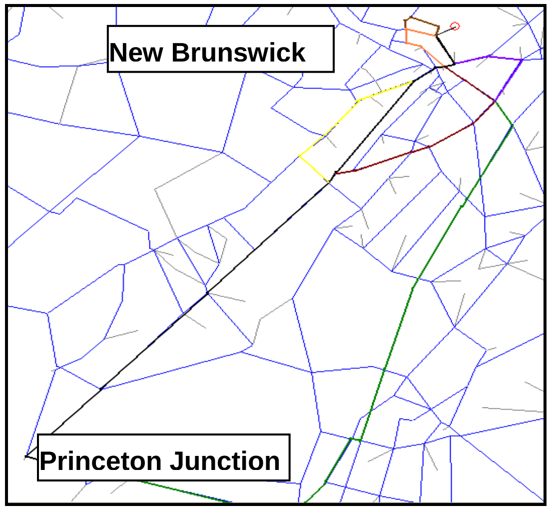


**Figure 10. K-shortest paths between New Brunswick and Princeton**

**Table 19. Marginal cost of each path – Methodology B**

| Cost Category | $MC_{opr}$ ($/trip) | Congestion | | | $MC_{acc}$ ($/trip) | $MC_{air}$ ($/trip) | $MC_{noise}$ ($/trip) | $MC_{maint}$ ($/trip | Sum ($/trip) |
|---|---|---|---|---|---|---|---|---|---|
| | | $MC_{time}$ ($/trip) | $MC_{ext}$ ($/trip) | $MC_{queue}$ ($/trip) | | | | | |
| **First** | 2.87 | 7.79 | 5.42 | 45.45 | 0.69 | 0.45 | 0.006 | 0.011 | 62.69*<br>17.24** |
| **Second** | 3.23 | 8.39 | 3.96 | 35.61 | 1.15 | 0.48 | 0.007 | 0.012 | 52.84*<br>17.23** |
| **Third** | 3.34 | 9.53 | 3.84 | 31.57 | 1.10 | 0.46 | 0.007 | 0.011 | 49.86*<br>18.28** |
| **Fourth** | 3.31 | 10.13 | 6.87 | 65.55 | 0.75 | 0.60 | 0.007 | 0.014 | 87.23*<br>21.68** |
| **Fifth** | 4.20 | 10.05 | 6.35 | 55.57 | 0.89 | 0.57 | 0.009 | 0.013 | 77.65*<br>22.08** |
| **Sixth** | 3.53 | 10.18 | 6.93 | 57.66 | 0.83 | 0.45 | 0.007 | 0.011 | 79.59*<br>21.93** |
| **Seventh** | 3.55 | 9.88 | 4.55 | 39.81 | 0.79 | 0.45 | 0.006 | 0.011 | 59.04*<br>19.24** |
| | | | | | **Weighted Average Marginal Cost** | | | | **66.98***<br>**19.67**** |

*: Marginal Queue Cost Included, **: Marginal Queue Cost Excluded

### 7.2.2. Cost Estimation for O-D Pair – Ocean-Monmouth Region:

***Methodology A:***

In this section, using Methodology A trip-based marginal cost from Ocean County to Monmouth County in the south is calculated. This trip is in a less congested area and a shorter trip. Figure 11 shows the shortest path from Ocean to Monmouth Counties during pm peak hours. The shortest path has 33.7 minutes of travel time, with 15.11 miles of distance, and 21,901 veh/hr of traffic volume.

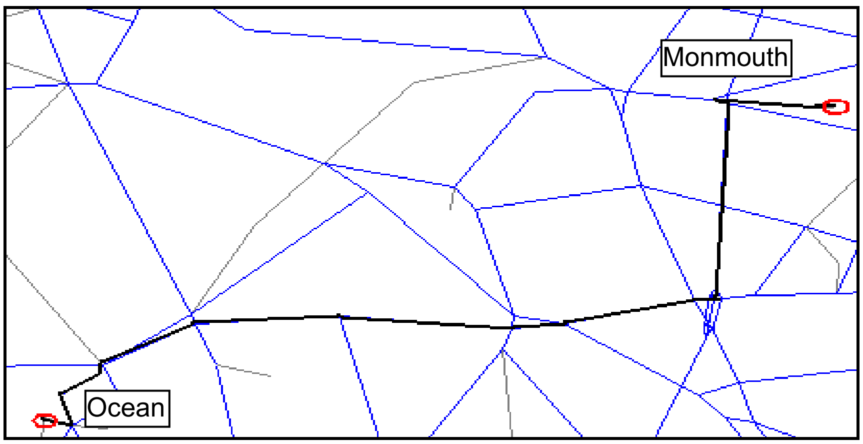


**Figure 11. Shortest path from Ocean to Monmouth**

Table 20 provides the trip-based marginal costs for each cost category estimated from the shortest path between the selected O-D pair. As can be seen from Table 20, marginal cost of one trip from Ocean County to Monmouth County is $8.27/trip. In addition, major portion of the cost values comes from congestion, maintenance and vehicle operating costs, followed by accident and air pollution costs. Noise costs have no significant contribution to the marginal cost of the trip between Ocean and Monmouth Counties. The reason for very small noise costs could be due to the fact that even though the selected trip is a shorter trip, the path is very congested and the traffic volumes are close to the road capacity. Therefore, these high volumes may have resulted in very low speeds, which reduce the noise costs.

**Table 20. Marginal cost of each cost category – Methodology A**

| Cost category | $MC_{opr}$ ($/trip) | Congestion | | | $MC_{acc}$ ($/trip) | $MC_{air}$ ($/trip) | $MC_{noise}$ ($/trip) | $MC_{maint}$ ($/trip | Sum ($/trip) |
|---|---|---|---|---|---|---|---|---|---|
| | | $MC_{time}$ ($/trip) | $MC_{ext}$ ($/trip) | $MC_{queue}$ ($/trip) | | | | | |
| **Marginal** | 2.54 | 4.66 | 0.26 | 0 | 0.54 | 0.26 | 0.0021 | 0.01 | 8.27 |

***Methodology B:***

In this section, trip-based marginal cost between Ocean and Monmouth Counties is estimated via Methodology B. Figure 12 shows seven different shortest paths between Ocean and Monmouth Counties during pm peak hours. As shown in Figure 12, the shortest paths mainly follow the first shortest path. Only fifth shortest path follows a different route. The only difference between the first four shortest paths is the arterial roads used to connect the first shortest path (black line). In addition, Table 21 provides the total travel time, distance, and total hourly volume observed at each shortest path. Travel time and distance values for each path are very close to each other except the fourth and fifth shortest paths; while total volume shows differences among different shortest paths.

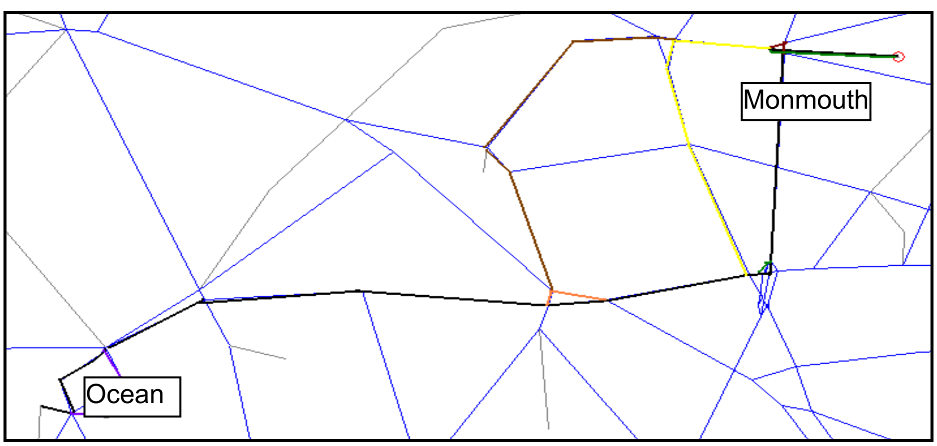


**Figure 12. K-shortest paths between Ocean and Monmouth**

**Table 21. Travel time and volume of each shortest path – Methodology B**

| Shortest Path | Travel Time (min) | Distance (mile) | Volume (veh/hr) |
|---|---|---|---|
| **First** | 33.7 | 15.11 | 21,901 |
| **Second** | 33.9 | 15.26 | 25,827 |
| **Third** | 34.16 | 15.22 | 19,387 |
| **Fourth** | 35.06 | 15.29 | 20,082 |
| **Fifth** | 35.13 | 25.44 | 20,114 |
| **Sixth** | 38.55 | 16.45 | 17,850 |
| **Seventh** | 42.45 | 15.67 | 11,530 |

Table 22 shows the trip-based marginal cost of each path, as well as the average cost values. When seven different paths are considered in the cost estimation; marginal cost of the trip increases to $10.32/trip. These findings show that similar to the first example, total marginal and average cost values between the selected O-D pair show differences between different paths, and none of the cost category follows a particular pattern according to different paths. Therefore, ignoring the other paths between the O-D pairs may result in under estimated cost values. Moreover, as seen from different cost categories, for an uncongested area, where there are no queue costs, the major portion of the marginal costs are shared by operating, time and accident costs.

**Table 22. Marginal cost of each path – Methodology B**

| Cost category | $MC_{opr}$ ($/trip) | *Congestion* | | | $MC_{acc}$ ($/trip) | $MC_{air}$ ($/trip) | $MC_{noise}$ ($/trip) | $MC_{maint}$ ($/trip | Sum ($/trip) |
|---|---|---|---|---|---|---|---|---|---|
| | | $MC_{time}$ ($/trip) | $MC_{ext}$ ($/trip) | $MC_{queue}$ ($/trip) | | | | | |
| **First** | 2.54 | 4.66 | 0.26 | 0 | 0.54 | 0.26 | 0.0021 | 0.01 | 8.27 |
| **Second** | 2.71 | 5.53 | 0.23 | 0 | 1.05 | 0.31 | 0.0021 | 0.01 | 9.85 |
| **Third** | 3.00 | 5.83 | 0.28 | 0 | 0.89 | 0.33 | 0.0022 | 0.007 | 10.34 |
| **Fourth** | 2.94 | 6.29 | 0.24 | 0 | 0.65 | 0.33 | 0.0021 | 0.008 | 10.46 |
| **Fifth** | 3.12 | 6.45 | 0.22 | 0 | 1.09 | 0.24 | 0.0010 | 0.01 | 11.13 |
| **Sixth** | 2.98 | 6.68 | 0.33 | 0 | 1.14 | 0.27 | 0.0014 | 0.009 | 11.41 |
| **Seventh** | 2.86 | 6.27 | 0.27 | 0 | 1.10 | 0.28 | 0.0016 | 0.01 | 10.79 |
| | | | | | **Weighted Average Marginal Cost** | | | | **$10.32 /trip** |

## 8. IMPACTS OF POLICY IMPLICATIONS ON TRIP-BASED FMC

When policy decisions, like capacity investments, are implemented on route sections, three different questions need to be answered:

1. What will be the changes in the O-D demand levels?
2. What will be the economic benefits realized due to the investment?
3. What will be the marginal/average trip cost between a given O-D pair before and after the improvements?

The impacts of capacity investments on a network can be categorized in three different ways: short-term impacts, mid-term impacts, and long-term impacts.

### 8.1. Short-Term Impacts

In the short run demand between O-D pairs can be assumed to remain unchanged. This fixed demand will be re-assigned onto the network to analyze the impact of improvements on the system. As shown in Figure 13, in the short-term demand function (D) remains the same, whereas supply function shifts from $S_1$ to $S_2$. Therefore, the new equilibrium becomes ($P_2$, $V_2$), i.e. volume increases and cost reduces.

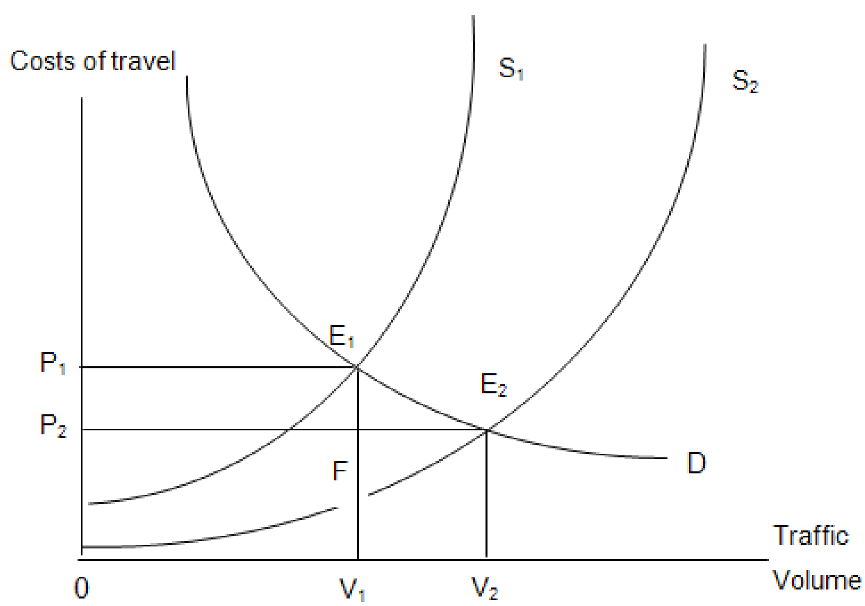


**Figure 13. Change in equilibrium travel cost and volume from capacity expansion**

## 8.2. Mid-Term Impacts

In the mid-term, travel demand between a given O-D pair changes as well. Some of these changes are *generative* (*induced traffic*) and some are *redistributive* (*diverted traffic*). Generative changes represent new travel that did not previously exist, including modal shifts. On the other hand, redistributive trips are route and schedule changes. These changes can be summarized as follows:

a. Shift to the improved route from alternative routes (redistributive)
b. Shift to the improved route from other modes (generative)
c. Shift to peak periods from peak shoulders (redistributive)
d. Some people who did not travel because of traffic conditions may start to travel (generative)
e. Trips made by carpool may be taken alone (generative)
f. Some people may opt to longer trips since the traffic flows smoothly (generative)

Induced traffic refers to all changes in trip making that are unleashed when a road is improved, not only newly added traffic but also trips diverted from other routes [(73,31)]. The induced travel hypothesis is grounded in economic theory and predicts that an increase in roadway supply reduces the time cost of travel, and thus (to the extent that demand is elastic) increases the quantity of travel demanded (or vehicle travel) [(74)]. The most common measure used in previous studies is the elasticity, the proportional change in one variable as a function of proportional change in the other variable. In case of road expansion, when a road capacity investment is implemented (supply change) travel times reduces (price) which results in an increase in the vehicle miles traveled (demand change). Then elasticity can be calculated as the ratio of the change in demand divided by the change in supply. This relationship between demand and supply can be summarized in Figure 14. When a capacity improvement occurs, supply function shifts to $S_2$ from $S_1$, and depending on the elasticity, demand function shifts to $D_2$ from $D_1$. Therefore, in the mid-term the new equilibrium is ($P_3$, $V_3$), i.e., volume increases and cost increases compared to the cost in the short-term equilibrium.

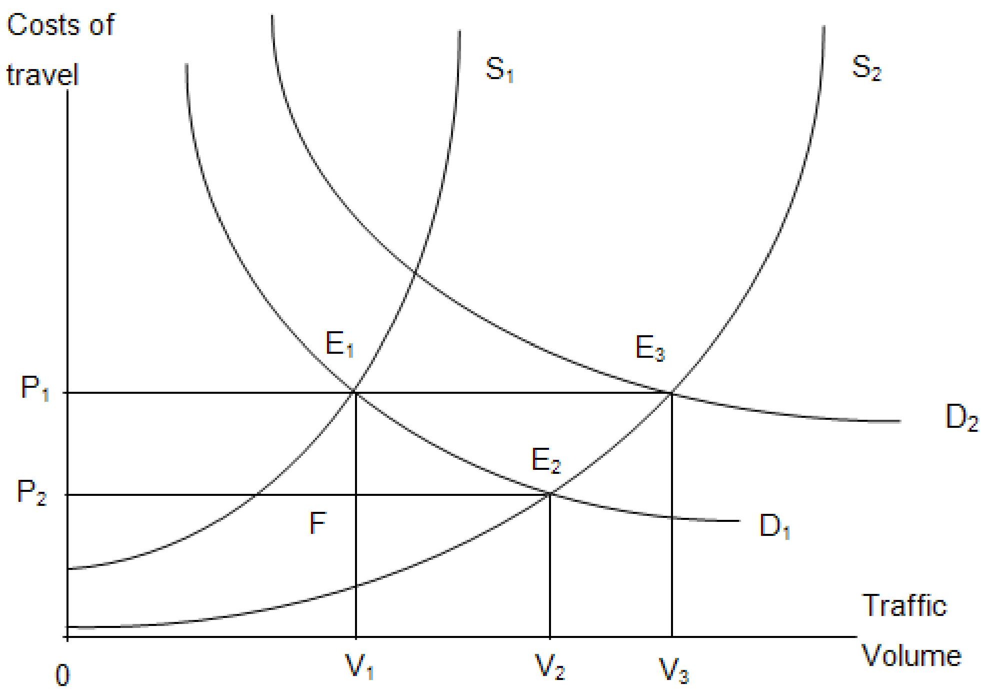


**Figure 14. Total shift in demand function from capacity expansion**

### 8.3. Long-Term Impacts

Long-term effects are related to how the land use patterns adjust to new capacity and the resulting spatial allocation of activities. If speeds are higher, many residences and businesses will tend to relocate over time often resulting in longer distance trips (75). Road improvements and the resulting smoother traffic flows spur building activities, like new housing, offices and retail stores near improved roadways. Since demand for transport is derived demand, depending on the location choice of firms and households, the shape and position of the demand function for transport will also change. Therefore, in the long-term, demand patterns between O-D pairs completely change based on the changes in the system due to land use changes.

## 9. SHORT-TERM IMPACTS OF POLICY IMPLICATIONS ON NORTHERN NEW JERSEY NETWORK

In this section, impacts of capacity investments on several route sections, namely NJ Route 18, NJ Route 17, NJ Route 3, and the Garden State Highway (GSP), are investigated, using the Northern New Jersey Travel Demand Model loaded network. For each of these highways, the capacity of the road sections with highest marginal cost values are improved by increasing the number of lanes (one lane in each direction is added to each road section). Then, using the same demand values the traffic assignment is performed in TP+ for the modified network, and the output obtained from TP+ is used for network comparison. In order to focus on multiple O-D pairs, TAZs around the improved road sections are selected and the changes in average marginal costs are calculated using the developed GIS-based tool. For each TAZ pair, 20 different O-D pairs are analyzed. Since analysis of mid-term and long term impacts requires new demand functions, only short term impacts are considered in this study.

Table 23 and Table 24 present the average marginal cost values for the original network, and the modified network, respectively. Table 25 and Table 26 show, respectively, the percent and absolute changes in each of the marginal cost categories after the capacity investment. Shaded cells in Table 25 and Table 26 refer to the cost categories which have increased or stayed the same after the capacity is improved. Table 25 shows the percent changes in the marginal costs for each cost category. The analysis results show that for all road section total marginal cost values have reduced after the capacity investment; while the highest reduction in marginal cost is observed at NJ Route 3, and the lowest reduction is observed at NJ Route 18 and GSP. The reason behind this fact could be due to several different factors. First of all, the queue congestion costs observed at NJ Route 18 is almost twice as large as the queue congestion costs observed at NJ Route 3, since the area around NJ Route 18 is much more congested than the area around other routes. Thus, only one lane increase may not be enough for NJ Route 18 to satisfy the excess demand in that region. Second, as observed from different paths calculated between different O-D pairs, after the network is improved, the increase in volume in NJ Route 18 is higher compared with the increase in volume in other routes, which resulted in overall higher volume compared with capacity investment.

The absolute and percentage changes in individual marginal cost categories after the capacity investment show that, for all road sections the highest reduction is observed in congestion related costs. This result indicates that after the network improvements, volume/capacity (v/c) ratio in these regions has been reduced to some extent which has decreased the travel times on these routes and congestion costs.

Overall, even though capacity investments can reduce the marginal cost of users, the amount of savings mainly depends on the characteristics of that region. Particularly, the amount of capacity investment highly depends on the amount of excessive demand that needs to be satisfied, and the reduced congestion delays. In general, the more congested a road, the more traffic is generated by increased demand. Increased capacity on highly congested urban roads generates considerable traffic due to high levels of latent demand [(76)]. Thus, if the road section to be improved is in a very congested area, capacity investments may result in overall higher usage of that road section which would not manage to reduce v/c ratios in that region. Since v/c ratio affects user costs nonlinearly, for the cases when v/c ratio is larger than 1, no significant reduction in cost of transportation would be observed.

## Table 23. Marginal cost values for the original networks

| Road | Period | $MC_{opr}$ ($/trip) | Congestion | | | $MC_{acc}$ ($/trip) | $MC_{air}$ ($/trip) | $MC_{noise}$ ($/trip) | $MC_{maint}$ ($/trip | Sum* ($/trip) | Sum** ($/trip) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $MC_{time}$ ($/trip) | $MC_{ext}$ ($/trip) | $MC_{queue}$ ($/trip) | | | | | | |
| SR 3 | a.m. | 0.96 | 3.52 | 1.94 | 36.20 | 0.33 | 0.42 | 0.005 | 0.05 | 7.23 | 43.43 |
| | p.m. | 0.97 | 3.57 | 1.09 | 24.81 | 0.37 | 0.39 | 0.004 | 0.05 | 6.44 | 31.25 |
| SR 17 | a.m. | 2.33 | 6.82 | 3.89 | 51.56 | 0.49 | 0.66 | 0.008 | 0.1 | 14.30 | 65.86 |
| | p.m. | 2.30 | 7.00 | 4.30 | 57.57 | 0.57 | 0.61 | 0.007 | 0.11 | 14.90 | 72.47 |
| SR 18 | a.m. | 1.97 | 7.45 | 9.39 | 61.76 | 0.69 | 0.46 | 0.01 | 0.1 | 20.07 | 81.83 |
| | p.m. | 1.92 | 7.09 | 5.22 | 41.95 | 0.75 | 0.41 | 0.008 | 0.09 | 15.49 | 57.44 |
| GSP | a.m. | 1.69 | 5.27 | 2.43 | 29.99 | 0.40 | 0.65 | 0.006 | 0.08 | 10.53 | 40.52 |
| | p.m. | 1.67 | 5.16 | 2.15 | 25.84 | 0.45 | 0.59 | 0.005 | 0.07 | 10.10 | 35.94 |

*: Marginal Queue Cost Included, **: Marginal Queue Cost Excluded

## Table 24. Marginal cost values for the modified networks

| Road | Period | $MC_{opr}$ ($/trip) | Congestion | | | $MC_{acc}$ ($/trip) | $MC_{air}$ ($/trip) | $MC_{noise}$ ($/trip) | $MC_{maint}$ ($/trip | Sum* ($/trip) | Sum** ($/trip) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $MC_{time}$ ($/trip) | $MC_{ext}$ ($/trip) | $MC_{queue}$ ($/trip) | | | | | | |
| SR 3 | a.m. | 0.93 | 3.21 | 1.89 | 27.75 | 0.29 | 0.39 | 0.003 | 0.04 | 6.75 | 34.50 |
| | p.m. | 0.97 | 3.36 | 0.90 | 16.69 | 0.37 | 0.36 | 0.003 | 0.04 | 6.00 | 22.69 |
| SR 17 | a.m. | 2.27 | 6.45 | 3.33 | 50.68 | 0.48 | 0.62 | 0.007 | 0.1 | 13.26 | 63.94 |
| | p.m. | 2.30 | 6.51 | 3.41 | 45.48 | 0.57 | 0.60 | 0.006 | 0.11 | 13.51 | 58.99 |
| SR 18 | a.m. | 1.90 | 7.09 | 7.38 | 57.01 | 0.66 | 0.45 | 0.01 | 0.08 | 17.57 | 74.58 |
| | p.m. | 1.82 | 6.42 | 4.56 | 40.19 | 0.73 | 0.39 | 0.007 | 0.08 | 14.01 | 54.20 |
| GSP | a.m. | 1.68 | 4.95 | 2.07 | 26.38 | 0.38 | 0.60 | 0.006 | 0.07 | 9.76 | 36.14 |
| | p.m. | 1.66 | 4.86 | 1.97 | 21.32 | 0.43 | 0.56 | 0.005 | 0.07 | 9.56 | 30.88 |

*: Marginal Queue Cost Included, **: Marginal Queue Cost Excluded

**Table 25. Percent changes in the marginal cost values**

| Road | Period | $MC_{opr}$ ($/trip) | Congestion $MC_{time}$ ($/trip) | Congestion $MC_{ext}$ ($/trip) | Congestion $MC_{queue}$ ($/trip) | $MC_{acc}$ ($/trip) | $MC_{air}$ ($/trip) | $MC_{noise}$ ($/trip) | $MC_{maint}$ ($/trip | Sum* ($/trip) | Sum** ($/trip) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SR 3 | a.m. | -3.12 | -8.81 | -2.58 | -23.34 | -12.12 | -7.14 | -40.00 | -20.00 | -6.53 | -20.55 |
| | p.m. | 0.00 | -5.88 | -17.43 | -32.73 | 0.00 | -7.69 | -25.00 | -20.00 | -6.84 | -27.39 |
| SR 17 | a.m. | -2.58 | -5.43 | -14.40 | -1.71 | -2.04 | -6.06 | -12.50 | 0.00 | -7.28 | -2.92 |
| | p.m. | 0.00 | -7.00 | -20.70 | -21.00 | 0.00 | -1.64 | -14.29 | 0.00 | -9.34 | -18.60 |
| SR 18 | a.m. | -3.55 | -4.83 | -21.41 | -7.69 | -4.35 | -2.17 | 0.00 | -20.00 | -12.46 | -8.86 |
| | p.m. | -5.21 | -9.45 | -12.64 | -4.20 | -2.67 | -4.88 | -12.50 | -11.11 | -9.56 | -5.64 |
| GSP | a.m. | -0.59 | -6.07 | -14.81 | -12.04 | -5.00 | -7.69 | 0.00 | -12.50 | -7.32 | -10.81 |
| | p.m. | -0.60 | -5.81 | -8.37 | -17.49 | -4.44 | -5.08 | 0.00 | 0.00 | -5.35 | -14.08 |

*: Marginal Queue Cost Included,  **: Marginal Queue Cost Excluded

**Table 26. Absolute changes in the marginal cost values**

| Road | Period | $MC_{opr}$ ($/trip) | Congestion $MC_{time}$ ($/trip) | Congestion $MC_{ext}$ ($/trip) | Congestion $MC_{queue}$ ($/trip) | $MC_{acc}$ ($/trip) | $MC_{air}$ ($/trip) | $MC_{noise}$ ($/trip) | $MC_{maint}$ ($/trip | Sum* ($/trip) | Sum** ($/trip) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| SR 3 | a.m. | -0.03 | -0.31 | -0.05 | -8.45 | -0.04 | -0.03 | -0.002 | -0.01 | -0.47 | -8.92 |
| | p.m. | 0.00 | -0.21 | -0.19 | -8.12 | 0.00 | -0.03 | -0.001 | -0.01 | -0.44 | -8.56 |
| SR 17 | a.m. | -0.06 | -0.37 | -0.56 | -0.88 | -0.01 | -0.04 | -0.001 | 0.00 | -1.04 | -1.92 |
| | p.m. | 0.00 | -0.49 | -0.89 | -12.09 | 0.00 | -0.01 | -0.001 | 0.00 | -1.39 | -13.48 |
| SR 18 | a.m. | -0.07 | -0.36 | -2.01 | -4.75 | -0.03 | -0.01 | 0.000 | -0.02 | -2.50 | -7.25 |
| | p.m. | -0.10 | -0.67 | -0.66 | -1.76 | -0.02 | -0.02 | -0.001 | -0.01 | -1.48 | -3.24 |
| GSP | a.m. | -0.01 | -0.32 | -0.36 | -3.61 | -0.02 | -0.05 | 0.000 | -0.01 | -0.77 | -4.38 |
| | p.m. | -0.01 | -0.30 | -0.18 | -4.52 | -0.02 | -0.03 | 0.000 | 0.00 | -0.54 | -5.06 |

*: Marginal Queue Cost Included,  **: Marginal Queue Cost Excluded

## 10. CONCLUSIONS AND DISCUSSIONS

This project has developed a state-of-the-art GIS-based interactive tool for calculating network-wide full marginal costs (FMC) of highway transportation in New Jersey. The new tool was then used to evaluate the short-term impacts and policy implications on the marginal costs of different trips. The primary focus of this final report is limited to short-term impacts, because the planning model that generated route traffic flows used in our study does not have a land use component that can capture longer-term changes in response to various network and policy changes. However, if route flows reflect this type of long-term changes then cost functions developed in this study will also reflect these long-term impacts. The approach used in this tool improves the state-of-the art in several ways:

1. In case of the FMC estimation, the smallest addition to a network is a trip, thus a trip should be considered as the basic decision making quantity, especially in the context of transportation planning [2, 45, 60]. To this extent, full cost estimation is trip based rather than distance based to realistically capture travelers' trip making decision process.
2. Unlike previous studies, the methodology presented here estimates trip based FMC by considering a set of feasible paths between each O-D pair. This approach enables the planners to realistically capture the effect of unit increase in demand. This is essential for accurately calculating network-wide marginal costs (Section 5.2).
3. With a novel multiple path generation algorithm, set of feasible paths used by various trip makers between the same O-D pair are recognized.
4. For each cost category (vehicle operating, congestion, accident, air pollution, noise and infrastructure costs), full cost functions that consider both *internal* and *external* costs are estimated using NJ specific data (Section 4).

The methodology presented in this study proposes a novel approach for calculating network-wide FMC of highway travel. Unlike previous studies, the methodology presented here estimates trip-based marginal costs, considering all feasible paths between each O-D pair. This approach enables transportation planners to realistically capture the effect of unit increase in demand. This is essential for accurately calculating network-wide marginal costs. The proposed methodology (Methodology B) is implemented in GIS using C programming language and Visual Basic for Applications (VBA), and calculates the FMC of a trip between a selected O-D pair. The proposed tool has several advantages. First, with the developed GIS-based tool, the origin and/or destination of a trip can be either single nodes; a set of nodes within each Traffic Analysis Zone (TAZ) or counties; or a set of randomly sampled nodes within the entire transportation network. This makes the proposed FMC estimation model a very useful tool for application in a real-world highway transportation improvement scenario. With the FMC estimation at the TAZ and county levels, the user can observe the changes in trip-based FMCs among different O-D pairs in a certain area. Moreover, the whole network selection helps the user to observe the distribution of trip-based FMC throughout the entire network. Second, the proposed tool, does not only estimate FMC between a selected O-D pair, but it can also compare two different networks, and estimate short-term impacts of network changes (lane and/or link additions, etc.) on the FMC of a trip (Section 6).

The illustration of the proposed FMC methodology on a sample network shows that the “traditional” distance-based approach overestimates the marginal cost of the network, and more importantly it provides marginal cost on the basis of distance rather than trip, which is the most basic way of considering travel behavior of drivers. Distance-based measures do not produce useful information regarding the network efficiency and the effectiveness of the transportation system [(2)], because they do not capture well-established basic mechanism of traveler decision making process (Section 7.1).

Results obtained from model application of the new tool on the Northern Jersey network demonstrate that FMC between an O-D pair exhibit differences among various paths that connect any single O-D pair. These results also demonstrate the importance of analyzing trips based on a number of factors in addition to travel times such as volume, capacity, road type, and distance (Section 7.2). Moreover, comparison of different cost categories show that for a congested area, the major part of the marginal cost comes from queue costs, followed time, operating, and accident costs. On the other hand, for an uncongested area, where there are no queue costs (volume < capacity), time, operating and accident costs constitute the major part of the FMC.

The analyses conducted to observe the short-term impacts of capacity improvement investments on several route sections (NJ Route 18, NJ Route 17, NJ Route 3, and the Garden State Parkway) demonstrate that even though capacity investments can reduce the marginal cost of users, amount of savings mainly depends on the characteristics of the region. Particularly, amount of capacity investment highly depends on the amount of excessive demand that needs to be satisfied, and the reduced congestion delays. In general, the more congested a road is, the more traffic is generated by increased demand. Increased capacity on highly congested urban roads attracts considerable traffic due to high levels of latent demand [(76)]. Thus, if a road section to be improved is in a very congested area, capacity investments may result in overall higher usage of this same road section which would not necessarily reduce v/c ratios in that region. Since v/c ratio affects user costs nonlinearly, for the cases when v/c ratio is larger than 1, significant reduction in transportation costs will not be obtained (Section 8).

The developed GIS-based tool will help transportation planners to estimate the changes in transportation costs due to a particular transportation demand management measure or supply change such as adding new lanes or improving existing lanes. This is a critical component of transportation planning, because demand patterns experience both spatial and temporal variations due to the changes in demand and supply, and an accurate cost estimation tool based on the new route flows will help planners to better quantify the effects of these variations and thus to better evaluate current and future transportation investment alternatives. Moreover, transportation planners will be able to study the changes in various components of marginal functions, namely operation, environmental, accident and others and evaluate various options based on the individual cost component of interest to them and the decision makers.

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## APPENDIX A – DERIVATION OF TRAVEL TIME DURING HYPER-CONGESTION

$$T(t) = \frac{L - J(t)}{V_1[Q(t)]} + \frac{J(t)}{V_2[C]} \qquad \text{(A. 1)}$$

$$T(t) = T_1(t,Q) + T_2(Q,C) \qquad \text{(A. 2)}$$

where;

$T(t)$ = Travel time (hr)

$T_1(t,Q)$= Regular travel time when capacity limit is not exceeded

$T_2(Q,C)$= Travel time spent at the physical queue when capacity limit is exceeded

$L$ =Roadway length (mile)

$J(t)$ = Length of the queue (mile)

$V_1[Q(t)]$ = Speed of the traffic for the congested conditions (mph)

$V_2[C]$ = Speed of the traffic for the hyper-congested conditions (mph)

$Q(t)$ = Flow rate (veh/hr)

$C$= Capacity of the bottleneck (veh/hr)

Suppose that $Q_J$ is the number of vehicles in the queue itself once it is encountered at time $t + T_1(t)$. Then, the formulation of $Q_J$ can be given as follows:

$$Q_J = Q - CT_1(t). \qquad \text{(A. 3)}$$

In the above equation, the first term on the right-hand side is the total volume entering to the roadway, whereas the second term refers to the vehicles that exited before the queue was formed.

By definition,

$$C = K_2.V_2(C) \qquad \text{(A. 4)}$$

$$C = \frac{Q_J}{J}.V_2(C) \qquad \text{(A. 5)}$$

Using equations A.4 and A.5, equation A.1 becomes:

$$T(t) = T_1 + \frac{Q_J.V_2[C]}{C.V_2[C]} \quad \text{(A. 6)}$$

$$T(t) = T_1 + \frac{(Q - CT_1)}{C} \quad \text{(A. 7)}$$

$$T(t) = \frac{Q}{C} \quad \text{(A. 8)}$$

For one hour queue duration, the time spent in the queue is:

$$T_2 = \frac{(Q - C)}{C} = \frac{Q}{C} - 1 \quad \text{(A. 9)}$$

## APPENDIX B – USER MANUAL FOR GIS-BASED FMC ESTIMATION TOOL

This manual intends to make a user familiar with the GIS-based Full Marginal Cost (FMC) Estimation tool, developed to estimate the FMC of highway transportation in New Jersey and to analyze of the developed cost models by applying them to Northern New Jersey network. In transportation, FMC measures the actual increase in costs due to an additional trip (mile) traveled. Hence FMC represents the additional costs that the State should consider to encourage efficient transportation use.

The methodology developed in this study estimates trip based FMC. This new approach considers a set of feasible paths between each O-D pair attractive to the users. The detailed description of the proposed methodology can be found in Section 5.2 of the report. This approach enables the planners to realistically capture the effect of unit increase in demand. This is essential accurately calculating network-wide marginal costs.

The GIS-based FMC estimation tool, implements the proposed methodology using C programming language and Visual Basic for Applications (VBA), and calculates the full marginal cost of a trip between a selected O-D pair. The proposed tool has several advantages as summarized below:

1. In the developed GIS-based tool, origin and/or destination of trip can be
    a. Manual Selection: Single node
    b. Manual Selection: User defined set of nodes within Traffic Analysis Zones (TAZ) (one TAZ for each origin and destination)
    c. County-to-County Selection: User defined set of nodes within a county (different county for each origin and destination)
    d. Intra-County Selection: User defined set of nodes within a county (same county for the origin and destination)

e. Network-wide Selection: User defined set of nodes within the whole network at hand

With the FMC estimation on TAZ and county level, the user can observe the changes in trip-based full marginal costs among different O-D pairs in a certain area. Moreover, the network-wide selection helps the user to observe the distribution of trip-based FMC throughout the entire network.

2. The proposed tool, not only estimates FMC between selected O-D pairs, but it also compares two different networks (before and after scenarios), and estimates the short term impacts of network changes (lane and/or link additions, etc. ) on the FMC of a trip.

The manual is divided into three parts. The first part describes the installation procedure and the necessary files for the program. The second and third parts help the user to get familiar with all the modules in the FMC estimation and impacts of policy implications sections of the program and how to use them.

## APPENDIX B.1 – INSTALLATION AND INITIALIZATION

### Required Software

ArcGIS, TP+, Viper

### Installation

Open the "GIS-based FMC estimation tool" located in the installation CD.

Copy the folder "NJ_FMC" under C Drive.

### Necessary Customizations in GIS for Manual Installation

1. The GIS software displays charts during the comparison analysis. Thus the required .ocx files should be registered. Simply follow the simple steps below

   a. Copy the files under SystemFiles folder to SYSTEM32 folder (located under C:\WINDOWS\ for Windows XP users, or located under C:\WINNT\ for Windows 2000 users).

   b. Open SYSTEM32 folder, hold down shift key and right click on one of the .ocx file (there are two of them MSCHART.OCX and MSCHRT20.OCX)

   c. Then click 'Open With…' from the menu

   d. From the opening 'Open With' dialog box, click the button 'Other…',

   e. Navigate to your windows\system32 directory and select the file 'RegSvr32.exe'. Do a file search for it if you have trouble locating the exact folder. On Windows 2000 it is typically located in c:\WINNT\System32. Click Open to select the file. Then click OK on the 'Open With' dialog.

   f. You should see a message indicating the file was successfully registered. If you see an error message, try restarting your computer and going through the above process again.

### Troubleshooting for both Manual and Automated Installation

Depending on the GIS version the user has, some errors may occur when the program starts. These errors are due to additional controls and references that are needed to be active for the FMC tool to run. The following steps focus on the error messages and the process to fix them.

The error messages that the user may get for missing controls and references are “cannot find the project” or “cannot find the library”. These error messages appear right after the user tries to run the FMC tool by clicking the  button.

Fixing the References:

1. Go to Tools → Macros→ Visual Basic Editor.
2. From the opening dialog box go to Tools → References
3. Navigate the opening window and make sure Microsoft Chart Control 6.0 (OLEDB), Microsoft Flexgrid Control 6.0 (SP3), Microsoft Scripting Runtime and MSFlexgrid objects are checked.
4. If any of these objects have “MISSING” sign in front of them, uncheck all the objects
5. Once the process is done click OK
6. Close the Visual Basic Editor dialog box to go to the main FMC tool window
7. Save the current version of the FMC Tool

Fixing the Controls:

1. Go to Tools → Macros→ Visual Basic Editor.
2. From the opening dialog box double click on any one of the User forms and activate it (as shown in Figure B. 1)
3. Go to Tools → Additional Controls
4. Navigate the opening window and make sure Microsoft Chart Control version 6.0, Microsoft DataGrid Control 6.0 (SP4), and Microsoft FlexGrid Control version 6.0 objects are checked.
5. Once the process is done click OK
6. Close the Visual Basic Editor dialog box to go to the main FMC tool window.
7. Save the current version of the FMC tool

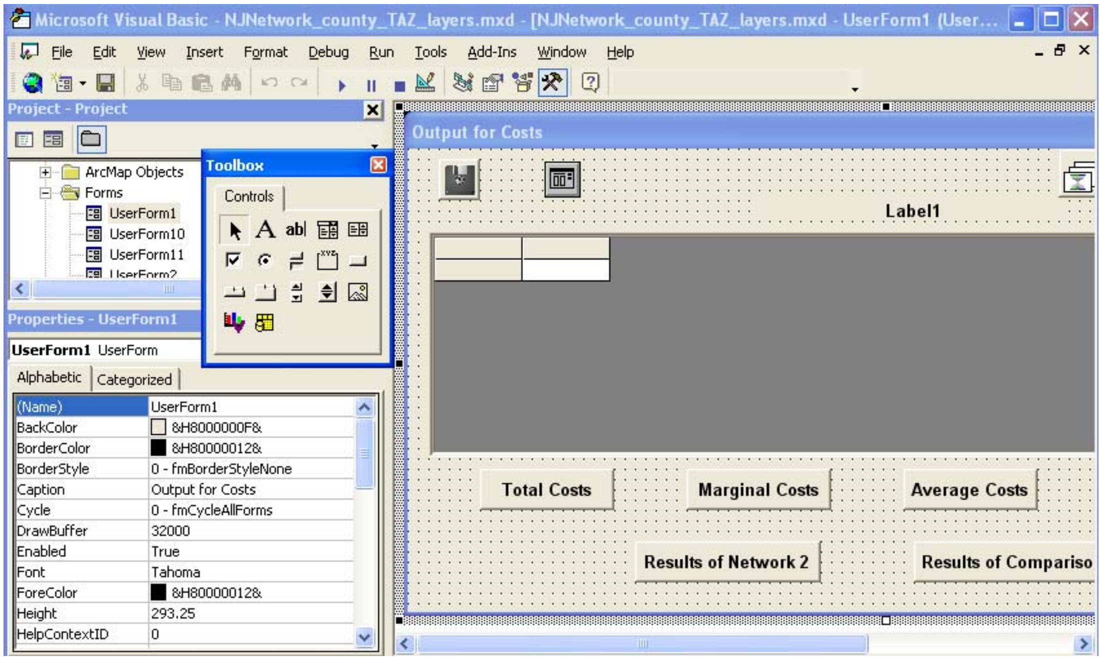



**Figure B. 1. Troubleshooting – User controls**

### Initialization

<u>Opening the Software</u>

1. Open the program “NJ_FMC_tool.mxd” under C:\NJ_FMC folder. (Figure B. 2). By default the program includes Zones layer (denoted by ZonesLayer), Traffic Analysis Zones layer (denoted by TAZ_NJRTM_Conf06data) and Highway layer (denoted by am_peak_2006).

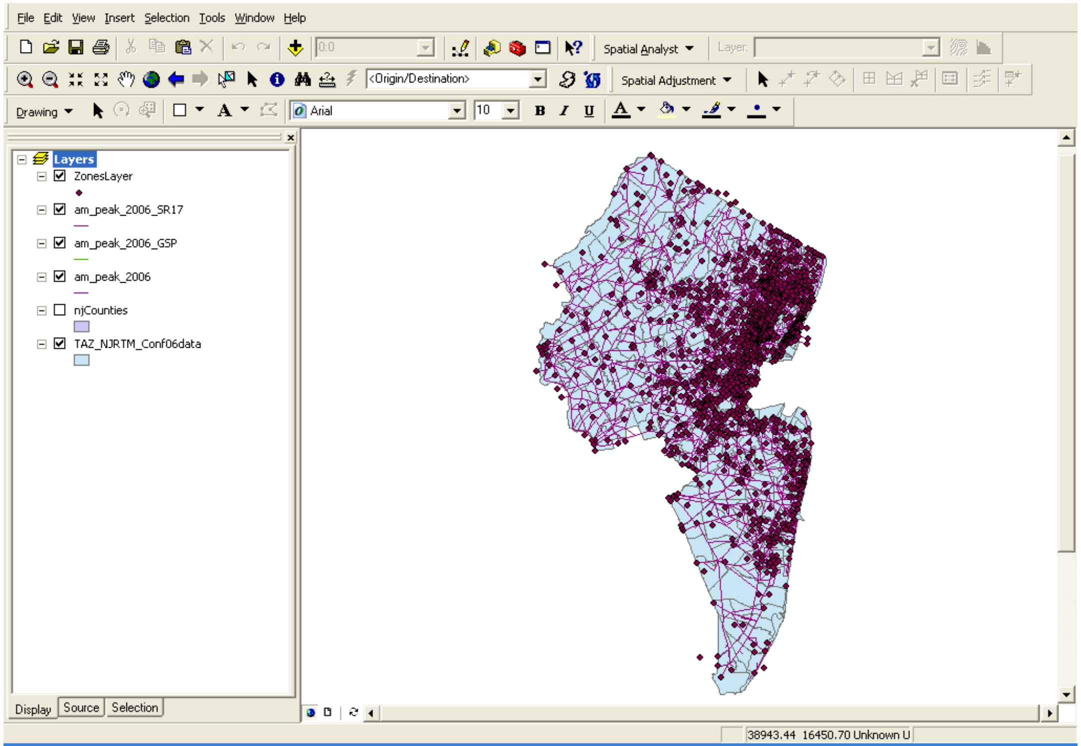



**Figure B. 2. Main window**

<u>Adding the Necessary Shape Files and Layers</u>

1. In order to conduct any analysis, the user should have the shape and data files required for the estimation process. These files can be obtained as follows.

   a. Open am peak, pm peak or offpeak loaded network obtained from TP+ program in Viper. (The extension of the loaded network is ".LOD")
   b. Go to Files → Export. Select "Shape Files (.shp)" from the opening window.
   c. Select a folder location for the output files to be saved (preferably the ShapeFiles folder under NJ_FMC directory)
   d. Give a name to the file which satisfies the following criteria: (1) am peak network name should start with "a", pm peak network name should start with "p", and offpeak network name should start with "o" (Recommended location for the shape files: C:\NJ_FMC\ShapeFiles)
   e. Click Save

Viper program automatically creates the shape files (name.shp) and data files (name.dbf) required for the FMC tool. (Figure B. 3)

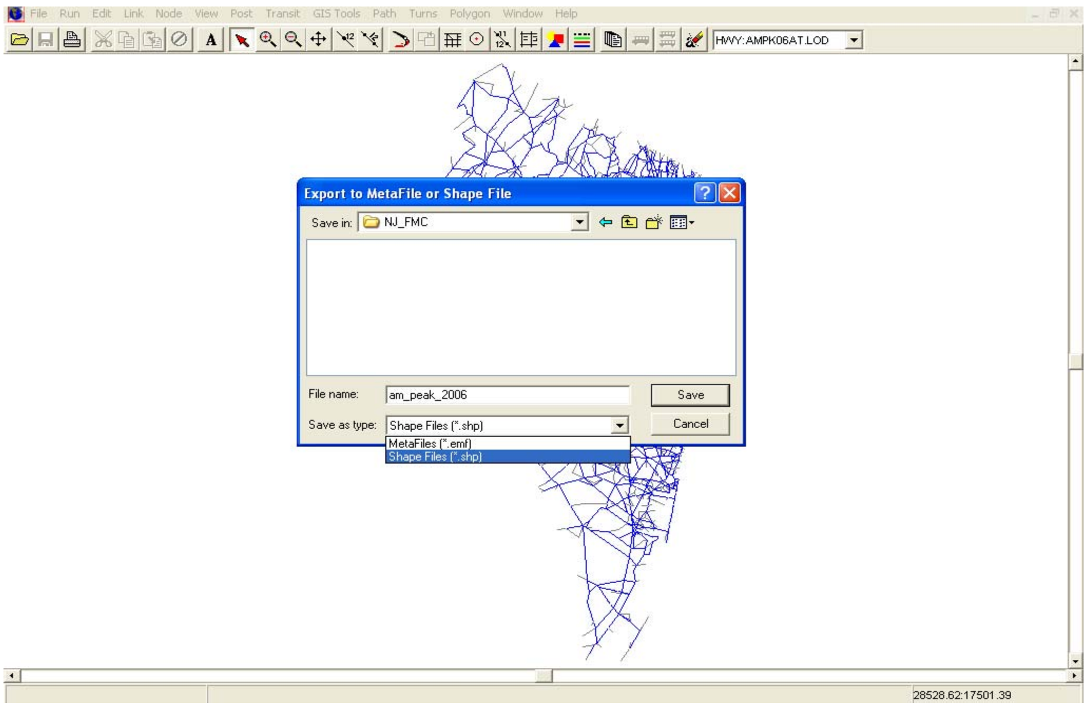



**Figure B. 3. File creation at Viper**

2. Copy the corresponding data file (name.dbf) located under ShapeFiles folder to the NJ_FMC folder
3. After creating the necessary files complete the following steps:
   a. Right click "Layers" from the window located at the left hand side of the NJ_FMC_tool (Figure B. 2)
   b. Select "Add Data…" option
   c. From the opening window go to the folder which has the shape files obtained from Viper. Select the name.shp file from the folder
   d. Click Add
   e. The corresponding layer will be shown under "Layers" window
4. Complete steps 1, 2 and 3 for each network to be analyzed.

For the convenience of the user, am peak, pm peak, and off-peak shape files for original networks (years 1996 and 2006) and for the modified networks (Route 3, Route 17, Route 18 and Garden State Parkway improvements) are created and saved under ShapeFiles folder.

## APPENDIX B.2 - FMC ESTIMATION

This section intends to make the user familiar with FMC estimation at different level of details as categorized below:

a. Manual Selection: Single O-D pair or Multiple O-D pair located in a Travel Analysis Zone (TAZ)
b. County-to-County: FMC estimation between different Counties
c. Intra-County: FMC estimation within a particular County
d. Network-wide: Network-wide FMC estimation considering the entire network at hand

In the following sections the steps required to complete each category is presented. Note that the shape file of the networks that is to be analyzed has to be present in the map document. If any of them is missing, an error message is given to the user, and the user is prompted to add the appropriate shape file.

### FMC Estimation Manual Selection:

1. Add the network to be analyzed by following Steps 2 and 3 of the Initialization section
2. Click  button located on the toolbar to start the FMC estimation
3. Select “Single Network Analysis”
4. Select the dbf file of the corresponding network from the browser by clicking 
5. Select Manual Selection
6. Click “Continue” to confirm (Figure B. 4)

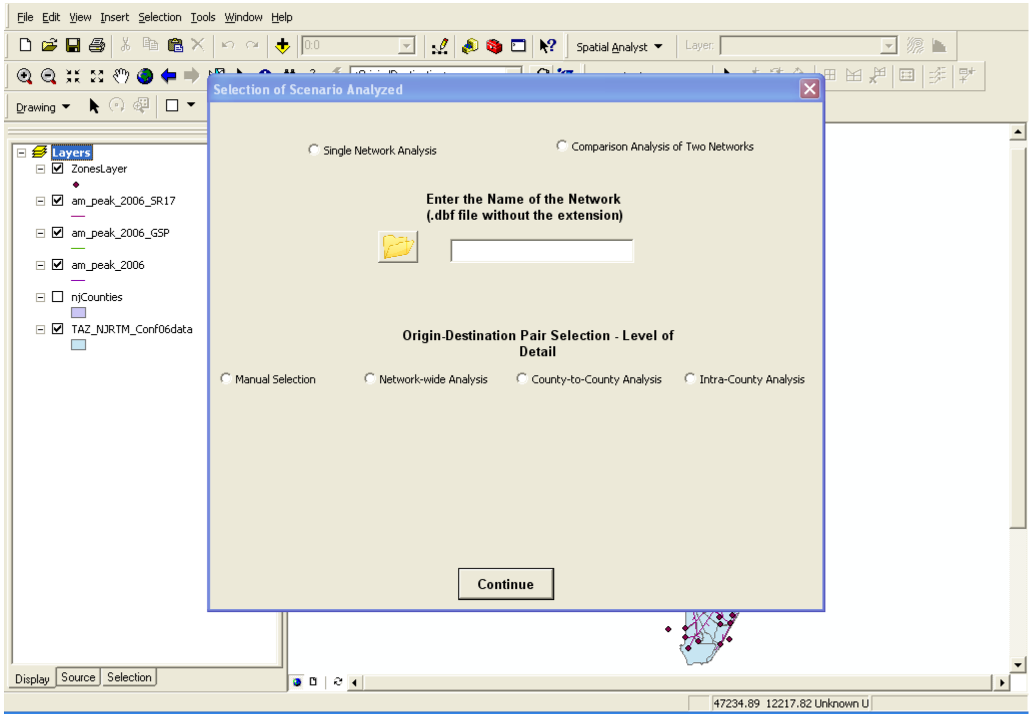



**Figure B. 4. FMC estimation - Manual selection**

7. Click OK to the opening window to start O-D selection
8. Click  button (this button allows you to select features from the map)
9. Origin selection
    a. If single node is to be selected click one node from the Zones layer. The selected node will be highlighted. If the multiple nodes are to be selected drag a rectangle around the area of interest with the help of the pointer
    b. Select “Origin” from the dropdown list located in the toolbar indicating that the selected node is the origin (Figure B. 5)
    c. Dehighlight the selection by clicking somewhere outside the map
10. Destination selection
    a. Complete task a of step 9
    b. Select “Destination” from the dropdown list located in the toolbar indicating that the selected node is the destination (Figure B. 6)
    c. Dehighlight the selection by clicking somewhere outside the map

11. If multiple O-D pairs have been selected specify the sample size from the opening window (how many O-D pairs will be analyzed) (Figure B. 7).
12. After the program finishes the result window automatically pops up (Figure B. 8).
13. To see the paths highlight the corresponding row from the results window
14. Click “Exit Application” to finish the analysis
15. Click  in the toolbar to clear all the highlighted paths.
16. The software automatically saves total, marginal and average costs, path information of each path (each k-shortest path for single O-D selection, and shortest path for multiple O-D selection case), and a final summary file of the estimation process. The final summary file includes the time that the FMC estimation is completed, name of the network, O-D selection type, and total, marginal and average cost tables of the corresponding network and O-D pairs. The corresponding text files can be found under (1) **single O-D pair**: NJ_FMC → single → NetworkName → OriginNo_DestinationNo (2) **multiple O-D pair**: NJ_FMC → multiple → NetworkName→ OriginZoneNo_DestinationZoneNo. The cost information is saved under names TotalCosts, MarginalCosts and AverageCosts for total, marginal and average cost results, respectively. The path information is saved under the same location and named as 1, 2, …These text files include the shortest path information of each origin destination pair for the multiple O-D selection case, and each k-shortest path information for the selected O-D pair (maximum of 7 different paths). The final summary file is saved under name final_NetworkName. For each run the output is also saved in folders under the ‘finalOutput’ folder. These folders are named in increasing order of the run number. Any missing folder in the sequence of run numbers is recreated as the latest folders. So, the final output of the latest run is in the last modified folder.

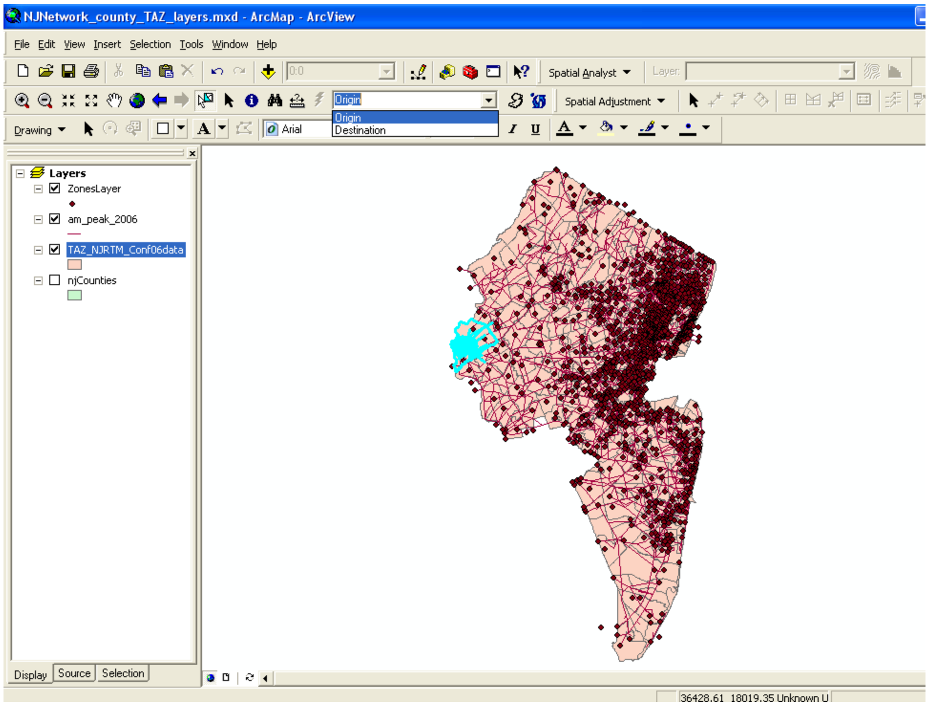



**Figure B. 5. FMC tool – Origin selection**

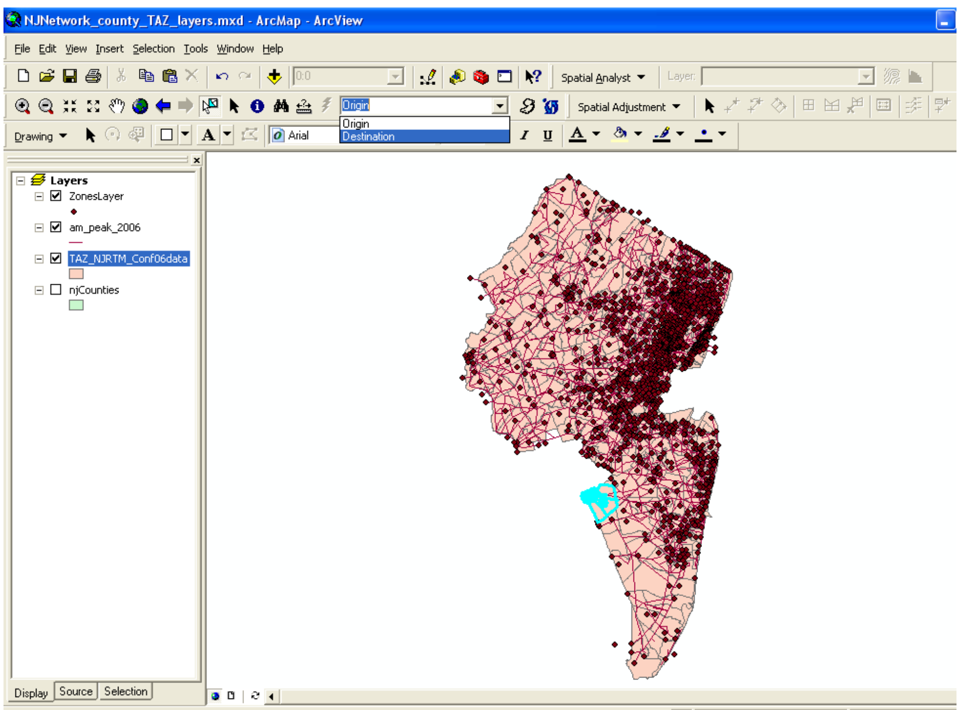



**Figure B. 6. FMC tool – Destination Selection**

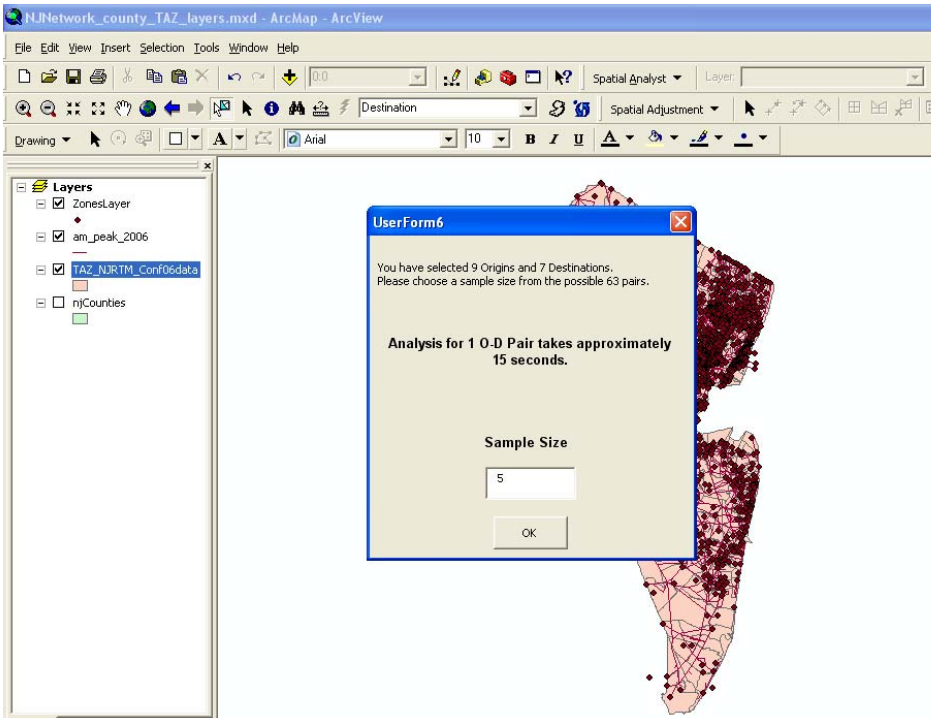



**Figure B. 7. O-D pair sample size selection**

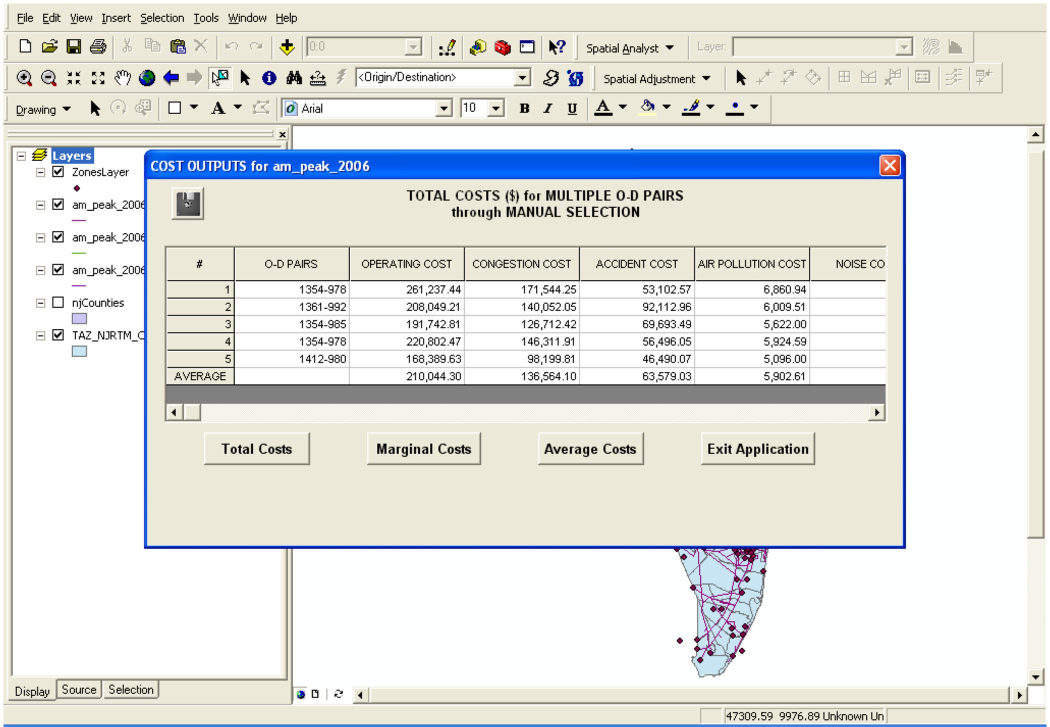



**Figure B. 8. FMC estimation results window**

**FMC Estimation County-to-County and Intra-County Selection:**

1. Add the network to be analyzed by following Step 2 and 3 of the Initialization section
2. Click  button located on the toolbar to start the FMC estimation
3. Select “Single Network Analysis”
4. Select the dbf file of the corresponding network from the browser by clicking 
5. Select County-to-County or Intra-County Selection
6. Select the name of the origin and destination counties from the dropdown list
7. Click “Continue” to confirm (Figure B. 9)

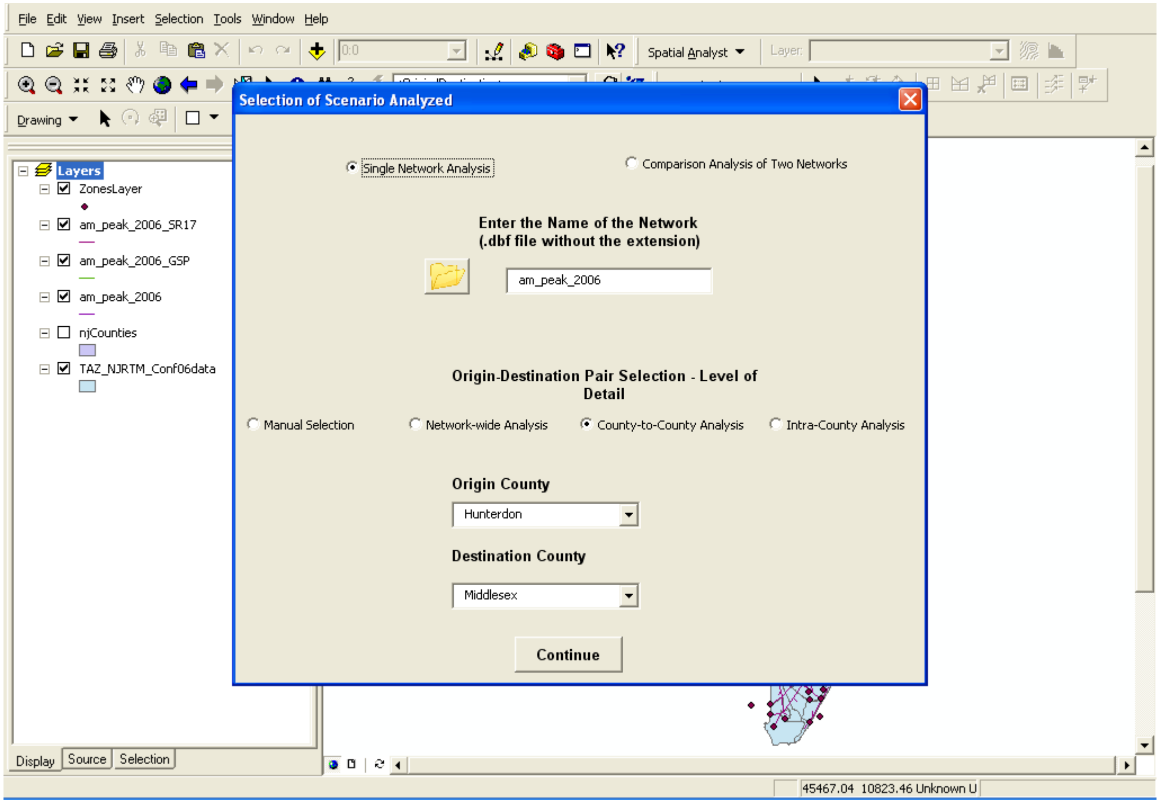



**Figure B. 9. FMC estimation county-to-county selection**

8. Specify the sample size from the opening window (how many O-D pairs will be analyzed) (Figure B. 7).
9. After the program finishes the result window automatically pops up (Figure B. 8).
10. To see the paths highlight the corresponding row from the results window
11. Click “Exit Application” to finish the analysis
12. Click  in the toolbar to clear all the highlighted paths.
13. The corresponding text files can be found under (1) **County to County analysis**: NJ_FMC → multiple → NetworkName → InterCounty → OriginCounty-DestinationCounty (2) **Intra-County analysis**: NJ_FMC → multiple → NetworkName → IntraCounty → CountyName. The file names for costs and paths are the same.

**FMC Estimation Network-wide Selection:**

1. Add the network to be analyzed by following Steps 2 and 3 of the initialization section
2. Click  button located on the toolbar to start the FMC estimation
3. Select “Single Network Analysis”
4. Select the dbf file of the corresponding network from the browser by clicking 
5. Select Network-wide Selection
6. Click “Continue” to confirm (Figure B. 10)

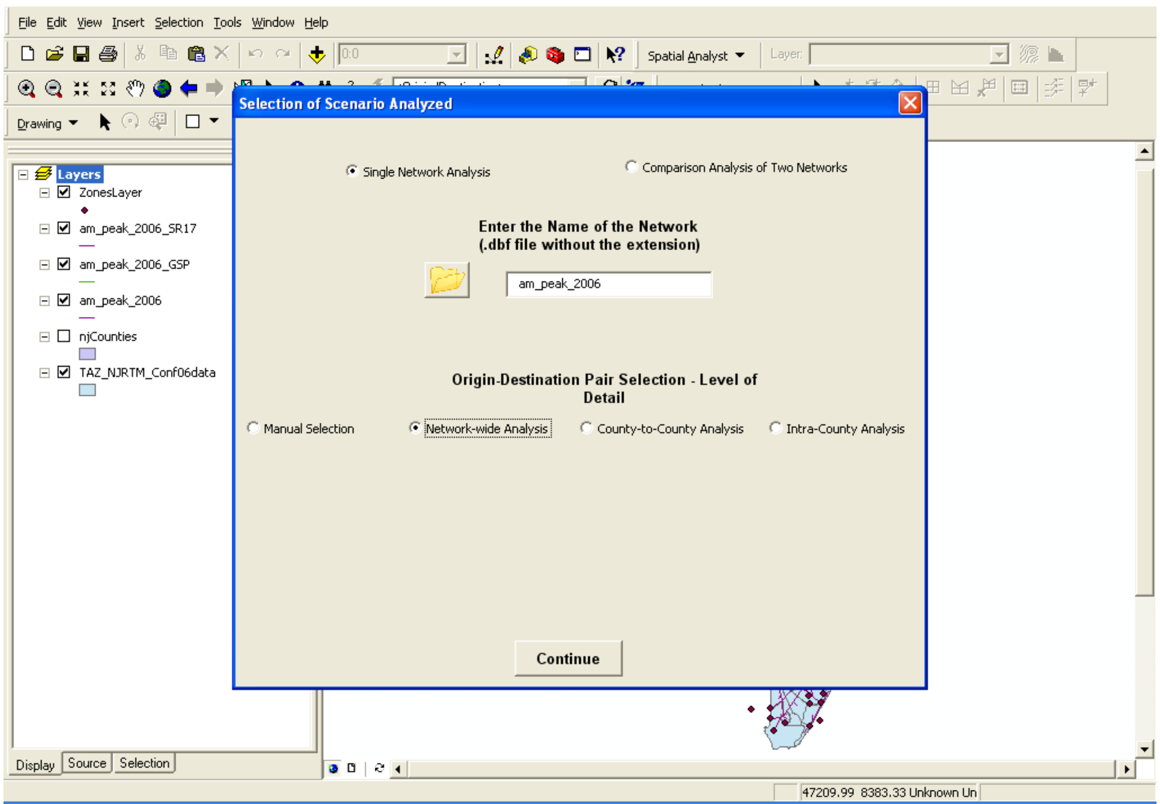



**Figure B. 10. FMC estimation network-wide selection**

7. Specify the sample size from the opening window (how many O-D pairs will be analyzed) (Figure B. 7).
8. After the program finishes the result window automatically pops up (Figure B. 8).
9. To see the paths highlight the corresponding row from the results window

10. Click "Exit Application" to finish the analysis
11. Click  in the toolbar to clear all the highlighted paths.
12. The corresponding text files can be found under NJ_FMC → multiple → NetworkName → Network. The file names for costs and paths are the same.

**PART C – IMPACTS ANALYSIS OF POLICY IMPLICATIONS**

This section intends to make the user familiar with estimation of the impacts of policy implications on the FMC of different trips at different level of details as categorized below:

a. Manual Selection - Single O-D pair or Multiple O-D pair located in a Travel Analysis Zone (TAZ)
b. County-to-County: FMC estimation between different Counties
c. Intra-County: FMC estimation within a particular County
d. Network-wide: Network-wide impact analysis considering the entire network at hand

In the following sections the steps required to complete each category is presented. Note that the shape files of both the networks that are to be compared have to be present in the map document. If any of them is missing, an error message is given to the user, and the user is prompted to add the appropriate shape file.

**Impact Analysis Manual Selection:**

1. Add the two networks to be analyzed and compared by following Step 2 and 3 of the Initialization section
2. Click  button located on the toolbar to start the impact analysis
3. Select "Comparison Analysis of Two Networks"
4. Select the dbf files of the corresponding networks from the browser by clicking 
5. Select Manual Selection

6. Click “Continue” to confirm (Figure B. 11)

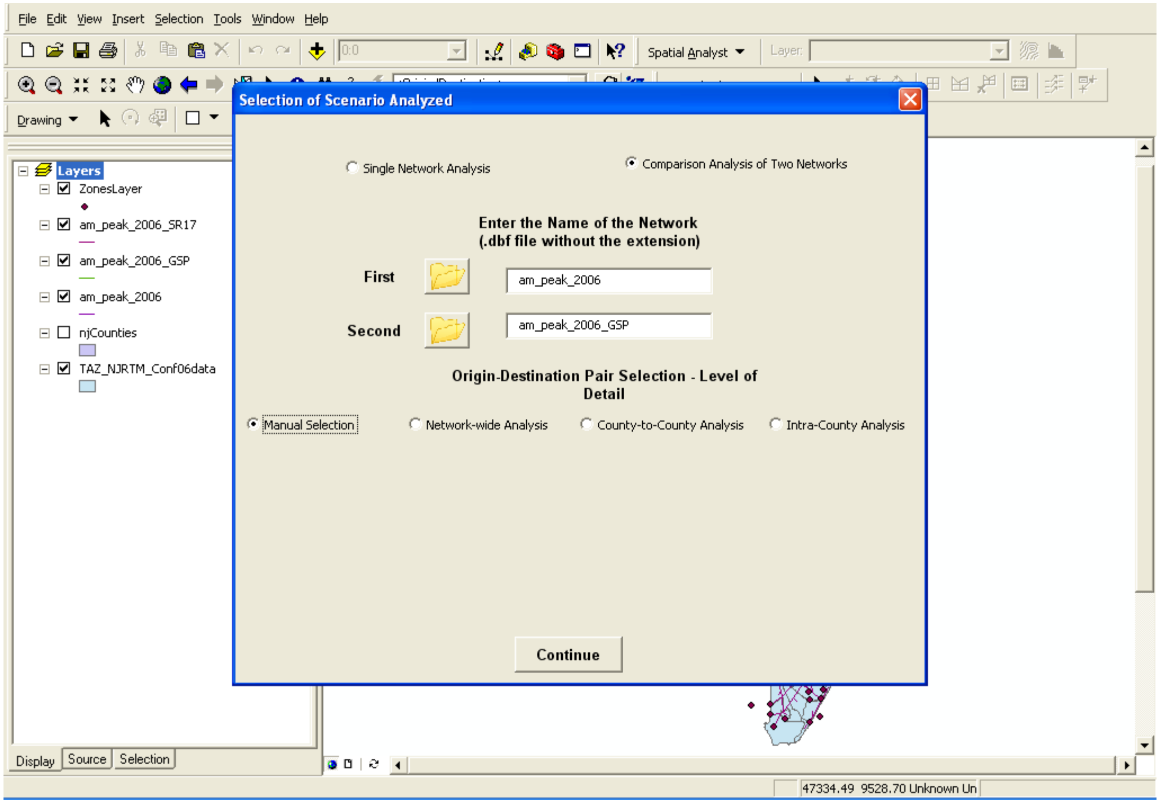



**Figure B. 11. Impact analysis manual selection**

7. Complete the Steps 7 – 11 of the “FMC Estimation Manual Selection” Section
8. After the program finishes the results of the original and modified network window automatically pops up (Figure B. 12). The user can observe the comparison results by clicking the “Results of the Comparison” button
9. The results for each network and comparison can be saved manually by clicking  from the results window.
10. To see the paths highlight the corresponding row from the results window
11. Click “Exit Application” to finish the analysis
12. Click  in the toolbar to clear all the highlighted paths.

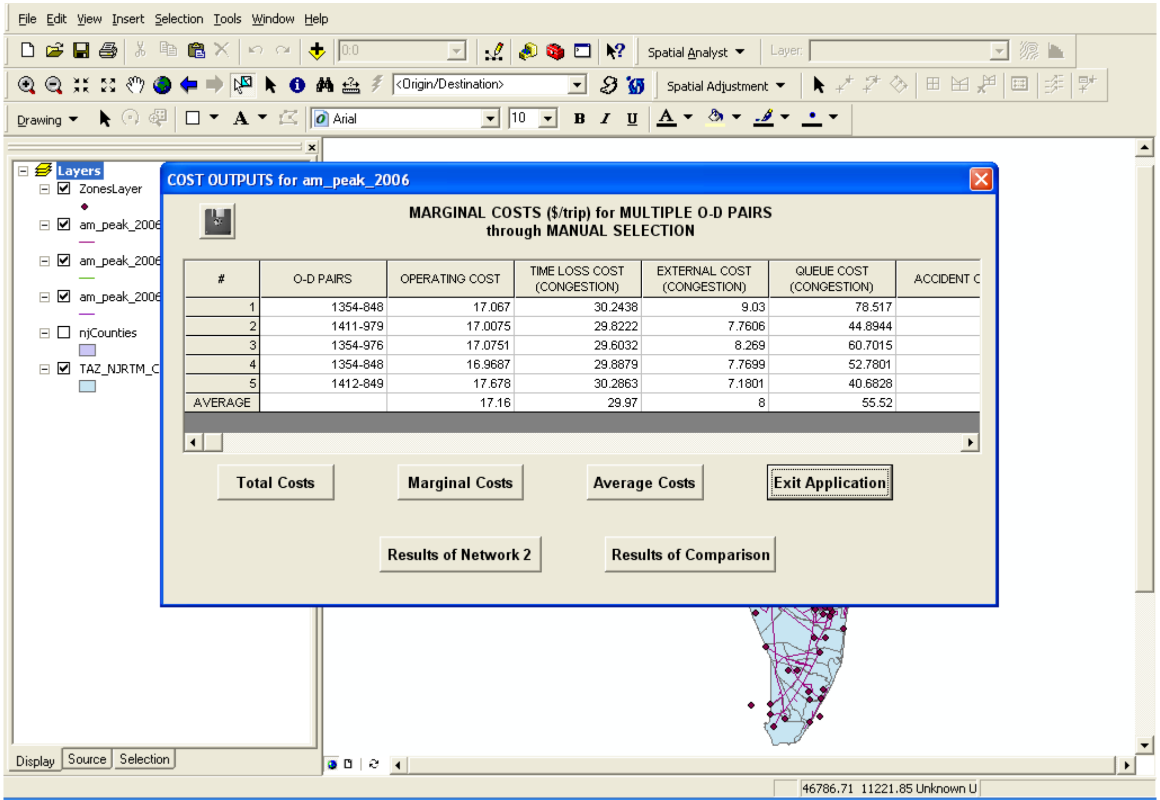



**Figure B. 12. Impact analysis results window**

**Impact Analysis County-to-County and Intra-County Selection:**

1. Add the networks to be analyzed and compared by following Step 2 and 3 of the initialization section
2. Click  button located on the toolbar to start the FMC estimation
3. Select “Comparison Analysis of Two Networks”
4. Select the dbf files of the corresponding networks from the browser by clicking 
5. Select County-to-County or Intra-County Selection
6. Select the name of the origin and destination counties from the dropdown list
7. Click “Continue” to confirm (Figure B. 13)

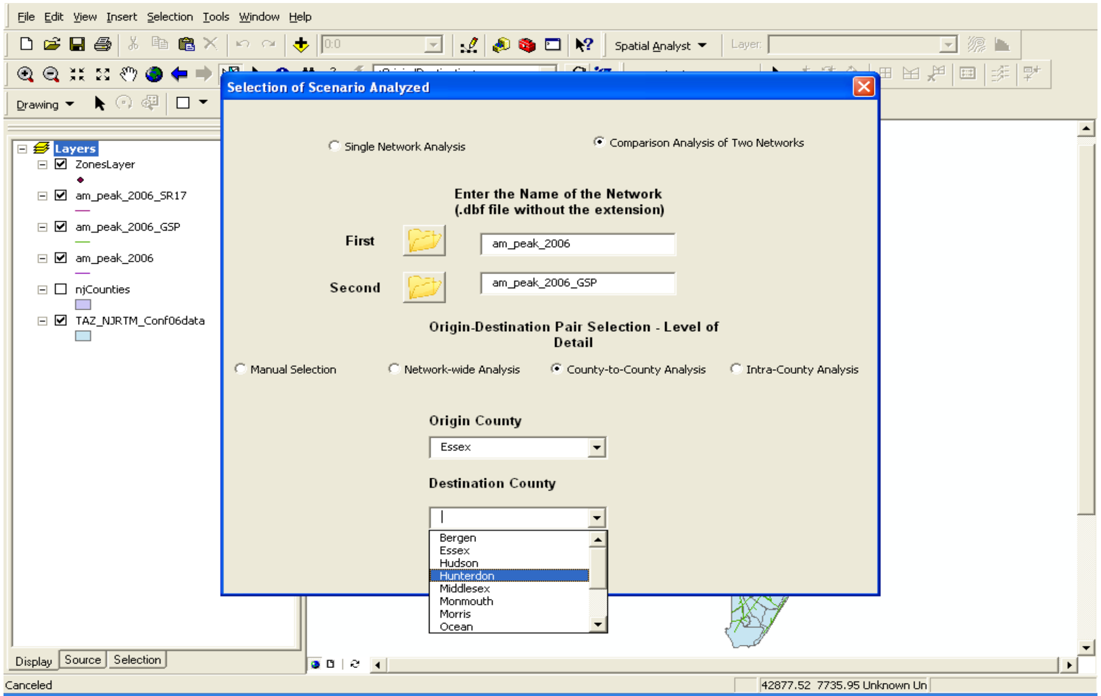
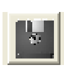



**Figure B. 13. Impact analysis county-to-county selection**

8. Specify the sample size from the opening window (how many O-D pairs will be analyzed) (Figure B. 7).
9. After the program finishes the result window automatically pops up (Figure B. 12).
10. The results for each network and comparison can be saved manually by clicking  from the results window.
11. To see the paths highlight the corresponding row from the results window
12. Click “Exit Application” to finish the analysis
13. Click  in the toolbar to clear all the highlighted paths.

**Impact Analysis Network-Wide Selection:**

1. Add the networks to be analyzed and compared by following Step 2 and 3 of the initialization section
2. Click  button located on the toolbar to start the FMC estimation

3. Select “Comparison Analysis of Two Networks”
4. Select the dbf files of the corresponding networks from the browser by clicking 
5. Select Network-wide Selection
6. Click “Continue” to confirm (Figure B. 14)

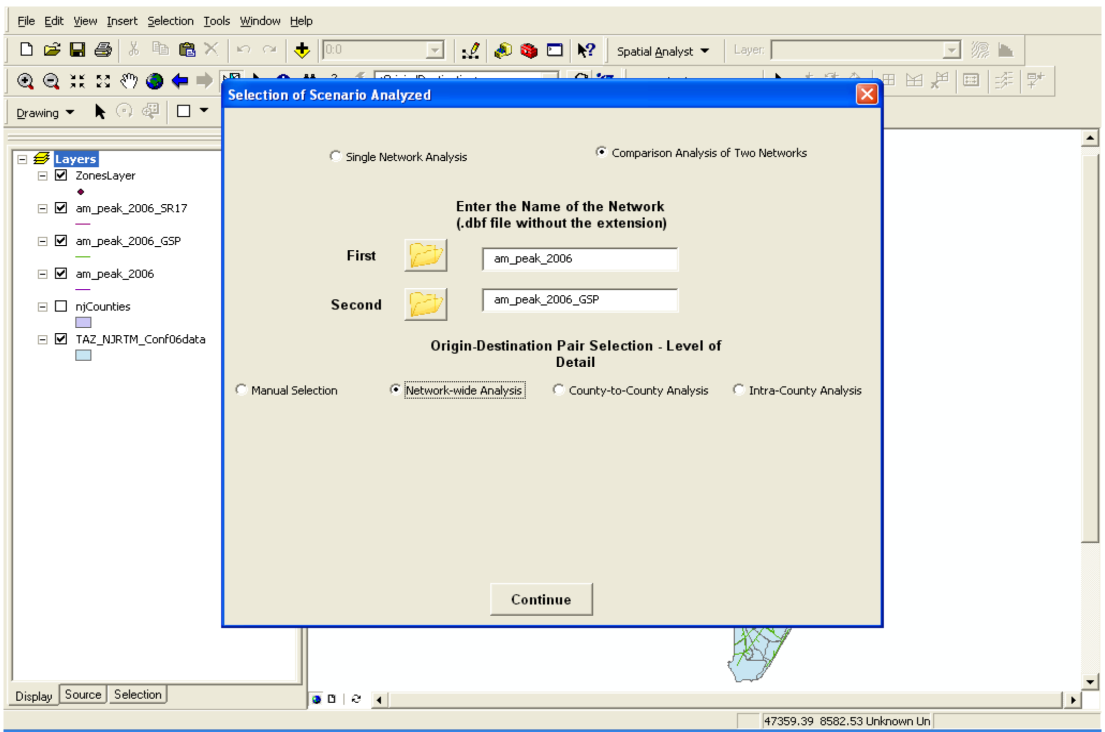



**Figure B. 14. Impact analysis network-wide selection**

7. Specify the sample size from the opening window (how many O-D pairs will be analyzed) (Figure B. 7).
8. After the program finishes the result window automatically pops up (Figure B. 8).
9. The results for each network and comparison can be saved manually by clicking  from the results window.
10. To see the paths highlight the corresponding row from the results window
11. Click “Exit Application” to finish the analysis
12. Click  in the toolbar to clear all the highlighted paths.