A Downtown Space Reservation System: Its Design and Evaluation

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(ABSTRACT)

This research explores the feasibility of providing innovative and effective solutions for traffic congestion. The design of reservation systems is being considered as an alternative and/or complementary travel demand management (TDM) strategy. A reservation indicates that a user will follow a booking procedure defined by the reservation system before traveling so as to obtain the right to access a facility or resource. In this research, the reservation system is introduced for a cordon-based downtown road network, hereafter called the Downtown Space Reservation System (DSRS). The research is executed in three steps. In the first step, the DSRS is developed using classic optimization techniques in conjunction with an artificial intelligence technology. The development of this system is the foundation of the entire research, and the second and third steps build upon it. In the second step, traffic simulation models are executed so as to assess the impact of the DSRS on a hypothetical transportation road network. A simulation model provides various transportation measures and helps the decision maker analyze the system from a transportation perspective. In this step, multiple simulation runs (demand scenarios) are conducted and performance insights are generated. However, additional performance measurement and system design issues need to be addressed beyond the simulation paradigm. First, it is not the absolute representation of performance that matters, but the concept of relative performance that is important. Moreover, a simulation does not directly demonstrate how key performance measures interact with each other, which is critical when trying to understand a system structure. To address these issues, in the third step, a comprehensive performance measurement framework has been applied. An analytical technique for measuring the relative efficiency of organizational units, or in this case, demand scenarios called network Data Envelopment Analysis (DEA), is used. The network model combines the perspectives of the transportation service provider, the user and the community, who are the major stakeholders in the transportation system. This framework enables the decision maker to gain an in-depth appreciation of the system design and performance measurement issues.

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Coming to the end of this journey has been the biggest achievement of my life so far. I have been imagining this day since the first day I started. At times, I felt that I would never arrive at the destination. Now, finally, I am proud that I have made it. Looking back, joy and excitement are mingled with confusion and frustration. Each day of this journey will be among the most valuable memories of my life.

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I would like to thank my parents, my husband, and my brothers for their unconditional love and support while I have been far away from them. Whatever I have achieved is theirs, and they are the most important part of my life.

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CHAPTER 1 Introduction

1.1 Problem Context

Congestion is permeating our daily lives. Transportation researchers and authorities alike are very concerned with the costs from congestion. Time that could be used in more productive and meaningful ways is wasted. Excess energy is consumed by automobiles waiting in line, exacerbating the global energy crisis. Millions of tons of carbon dioxide and other emissions are generated and released into the air. The adverse impacts of traffic congestion are magnified in urban metropolitan areas. From Austin-San Marcos, TX to Los Angeles-Orange County, CA to Washington-Baltimore, DC-MD-VA, all of these urban areas are suffering with the traffic congestion pandemic (Downs, 2004). The need for an antidote to congestion is increasingly evident as the problem grows worse.

Although transportation authorities and researchers have struggled with seeking new approaches that attempt meet the nation's demand for mobility, the problems associated with congestion have never lessened. In the beginning, transportation authorities and researchers emphasized solving congestion problems by building more roadways and bridges. Later, they began to realize that it is impractical, if not impossible, to infinitely accommodate travel needs, due to geographic, economic and environmental constraints. They agreed that travel demand has to be managed in order to induce people to use the existing infrastructure more efficiently. Thus, transportation researchers proposed Travel Demand Management (TDM) strategies.

An advantage of TDM is its ability to operate within the existing infrastructure. TDM uses a variety of mechanisms to consequently influence travel behavior. The altered travel behavior will reduce total travel demand, and existing road systems can provide a higher level of service. Popular TDM strategies include increasing vehicle occupancy through BRT (Bus Rapid Transit), carpool, HOV (High Occupancy Vehicle) and HOT (High Occupancy Toll) lanes. These approaches have encouraged many city authorities to actively promote public transportation in combination with other TDM strategies, such as congestion pricing and parking management. Transportation professionals also advocate strategies such as parking cash-outs (where employers are encouraged to give employees the cash equivalent of any parking subsidy),

pay-as-you-drive insurance, and park-and-ride facilities. (Victoria Transportation Policy Institute, Online TDM Encyclopedia, 2008). In addition, researchers are also actively working on new approaches to supplement and enrich the TDM field, including trip reservation systems and auction-based congestion pricing. In a trip reservation system, travelers must make reservations in advance to use existing transportation infrastructures, i.e., highways and urban streets. In the auction-based congestion pricing system, road users must submit bids with their preferred time slots for travel, and the auction determines the winners of the bids (Teodorović et al., 2006; Sheri Markose, 2006; Iwanowski, 2000, 2003).

Both transportation professionals and the public recognize the infeasibility of building more roads, but it is still difficult to get the public to accept many of the TDM strategies. TDM actions are hindered by many social, economic, and political obstacles. Acknowledging the merits and complications of TDM strategies, this research will further explore the trip reservation system for a downtown area, so called the downtown space reservation system, for the purpose of traffic congestion management

1.2 Research Assumptions and Questions

This research supports the concept of TDM by constructing an innovative TDM strategy framework. The research seeks to further the general TDM objective: maximizing the efficiency and utilization of existing transportation systems. The fundamental hypothesis of this research is that by reducing excessive travel demand (trips) when travel demand exceeds the transportation capacity will effectively mitigate traffic congestion. If the excessive demand only exists during peak periods, it can be shifted to non-peak periods, when the transportation resource is underutilized. If time and space shifts are not sufficient to reduce demand, it must be reduced either by requiring increased use of alternative travel modes that do not consume inadequate resources or by decreasing the number of trips. This would lead to a better utilization of existing road networks.

An important part of the reservation system as a TDM strategy is to clearly address a priority issue. In this research, the stated priority is to make the limited transportation resources available to more people, rather than more vehicles. As traffic congestion is a consequence of individual travel choices, in a TDM strategy individuals may need to compromise their preferences for specific transportation modes, such as private single-occupancy vehicles (SOVs)

and large-sized vehicles. This compromise can be offset by benefits: As some people give up driving alone and choose their secondary travel mode, more people may enjoy a better transportation experience, with shorter travel times and less polluted air.

This research focuses on surface transportation. We do not consider the effect of travel mode shift or other factors involving other transportation alternatives (such as underground transportation and light rail transit) on surface transportation. In practice, these non-surface transportation modes play an important role. For example, the availability of alternative modes of transportation can influence the use of surface transportation, and better service in underground transportation is likely to cause more people to give up driving. However, for simplicity, in this research we assume that the impact of these non-surface transportation systems on surface transportation is negligible. In other words, the alternative modes can accommodate the shift in demand with sufficient capacity. In addition, in this research the capacity of the surface transportation system in the studied areas is fixed, and physically expanding capacity in the short run is not feasible.

The research attempts to answer the following questions. Each of the questions will be addressed in a stand-alone essay.

(1)   How can one model and construct a reservation system that effectively reduces traffic congestion in a downtown city area?

As stated, none of the TDM strategies itself is a panacea for the congestion problem; a specific strategy may only fit in certain circumstances. For instance, cordon-based congestion pricing may work well in a downtown city like London, but it may not work in a location where congestion primarily involves a few arterials crossing the city. In order to make the TDM effective, a solution must be based on the exact congestion problem in a specific area. The purpose of this research is to address traffic congestion in a busy and crowded downtown area with a reservation system based on the unique attributes of the road network, the traffic composition, and travel behavior in such an area.

(2)   How would a downtown space reservation system impact traffic in the network?

TDM strategies generally will have great impact on peoples' travel behavior. The behavior changes will be manifested in their daily travel decisions, such as whether to travel, when to travel, and to which destinations. While travel behaviors associated with these decisions are eventually realized in an actual transportation road network, traffic flow associated with the changed travel patterns can only be seen after the trips are actually executed in a transportation network. However, at the time of devising a TDM strategy, it is not feasible to collect information or data from "the real world" so as to pursue an impact analysis. In addition, vehicles in a transportation network are not isolated. Instead, they interact with each other in many ways. Different drivers have different driving habits, and different vehicles have different mechanical characteristics. The synergic consequences of the interactions can hardly be analyzed with a traditional analytical approach. In this research, both of these difficulties are addressed through the use of a computer micro simulation. The simulation is used as an alternative modeling approach to represent a real-life situation in a hypothetical environment—to investigate how the traffic and network in a system will behave after the reservation system is introduced, and this is addressed in the second essay of this dissertation.

(3)   What are the appropriate methodologies to evaluate the impact of the reservation system on traffic and to measure system performance?

Once the reservation system is applied in a network, it takes effect over time and space. During this process, multiple stakeholders will be impacted by the system. To capture the multiple perspectives, a macro performance measurement framework is defined. The framework takes into account multiple perspectives concurrently, including users, transportation system providers, and communities. In addition, performance measurement typically requires an appropriate benchmark so that one can improve system performance by moving towards a performance target. The measurement technology used in this research– Data Envelopment Analysis (DEA) – is well known for its capability of providing an integrated relative system performance index. The index provides a valuable guidance on setting an appropriate performance target, and this is addressed in the third essay of this dissertation

1.3   Research Contributions

Many TDM strategies have been extensively tested in both academia and in practice. Practice indicates that a TDM strategy can be a viable solution for the traffic congestion problem

if used appropriately. For traffic congestion in a downtown area, the common congestion relief approaches are parking management, congestion pricing, and restriction rules. However, none of these approaches can provide a comprehensive management scheme for the whole area. Parking management and restriction rules may only have a limited effect. Congestion pricing, which has been implemented in cities such as London and Stockholm, shows significant results in reducing traffic congestion. However, in general, it is still hard to predict how the traffic is going to behave on a daily basis. Therefore, there is a need to devise an alternative TDM strategy, such as the downtown space reservation system, that takes this issue into account. With reservation information, planners can become aware of the particular travel demand for a day and the possible traffic situation in advance. Clearly, this strategy is not intended to be a complete substitute for any other TDM strategy. Rather, it is intended to expand the solution domain for traffic congestion in metropolitan areas. The research is an initial step in this direction.

The proposed method seeks to provide transportation engineers and policy makers with an alternative means to mitigate traffic congestion in a metropolitan city. There are still many related issues that need to be carefully examined before the concept can be put into practice, such as equity and public acceptance. It is not feasible to examine all of the problems in a single research effort, and the reservation concept as a possible effective TDM is still in its experimental stage for the moment. But ultimately, when the method has matured both in terms of its technical and social merits, it could serve as an effective strategy to mitigate traffic congestion in a downtown city area.

Additionally, the methodologies used in this research could also provide a framework for research for other TDM strategies. It uses a three step framework consisting of: analytical modeling, simulation modeling, and performance evaluation. The three steps are developed sequentially; each step has an independent focal point and is also related to each of the other steps. Overall, the methodology not only provides an approach to alleviate congestion problems, but also establishes a research framework for using various methodologies (analytical modeling, simulation, and performance measurement) in designing and evaluating TDM strategies. This general framework could be used for other TDM strategies, such as a congestion pricing system or intelligent parking management systems.

1.4 Organization of Dissertation

The dissertation has three main parts, each of which is written as a stand-alone essay. The first essay chiefly focuses on question (1). The second essay addresses question (2), and the third focuses on question (3). In the first essay, a TDM model is developed using classic optimization techniques in conjunction with an artificial intelligence technology. This is the groundwork of the entire research, and the second and third essays are built upon it. In the second essay, a traffic simulation is conducted to reveal the impact of the strategy on a hypothetical network. The simulation model is capable of providing desired measures in terms of different performance indexes that are commonly used in transportation research. However, the measures themselves are only numbers, of limited use. They become meaningful for real-life guidance if, and only if, people can generate the insights that are derived from interpreting the numbers, and if those insights are generated across multiple important transportation dimensions such as level of congestion, vehicle miles and/or person miles. For this purpose, a comprehensive macro performance measurement system (model) is introduced, and the outputs from the simulation are used to provide data for variables in the performance measurement model. This makes up the main body of the third essay. The structure of the dissertation is shown in Figure 1-1 below.
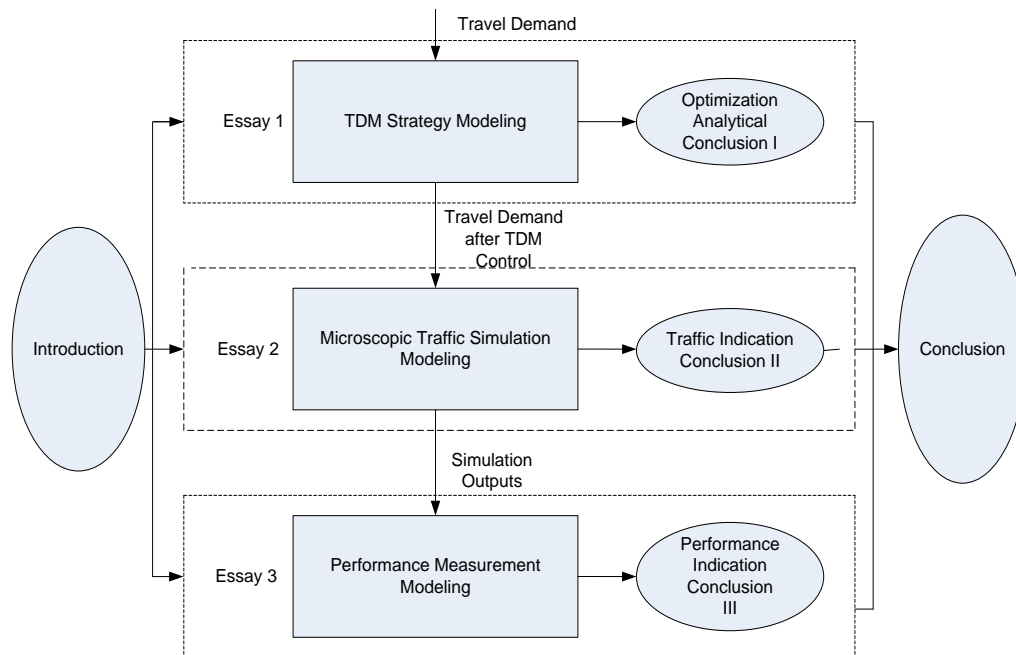
Figure 1-1 Dissertation Organization Structure

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Overall, the dissertation is organized as follows:

Chapter 2 will provide a review of literature that is related to the research but is not covered in the three essays. In Chapters 3, 4, 5, the first, the second and the third essay will be presented, respectively. In Chapter 6, the results of the three essays will be summarized and directions for future research will be provided. Programming codes that support each of the three essays and example simulation output files have been included as appendices at the end of this document. In addition, two published papers (one conference paper and one journal paper) that have been accomplished within this research and journal reviewers' comments associated with the first two essays that are currently under review are also included as Appendices.

CHAPTER 2 Literature Review

The literature review related to the research is divided into five categories, including: (1) an overview of TDM in practice and literature; (2) a basic introduction to artificial neural networks and their application in transportation; (3) a brief overview of traffic simulation models and software packages; (4) performance indicators commonly used in transportation performance measurement; and (5) an examination of Data Envelope Analysis and Network DEA and its application to transportation.

2.1 Travel Demand Management (TDM)

In this section, following a generic introduction to TDM, congestion pricing and highway booking experiences in both academia and practice are elaborated. This overview provides a theoretical basis for the DSRS. Finally, the extant methodologies for determining a road network capacity in traffic analysis will be introduced.

2.1.1 Travel Demand Management

Travel Demand Management is a broad concept. Any action or set of actions aimed at influencing people's travel behavior in such a way that alternative mobility options are taken and congestion is reduced can be referred to as TDM (Meyer 1999). According to Victoria Transportation Policy Institute (VTPI), TDM, also referred as mobility management, is a general term for various strategies that increase the efficiency of the existing transportation system (VTPI, Online TDM Encyclopedia, 2008). The original concept of TDM goes back to the 1970s and 1980s, when it was intended to provide alternatives to single-occupancy travel to save energy, improve air quality, and reduce peak period congestion (FHWA, 2004). In 1972, when the Urban Mass Transportation Administration established guidelines for the selection of capital projects, special attention was given to programs by which traffic congestion is reduced, including increasing vehicle occupancy by encouraging car pooling, reducing vehicle usage with pricing disincentives, encouraging transit riding, and banning private automobiles from sections of central business districts (CBD) during work days. Although they were not labeled as TDM policies at that time, the essence of TDM emerged naturally.

TDM focuses on improving the movement of people, rather than auto vehicles, and giving priority to more efficient modes of mobility, such as walking, cycling, ridesharing, public transit, and so on (Hattum, 2004). TDM strategies can be divided into four major categories, according to the way they affect travel: (1) *improved transportation options*; (2) *incentives to use alternative modes or reduce driving*; (3) *parking and land use management*; and (4) *policy and institutional reforms* (http://www.vtpi.org/tdm/tdm51.htm). Each category includes a variety of strategies, e.g., congestion pricing, parking cash-out, ridesharing, etc. A summary of the strategies is provided in Figure 2-1. Some of the strategies provide incentives to change trip scheduling, route, mode or destination. Others reduce the need for physical travel through land use management and telecommuting. Different objectives are achieved through the various TDM strategies, including congestion reduction, energy conservation, emissions reduction, health and fitness improvement, improved livability, and more affordable transportation. These strategies engender significant synergic impacts by shifting travel time, reducing vehicle travel, shifting modes, and increasing walking and cycling.
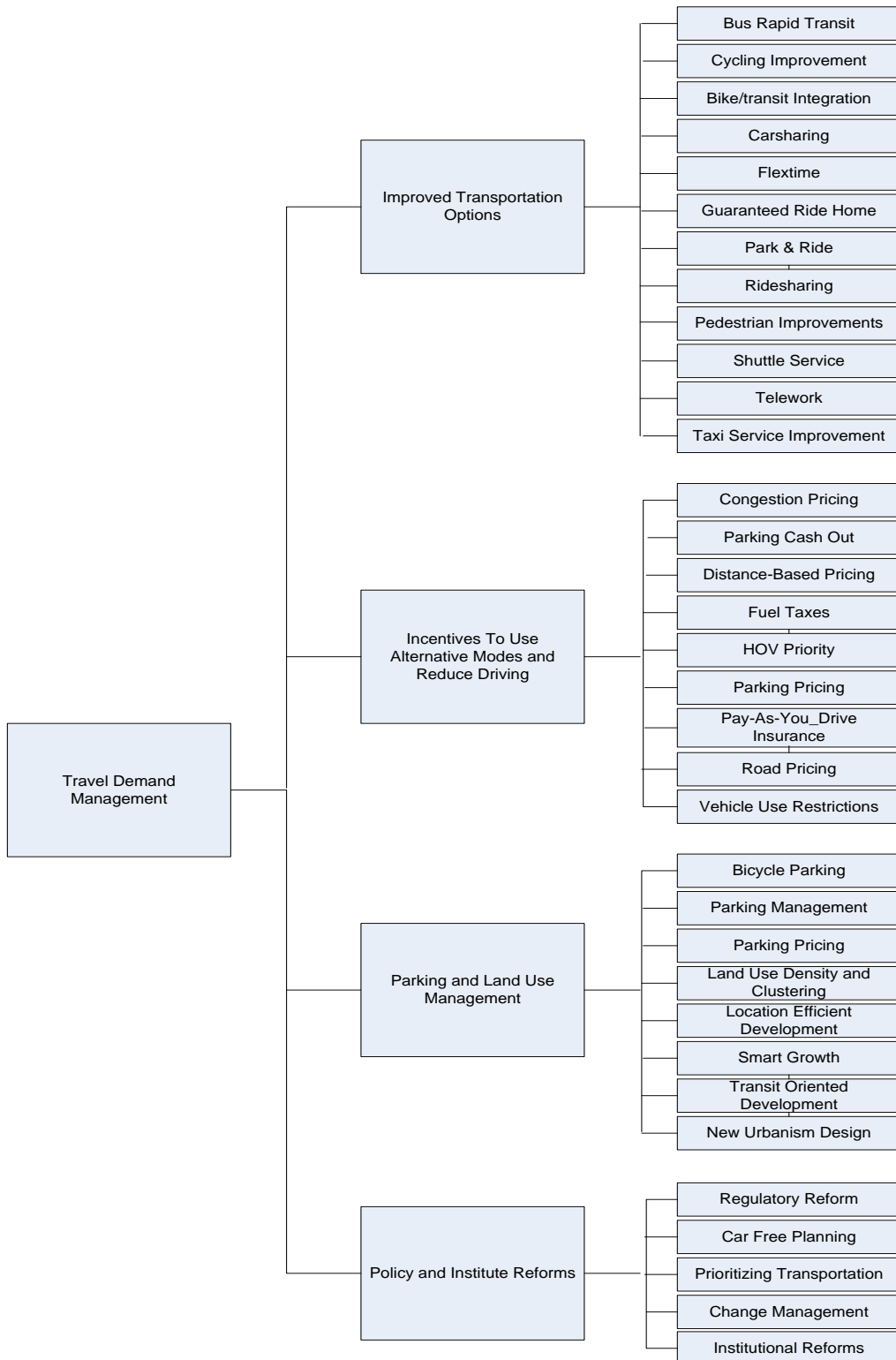
Figure 2-1 A Summary of TDM Strategies

2.1.2 Congestion Pricing

One of the most popular TDM strategies, which has been explored extensively in academia and in practice, is congestion pricing. It falls under the second category; nevertheless, strategies in support of the first category, such as significant improvement in public transit, are an indispensible and complementary part of a congestion pricing policy. Although pricing schemes for the DSRS will not be explored in this research, research associated with cordon-based congestion pricing provides a basic reference point for questions such as how the price could be set, what implementation barriers exist, and so forth.

Pigou (1920) and Knight (1924) are accredited with being the first to promote a pricing mechanism in congestion management. However, it is widely acknowledged that William Vickery was the father of congestion pricing. He proposed congestion pricing in the early 1950s for the New York City subway system. Later, he identified the potential for road pricing to influence people's travel behavior (Vickery 1955, 1963, 1969). Following the steadfast promotion of congestion pricing theory, severe traffic congestion problems have encouraged many economists and transportation researchers to develop models of optimal pricing and to evaluate the effects of various congestion pricing schemes (Verhoef 1999, 2000, 2002, 2003, 2005; Yang 1997).

Theoretical analyses of congestion pricing have been focused on the first-best strategy, in which all links in a network are charged. However, in practice, cordon-based congestion pricing, the so-called second-best pricing strategy, has been extensively explored. The second-best pricing policy aims at charging portion of links in the network, while the first-best strategies assume that marginal external cost[2] is charged on each link so that the optimal network traffic flow condition can be obtained. The perfect first-best marginal cost pricing policy is a construct of little practical interest or application. It is impractical to charge users on each network link, in view of a variety of technical, political, social, psychological and institutional obstacles (Verhoef 1999). Especially for a downtown network, the nature of network and congestion has limited researchers to the second-best strategies, such as cordon-based congestion pricing. While cordon

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[2] Marginal external cost is the cost a vehicle imposes on other motorists, including congestion, environmental effects, noise annoyance, and accidents.

tolls are less optimal than first-best pricing tolls, they are relatively straightforward for drivers and generally easier to implement administratively.

Studies of cordon-based congestion pricing have been conducted by many researchers from different perspectives. Two major areas have been explored, cordon design and pricing, which are also applicable for the DSRS. May (2002) evaluated the impact of cordon design on the performance of cordon-based pricing in terms of economic efficiency (measured in revenue) and environmental impacts. With a set of tests, it was demonstrated that performance critically relies on the cordon locations. Zhang and Yang (2004) investigated a method to determine the optimal selection of both toll levels and toll locations in cordon-based congestion pricing using graph theory. Wong and his colleagues (2005) formulated user-optimal travel behavior (route choice) to a central business district (CBD) with and without toll pricing. Their model and representation allow for easier selection of one or multiple toll cordon(s) in the city and a better evaluation of the user benefits of cordon tolls, as well as their impact on social welfare. Sumalee (2005) developed a Genetic Algorithm-based methodology to identify the optimal toll level and cordon location. While this research mainly focused on the mathematical problem of obtaining optimal toll levels and toll locations, Mun (2003) investigated the different effects of cordon pricing on the spatial patterns of trip-making and traffic congestion in varied locations. Akiyama et al. (2004) examined the effects of cordon pricing and its alternatives. Both of the papers suggested that cordon pricing behaved well from an economic welfare point of view. The body of the literature suggests that cordon-based pricing as a second-best strategy is preferred from a practical perspective, while first-best pricing still constitutes a helpful point of reference as an upper bound, despite being purely theoretical.

In addition to the theoretical work, two prominent practical examples of congestion pricing exist in London and Stockholm. Since February 2003, the City of London has charged a fee for driving private automobiles in its central area during weekdays as a way to reduce traffic congestion and raise revenue to fund transportation improvements (Transport for London, http://www.tfl.gov.uk/roadusers/congestioncharging/). This has significantly reduced traffic congestion, improved bus and taxi service, and generated substantial public revenues. Public acceptance has grown, and as a consequence this policy may be expanded to other parts of London and other cities in the U.K. This initiative has been widely acknowledged as a success of

TDM in practice (Litman, 2006b). More recently, in 2006, Stockholm put into place a seven-month congestion-charging trial in the central area of the city. The results of the trial revealed that vehicle traffic declined more than expected in relation to the traffic goals of the congestion tax. The number of vehicles passing through the charging cordon area during the morning and afternoon/evening peak periods was significantly reduced. A direct consequence of the declining traffic was improved accessibility to the downtown area and more efficient public transit service (Hugosson and Sjöberg, 2006). The public became more positive as they experienced the trial, and in a referendum at its conclusion, the residents of Stockholm municipality voted to implement congestion pricing permanently (Swedish Road Administration, http://www.vv.se/).

Many other cities have been working on developing and analyzing a range of potential congestion solutions. In May 2004, the mayor of Washington, D.C. launched the Mayor's Downtown Congestion Task Force with Council members and members of the business community, Advisory Neighborhood Commissions, business improvement districts and relevant city agencies. The Downtown Congestion Management Task Force was convened to consider the problems of congestion in the downtown area with the goal of better managing congestion, supporting economic development, and encouraging "thinking big" and recommendations for new solutions (Dan Tangherlini, 2004). New York City, noting the benefits of experiences in European cities, has taken an initial step in congestion management by establishing a "New York City Traffic Congestion Mitigation Commission" to work on a plan to implement congestion pricing in Manhattan (Zupan, Perrotta, 2003). In August 2007, the U.S. Department of Transportation (USDOT) awarded approximately $354 million to New York City to implement the Mayor's congestion pricing program, in which $8 was to be charged to enter and exit Manhattan below 86th Street on weekdays between 6:00 a.m. and 6:00 p.m. (The New York Times, http://cityroom.blogs.nytimes.com/2007/08/14/us-will-give-new-york-354-million-for-congestion-pricing/?hp). Despite passage by the City Council and an unprecedented coalition of supporters, congestion pricing was not enacted by the New York State Legislature in 2008. However, many transportation professionals believe that it remains one of the only options on the table to ease New York City's traffic congestion and underfunded public transit (http://www.transalt.org/). As popular press has indicated, many other U.S. metropolitan cities have demonstrated a high interest in congestion management after reviewing the success of congestion pricing implementations in Europe.

As the theory and practice of congestion pricing becomes mature, some researchers place their emphasis on another domain, known as reservation systems in travel demand management (Wong, 1997; Akahane and Kuvahara, 1996; Feijter et al, 2004; Edara, 2005, 2008). Drawing upon their work, this research further explores the concept and method of integrating reservation/booking and the application of TDM.

2.1.3 Transportation Network Capacity

TDM is committed to improving the capacity utilization of an existing transportation network and providing a limited resource (road network) to the right people at the right time. Therefore, it is important to define the capacity of the existing network. Capacity, however, is a flexible notion. It can be measured in various ways. In many cases, performance of the transportation facility/system is measured by level of service. In order to maintain a certain level of service quality, capacity analysis has to provide a means of estimating the maximum amount of traffic that the system is able to carry.

In the Highway Capacity Manual (HCM) (1994), the capacity of a transportation facility indicates its ability to accommodate a moving stream of people or vehicles. Capacity is defined as the maximum hourly rate at which persons or vehicles can reasonably be expected to traverse a point or uniform section of a lane or roadway during a given time period under prevailing roadway, traffic and control conditions.

Wong (1997) measured a road network capacity using the greatest common multiplier for existing flows that could be accommodated subject to capacity constraints, cycle time and other restrictions by solving a network equilibrium problem. The capacity indicated the maximum attainable throughput of the given network. Yang (2000) determined the capacity of urban transportation networks through equilibrium traffic assignment. In the model, it is assumed that the traffic flow on each link cannot exceed a given upper bound (link capacity). The capacity is the additional demand that can be accommodated by the network so that flow on each link is still within the link capacity. In the same paper, Yang also suggested broadening the definition of capacity to encompass queuing and other storage capacity constraints.

Chen (2002) expanded capacity analysis on the basis of reliability, and introduced the concept of capacity reliability as a network performance index in conjunction with connectivity

and the reliability of travel time. Capacity reliability is defined as the probability that the network can accommodate a certain traffic demand at a required service level while accounting for drivers' route choice behavior.

Daganzo (2005, 2007) proposed a modeling approach for controlling aggregate vehicular accumulations and accumulative flows by district and time of day so as to improve urban city mobility and relieve congestion. The basic idea of the model is to view the system as a reservoir or sets of interconnected reservoirs, and the city traffic is modeled at an aggregate level by monitoring and controlling the input/output traffic flow to the city. Essentially, the maximum aggregate vehicular accumulations can be viewed as the capacity of the district, and the inflow/outflow is the channel to ensure that the capacity is not violated at any time. This notion of capacity will be adopted in this research.

2.2 Artificial Neural Networks

2.2.1 General Introduction of Artificial Neural Networks

Artificial neural networks are information processing technology—a mathematical model and computational model (Trappenberg, 2002). Essentially, they involve a network of simple processing components that function similarly to a biological brain and nervous system together. The information processing element in the human brain is composed of neurons. Many neurons functioning in groups form a neural network. And finally, the collection of neural networks forms the brain. Similarly, an artificial neural network is composed of artificial neurons.

An artificial neuron has properties similar to a biological neuron, receiving inputs (x1, x2, …, xn), processing the inputs, and delivering outputs (Figure 2-2). The neurons in an artificial neural network are also called processing elements (PEs). The summation function gives the weighted average of all the inputs to the neuron as an output. Then the output has to be modified to a reasonable value (suppressing the output within a certain range and avoiding very large or small values) through the transfer function. There are various transfer functions: step function, sigmoid function, and hypertangent function.
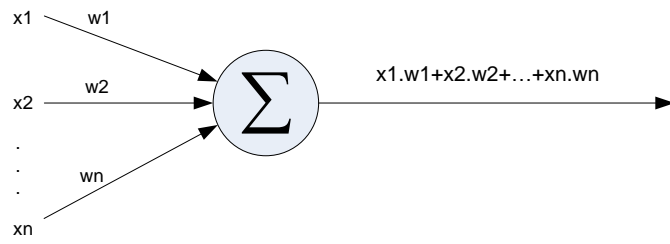
Figure 2-2 Structure of an Artificial Neuron

A neural network consists of multiple neurons. They are arranged in different architectures. Figure 2-3 shows a typical multi-layer perceptron (MLP)—a three-layer feedforward neural network with a backpropagation learning algorithm. The three layers include an input layer, a hidden layer, and an output layer. Each layer consists of a group of neurons. "Feedforword" indicates information flows in one direction only, from the input layer to the hidden layer and to the output layer. The backprogagation learning algorithm compares the responses of output units to the desired response and readjusts the weights in the network so that the next time the same input is presented to the network, the network's response will be closer to the desired response.
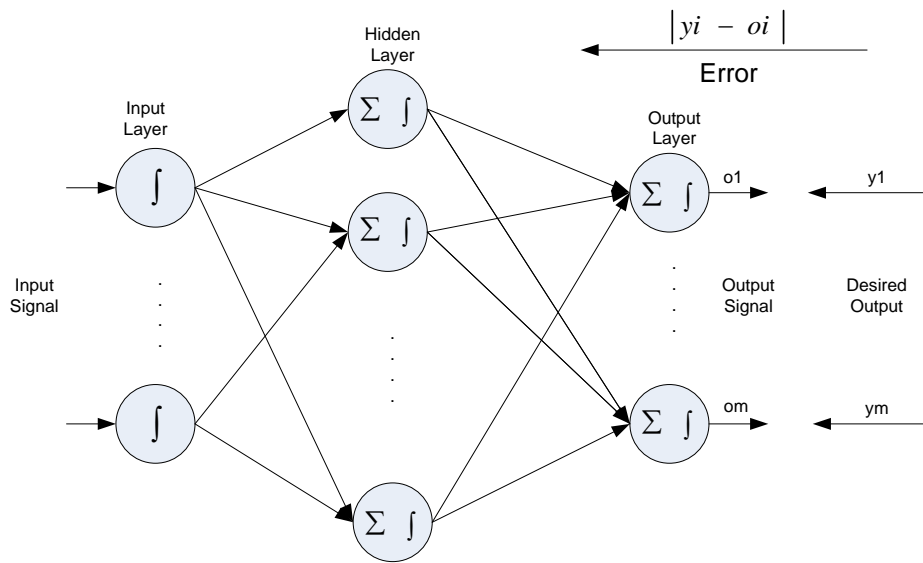
Figure 2-3 MLP- Network

The following set of criteria can be used to characterize a neural network (Teodorović and Vukadinovic 1998):

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(1) The number of processing elements.

Processing elements (neurons) are the basic functional units of a neural network. Generally, they are organized in different layers. Different layers have different functionalities. For instance, the input layer receives signals from an outside information resource, the hidden layer transforms the signals from the input layer to the output layer, and the output layer finally provides the desired information. Figure 2-3 shows a general three-layer network. In some types of neural networks, the neurons may not be arranged in layers, e.g., in a fully recurrent network. However, no matter which type is used, for each processing element the network simply multiplies an input by a set of weights and transforms it into an output value. Therefore, a neural network can be viewed as working from a large number of very simple processing elements that individually deal with pieces of a big problem.

(2) Connectivity of the processing elements.

Each neuron in one layer is connected with the neurons in other layers by a synapse. Layers can be fully connected or partially connected. Whether it is fully connected or partially connected is determined both in terms of the neural network structure/type and the practical problem requirements. Generally, an artificial neural network uses connected lines to represent connection weights between the two connected elements. The quality of those weights is fundamental to the network, because after the topology is decided, generally the neural network will be adjusted by changing the weights.

(3) The rule of information propagation through the network.

Information flows through the network in various ways. The simplest way is the feedforward information movement, where the information flows in one direction from input layer to hidden layer (if any) and to output layer and no direct loop is formed. Both single-layer perceptron and multi-layer perceptron belong to this category. In contrast to the feedforward movement, information can also be propagated from later layer to earlier layer. It is bi-directional information flow.

(4) Transfer functions.

The performance of an artificial neural network is highly reliant on both the weights and the transfer function. The transfer function is also referred to as the activation function or transformation function. The transfer function ensures the output value of the network falls in a reasonable range and that there is no extreme value, either too small or too large. Sigmoid function is one of the transfer functions commonly used in neural network applications. For example, if an output of a processing element is Y, the normalized value of Y is:

$$Y_T = \frac{1}{1 + e^{-Y}}$$

An example is provided to illustrate how the transfer function works (Figure 2-4).
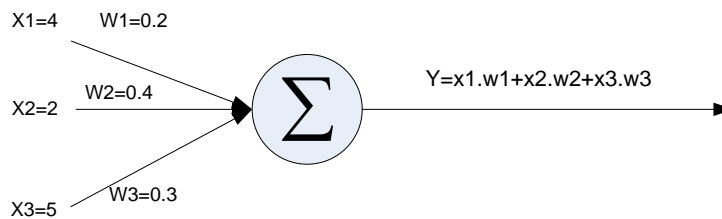
Figure 2-4 Example Illustration

$$Y=4 \times 0.2 + 2 \times 0.4 + 5 \times 0.3 = 3.1$$

The sigmoid transformation results in:

$$Y_T = \frac{1}{1 + e^{-3.1}} = 0.9569$$

(5) Learning rules.

So called "learning" is actually the modification of network parameters (weights) to improve the neural network performance. Rules for changing the parameters have to be specified. One class of learning methods is called supervised learning. An example

of supervised learning is adjusting the weights according to the measured errors (cost functions), which are generally defined as the difference of the output of the neural network and a pre-specified desired output. The mean-squared error is a commonly used cost function. It is to be minimized in the network training process. In the process, the weights are adjusted to achieve the minimization objective. The weights are changed according to gradient descent. This prescribes the direction of the changing. This kind of learning rule is used when the desired performance is known. The other class of learning method is unsupervised training. In this learning process, there is no desired external signal available, so the network must self-organize according to some internal rules of input vectors in response to the environment. (For more details, see Trappenberg, 2002.)

Two major phases are included when building a neural network. First, neural network topology has to be determined, i.e., the number of neurons and their arrangement architecture, transfer function, and learning rules. After the construction phase, building turns to the training and testing phases. In the training phase, the network is trained with historical data. Taking the MLP-network in Figure 2-3 as an example, the training process is illustrated in Figure 2-5. Then one can use another set of data to test the trained network to determine whether it achieves the desired performance.
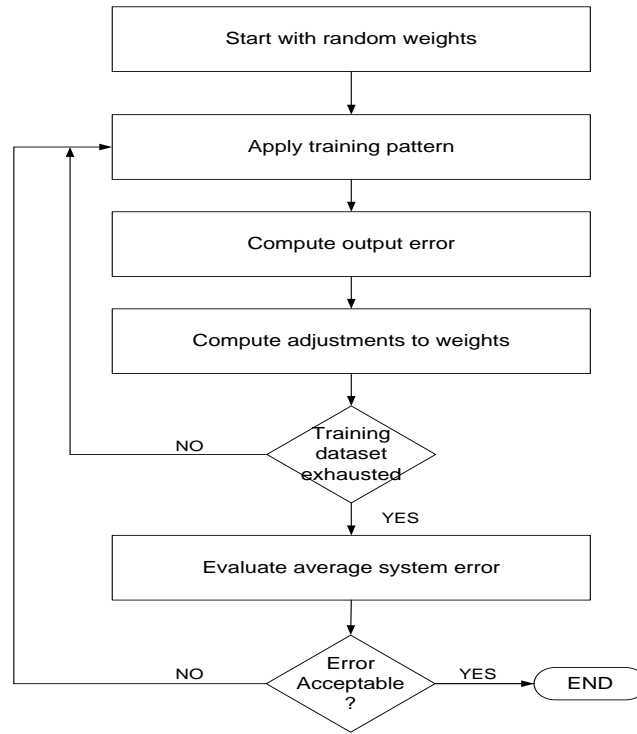
Figure 2-5 MLP Network Training Process

2.2.2 *Application of Artificial Neural Networks in Transportation*

Artificial neural network theory has been widely applied in many fields, including transportation, since its resurgence in 1980s. Many of the applications are designed for realizing its capacity for "real time" decision making. Teodorović (1998) provides a rich literature overview of neural networks in transportation to date. Application fields include transportation demand forecasting, dynamic dial-a-ride problems, vehicle schedule disturbance, and real-time estimation of an origin-destination matrix. The capability of capturing complex relationships, learning from historical data and adapting to new situations makes the neural network a viable tool for these problems.

Researchers have applied the capabilities of artificial neural network in a variety of TDM settings. Edara (2003) developed a mode choice model using neural networks. When compared to traditional models, including the logit model and regression methods, the proposed new model provides the best results. Later, Edara (2005) used artificial neural networks in the highway space inventory control system to realize real time decision making capability. Ki (2006) used back-propagation neural networks for vehicle classification for inductive-loop detectors and

verified that they improved vehicle classification accuracy significantly. Teodorović (2006) developed an "intelligent" intersection signal control system with neural networks combined with dynamic programming. The system made "real time" decisions about the extension of current green time. Teodorović and Edara (2007) applied neural networks in a real time road pricing system that combined Dynamic Programming and Neural Networks to make "on-line" decisions about toll values. The application of neural networks in this research is in a similar category.

2.3 Traffic Simulation

Simulation is defined as dynamic representation of some part of the real world achieved by building a computer model and moving it through time (Drew, 1968). Since the late 1950s, traffic simulation has become a powerful tool to help transportation professionals make key decisions in transportation planning, training and demonstrations, as computer technology has enabled more sophisticated simulation processes. In some cases, computer simulation is the only way that physical processes can be studied and interpreted. Simulation models also can build a bridge between other types of models because of their ability to incorporate elements from conventional traffic, economic and land use models.

Traffic simulation programs can be classified in several ways. The basic classifications include microscopic vs. mesoscopic vs. macroscopic, and continuous vs. discrete time. According to the problem type, the programs can be separate intersection, road section or network simulations (Pursula 1999).

The most popular classification is according to the details in a simulation. The level of details in simulation models increases from macroscopic via mesoscopic to microscopic. Macroscopic models describe the traffic at a high level of aggregation as flow, without considering its constituent parts, whereas microscopic models describe the behavior of the entities making up the traffic stream, as well as their interactions, in detail. Mesoscopic models are at an intermediate level of detail—for instance, describing the individual vehicles, but not their interactions. In the remainder of this section, a brief overview of the three simulation types is presented.

2.3.1   Macroscopic Simulation

Macroscopic simulation models are based on the relationships between the flow, speed, and density of the traffic stream to analogous physical phenomena, such as the flow of a fluid or gas. In a macroscopic simulation, roads are divided into sections, and the simulation keeps track of vehicles section-by-section rather than by tracking individual vehicles. The evolution of traffic over time and space is evaluated using a set of differential equations. One advantage is that the data needed for micro-simulation (flow and speed) is at the same level of aggregation as the data supplied by the general transportation measurements. Meanwhile, macroscopic models have considerably fewer demanding computer requirements in comparison to microscopic models. Boxill and Yu (2000) provide a list of macroscopic traffic simulation software packages on the market.

2.3.2   Mesoscopic Simulation

Mesoscopic simulation models combine the properties of microscopic and macroscopic simulation models. They describe vehicles at a high level of detail, but without considering their intersections. The models fill the gap between the aggregate level approach of macroscopic models and the individual interactions of microscopic models. This type of traffic simulation model has recently increased in popularity. However, compared with other simulation types, there are fewer software packages available in this category (Boxill and Yu, 2000). In mesoscopic simulation, vehicles are grouped into packets and routed through the network. A packet of vehicles acts as one entity, and its speed on each link is derived from a speed-density function defined for the link. The lane changing and acceleration/deceleration of vehicles is not modeled. The main application of mesoscopic models is in areas where the detail of microscopic simulation might be desired, but is infeasible due to a large network, or where limited resources are available to be spent on the model. Mesoscopic models provide less fidelity than micro-simulation tools, but are superior to macroscopic models.

2.3.3   Microscopic Simulation (Kitamura and Kuwaiiara, 2005)

Microscopic simulation attempts to describe the movements and interactions of each vehicle/entity. Unlike macroscopic simulation, speed, volume and density in microscopic simulation are not model variables. Instead, they are measures derived from the interactions of all vehicles with the infrastructure and with other vehicles. The car-following model and the lane

changing model are the most important parts of microscopic simulation. Vehicles' behavior (drivers' behavior) is primarily governed by them. The car-following model describes the vehicle's braking and accelerating behavior due to its interaction with the vehicle in front. The lane-changing model describes the behavior of changing lanes based on the driver's preference and the situation in both the current lane and adjacent lanes. In addition, a route choice model is involved, describing how drivers make decisions on which path to take from their starting location (origin) to their destination and how they react to traffic and route information along the way.

In microscopic simulation, travel demand is normally represented in two ways in order to incorporate two types of traffic assignment (i.e., static traffic assignment and dynamic traffic assignment). One method is to model the flows of traffic entering the network together with the turning percentages at each intersection (i.e., the percentage of vehicles that turn left, right or go straight for each intersection approach). This is generally used in static traffic assignment. Another method is to divide the modeled road network into zones and define the number of vehicles that want to travel from each zone to other zones in an Origin/Destination matrix (OD matrix)[3]. This is the major demand input format used in dynamic traffic assignment.

Microscopic simulation is the most popular traffic system simulation application (Pursula 1999). Hence, there are more micro-simulation packages on the market, such as CORSIM, VISSIM, and AIMSUN2. At the micro level, a great amount of detail is needed when modeling a road network, as well as effort to calibrate the large number of model parameters. Micro-simulation also requires much greater computer time and storage requirements. This limits the network size and the number of simulation runs in an application. Boxill and Yu (2000) provide a comprehensive list of the microscopic traffic simulation software.

In conclusion, each of these models has its own advantages and problems. Selection of a software package in a simulation project depends on the problem to be solved and the resource availability, including the software package and the data sources, because different packages may require different data and information to build a simulation model.

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[3] Trip chain file and OD matrix

2.4 Performance Evaluation in Transportation

This section provides a comprehensive review of performance indicators commonly used in performance evaluation by transportation professionals. The various indicators reflect the different objectives pursued by the particular program or organization, including overall transportation efficiency and effectiveness, congestion mitigation, and transportation sustainability. The experiences and indicators in literature are indispensable reference resources for selecting performance measures in our performance evaluation framework in Chapter 5.

2.4.1 Traffic, Mobility, Accessibility

Performance evaluation is an important component of any policy, program and project. It helps to assess how the system progresses toward achieving predetermined goals. Wrong performance measures can result in inadequately assessing transportation needs and misallocating transportation resources. In addition, performance measures help to enhance communication between different stakeholders. In the past years, transportation operators have increasingly embraced the concept of performance measurement to track the trends of key indicators of how the transportation system is performing. Substantial work related to transportation performance measures has been carried out by various transportation organizations/professionals.

The Oregon Department of Transportation (Reiff, 2005) developed a comprehensive framework for analyzing and selecting performance measures. Within the framework, they compiled a list of 750 performance measures that encompasses performance measures from the Texas Transportation Institute (TTI) urban mobility study to the National Cooperative Highway Research Program (Reiff, 2005). The performance measures are categorized by policy areas, including mobility, accessibility and sustainability. The work provides comprehensive and generic performance measurement guidance for most transportation planning and management strategies.

Litman (2003; 2006a; 2006; 2007; 2008) places a great emphasis on defining performance measurement issues that focus on TDM strategies. He stresses that various underestimates exist in current TDM performance measurements that use traditional economic evaluation methods. For instance, cost-effectiveness analysis considers only direct impacts and a single objective. This may overlook additional costs and benefits to the participants and society.

He advocates that TDM evaluation and performance measurement pay attention to accessibility, rather than focusing on traffic only. All together, three categories of performance measures/indicators [4] —conventional transportation indicators, comprehensive performance indicators, and TDM performance indicators—are summarized. Conventional transport indicators mostly consider vehicle traffic conditions; comprehensive performance indicators take into account a wider range of travel modes and impacts; and the additional TDM performance indicators are suitable for evaluating TDM strategies.

The three categories of indicators reflect the perspectives of traffic, mobility, and accessibility. Litman (2007) elaborates on the different emphases among the three perspectives (Table 2-1). Traffic refers to vehicle movement, and assumes that "travel" means vehicle travel and "trip" means vehicle-trip. Mobility refers to the movement of people or goods. It assumes that "travel" means person- or ton-miles, and "trip" means person- or freight-vehicle trip. Accessibility refers to the ability to reach desired goods, services, activities and destinations. Basically, vehicle traffic is a subset of mobility, and mobility is a subset of accessibility.

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[4] Performance measures/indicators are often referred to as measure of effectiveness (MOE).

Table 2-1 Comparing Transportation Measurements (Litman, 2007)

	Traffic	**Mobility**	**Accessibility**
Definition of Transportation	Vehicle travel.	Person and goods movement.	Ability to obtain goods, services and activities.
Unit of measure	Vehicle-miles and vehicle-trips	Person-miles, person-trips and ton-miles.	Trips.
Modes considered	Automobile and truck.	Automobile, truck and public transit.	All modes, including mobility substitutes such as telecommuting.
Common performance indicators	Vehicle traffic volumes and speeds, roadway Level of Service, costs per vehicle-mile, parking convenience.	Person-trip volumes and speeds, road and transit Level of Service, cost per person-trip, travel convenience.	Multi-modal Level of Service, land use accessibility, generalized cost to reach activities.
Assumptions concerning what benefits consumers.	Maximum vehicle mileage and speed, convenient parking, low vehicle costs.	Maximum personal travel and goods movement.	Maximum transport options, convenience, land use accessibility, cost efficiency.
Consideration of land use.	Favors low-density, urban fringe development patterns.	Favors some land use clustering, to accommodate transit.	Favors land use clustering, mix and connectivity.
Favored transportation improvement strategies	Increased road and parking capacity, speed and safety.	Increased transport system capacity, speeds and safety.	Various strategies to increase transport and land use system capacity, efficiency and safety.
Implications for TDM	Considers vehicle travel reductions undesirable, except where congestion is extreme.	Supports TDM strategies that improve personal and freight mobility.	Supports TDM whenever it is cost effective.

Mobility is defined as the ability to reach a destination in a time and at a cost that are satisfactory (TTI, 2005). Perhaps one of the most prominent studies in mobility is the annual Texas Transportation Institute Mobility Report. Considering that the ultimate goal of transportation is to get people and goods safely, quickly, and reliably to their destination, mobility is the primary means for achieving that goal. A family of mobility measures has been

developed by TTI (Schrank, 2004; 2005; 2007). The major measures of mobility used in the report are:

- Travel delay: the amount of additional travel time, relative to free flow conditions.

- Travel time index: the ration of peak period travel time to travel time at free flow conditions.

- Buffer index: a measure of network reliability and an estimate of the additional time that a traveler needs to budget during peak-period travel to be assured of arriving on time with a 95 percent level of confidence.

- Congestion cost: calculated for the value of travel time delay ($13.45/hour of personal trip, and $71.05/hour of truck time) and excess fuel consumption.

- Annual delay per traveler: extra travel time for peak period travel during the year divided by number of travelers who begin a trip during the peak period (6:00 to 9:00 a.m. and 4:00 to 7:00 p.m.).

The annual TTI urban mobility study presents details on the trends on each of the measures over 85 urban areas in the states. Additionally, TTI (TTI, 2005) provides nine basic principles of mobility measurement to guide the development of a mobility monitoring program (Table 2-3), as well as a quick reference guide to mobility measure selection. The study emphasized that mobility performance must be based on the measurement of travel time, and multiple metrics should be used to report congestion performance. Traditional HCM-based performance measures (such as level of service) should be considered as supplementary measures in the mobility monitoring process, rather than primary measures. Customer satisfaction measures should also be included with quantitative mobility measures for monitoring congestion outcomes. Both vehicle-based and person-based performance measures should be developed in monitoring mobility.

Accessibility is another common measurement perspective in transportation. The prominence of accessibility measurement is due to the fact that it expands the range of impacts considered to include non-transportation components. It takes into account other factors, including impacts on alternative modes, land use and safety. The definition of accessibility is not

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yet precise (Litman, 2007). For example, ODOT define accessibility as "number of opportunities available to zonal households within t minutes by mode m, or comprehensive accessibility measures using the destination choice model "inclusive value" that captures the travel time and cost of accessing and the number and quality of those opportunities" (Reiff, 2005, p.11). Reiff uses transportation cost index (TCI) to assess accessibility. Litman defines the concept of accessibility as "the ease of reaching goods, services, activities and destinations" (Litman, 2007, p. 3).

Accessibility-based transportation evaluation tends to provide more integrated analysis by considering many factors that are omitted in traditional mobility measurement, such as door-to-door measurement, the travel links from origins to vehicles and from vehicles to destination, and qualitative factors of comfort and convenience. Additionally, in accessibility-based transportation evaluation, non-motorized people have the same priority as motorized people. Pedestrians and bicycle riders are treated as equals of vehicle drivers. Accessibility measurement integrates different components in the urban system, including transportation, land use, and economic activities.

Compared with mobility, accessibility is relatively difficult to measure, not only because of the lack of precise definition, but because the inclusion of a variety of factors complicates the assessment, including personal mobility, the degree of integration among transport system links and modes, land use factors and so on. Although the inclusion of these factors increases the complexity of the performance measurement process and requires more comprehensive data than the traditional mobility-based evaluation, many transportation professionals emphasize that transportation evaluation fundamentally ought to be accessibility-based, rather than mobility-based (Litman, 2007).

The aforementioned definitions of accessibility are descriptive. A quantitative form of accessibility states that "accessibility at point 1 to a particular type of activity at area 2 (say, employment) is directly proportional to the size of the activity at area 2 (number of jobs) and inversely proportional to some function of the distance separating point 1 and area 2" (Sathisan and Srinivasan, 1998, p. 79). The measure of accessibility is place-based and involves measurement of spatial separation of individuals and activities. Two commonly used measures are cumulative opportunity measures and the gravity-based model (Niemeier, 1997). The

cumulative opportunity approach counts the number of potential opportunities that can be reached within a predetermined travel time (or distance), and the gravity-based model uses the denominator of the gravity model to evaluate accessibility (El-Geneidy and Levinson, 2006).

Among the three performance measurement perspectives, although accessibility-based measurement is considered more comprehensive and integrated, there is no one-size-fits-all solution to transportation performance measurement. Which category to use in an evaluation program is affected by various factors, such as how the problem is defined in the specific program and what resources are available. One has to carefully examine the uniqueness of the problem to select appropriate performance indicators.

2.4.2   Sustainability in Transportation systems

The concept of sustainability originated with economic and social development. The basic concept of sustainable development is development that meets the present need without compromising the ability of future generations to meet their needs. The concept reflects the integration of human activities and the need to coordinate decisions among different sectors. There is no standard definition for transportation system sustainability. Joen and Amekudzi (2005) provide a summary of a set of working definitions of sustainability from different organizations, including:

Definition 1 (Ontario Roundtable on Environment and Economy, Canada):

(1) Produce outputs (emissions) at a level capable of being assimilated by environment.

(2) Have a low need for inputs of non-renewable resources.

(3) Minimize disruption of ecological processes, land use is also minimized as well as uses of sensitive habitats.

Definition 2(Organization for Economic Cooperation and Development):

Environmentally sustainable transportation is transportation that does not endanger health or ecosystems and that meets needs for access consistent with (a) use of renewable resources at below their rates of regeneration and (b) use of non-renewable resources below the rates of development of renewable substitutes.

Definition 3(Transportation Association of Canada):

(1) In the natural environment: limit emissions and waste within the urban area's ability to absorb/recycle/cleanse; provide power to vehicles from renewable or inexhaustible energy sources; and recycle natural resources used in vehicles and infrastructure.

(2) In society: provide equity of access for people and their goods, in this generation and in all future generations; enhance human health; help support the highest quality of life compatible with available wealth; facilitate urban development at the human scale; limit noise intrusion below levels accepted by communities; and be safe for people and their property.

(3) In the economy: be financially affordable in each generation; be designed and operated to maximize economic efficiency and minimize economic costs; and help support a strong, vibrant and diverse economy.

Definition 4 (California Department of Transportation):

A sustainable transportation system meets the basic mobility and accessibility needs of current and future generations.

Definition 5(Procedure for Recommending Optimal sustainable Planning of European City Transport Systems):

A sustainable urban transport and land use system: (1) provides access to goods and services in an efficient way for all inhabitants of the urban area; (2) protects the environment, cultural heritage and ecosystems for the present generation, and (3) does not endanger the opportunities of future generations to reach at least the same welfare level as those living now, including the welfare they derive from their natural environment and cultural heritage.

Definition 6 (The Center for Sustainable Transportation, Canada):

(1) Allows the basic access need of individual and societies to be met safely and in a manner consistent with human and ecosystem health, and with equity within and between generations;

(2) Is affordable, operates efficiently, offers choice of transport mode, and supports a vibrant economy;

(3) Limits emissions and waste within the planet ability to absorb them, minimizes consumption of non-renewable resources, reuses and recycles its components, and minimizes the use of land and the production of noise.

Definition 7(Victoria Transport Policy Institute, Canada):

Providing for a secure and satisfying material future for everyone, in a society that is equitable, caring and attentive to basic human needs

Definition 8(Department of Sustainable Development, U.K.):

Sustainable development is about ensuring a better quality of life for everyone, now and for generations to come. This requires meeting four key objectives at the same time in the U.K. and the world as a whole: (1) social progress which recognizes the needs of everyone; (2) effective protection of the environment; (3) prudent use of natural resources and (4) maintenance of high and stable levels of economic growth and employment.

The definitions have one commonality, which is that sustainable transportation must balance a variety of economic, social and environmental goals (Litman 2008). A three-dimensional framework for sustainability is often adopted in research and practice. The three consensus dimensions include economic development, environmental preservation, and social development. These are considered as the essence of sustainability. Among the three dimensions, the economic aspect of transportation sustainability includes traffic congestion, infrastructure costs, consumer costs, accident damages, and depletion of non-renewable resources. The social aspect includes equity, impacts on the mobility disadvantaged, human health impacts, community cohesion, community livability, and aesthetics. Finally, the environmental aspect includes air pollution, climate change, noise and water pollution, habitat loss and hydrologic impacts, and depletion of non-renewable resources (Litman, 2006).

Joen (2007) presents a summary of indicators with respect to each dimension and its corresponding goal (Table 2-2). Litman (2008) also provides a list of sustainability indicators commonly used in practice (Table 2-3 to Table 2-5). Litman's list of sustainability indicators is more detailed than Joen's: non-driving modes (e.g., walking, biking), people disadvantaged by TDM, freight/delivery business, tourism, etc., are explicitly included. Therefore, it is more helpful for evaluating a TDM project.

Table 2-2 Sustainability Goals and Performance Measures (Joen 2007)

Sustainability Dimension	Goals and Objectives	Performance Measures
Transportation System Effectiveness	A1. Improve Mobility	A11. Freeway/arterial congestion
	A2. Improve System Performance	A21. Total vehicle-miles traveled A22. Freight ton-miles A23. Transit passenger miles traveled A24. Public transit share
Environmental Sustainability	B1. Minimize Greenhouse Effect	B11. CO_2 emissions B12. Ozone emissions
	B2. Minimize Air Pollution	B21. VOC emissions B22. CO emissions B23. NO_X emissions
	B3. Minimize Noise Pollution	B31. Traffic noise level
	B4. Minimize Resource Use	B41. Fuel consumption B42. Land consumption
Economic Sustainability	C1. Maximize Economic Efficiency	C11. User welfare changes C12. Total time spent in traffic
	C2. Maximize Affordability	C21. Point to point travel cost
	C3. Promote Economic Development	C31. Improved accessibility C32. Increased employment
Social Sustainability	D1. Maximize Equity	D11. Equity of welfare changes D12. Equity of exposure to emissions D13. Equity of exposure to noise
	D2. Improved Public Health	D21. Exposure to emissions D22. Exposure to noise
	D3. Increase Safety and Security	D31. Accidents per VMT D32. Crash disabilities D33. Crash fatalities
	D4. Increase Accessibility	D41. Access to activity centers D42. Access to major services D43. Access to open space

Table 2-3 Economic Indicators of Sustainable Transportation (Litman 2008)

Indicator	Description
User Satisfaction	Overall transport system user satisfaction ratings
Commute Time	Average door to door commute travel time
Employment Accessibility	Number of job opportunity and commercial vehicles within 30 min travel distance of residents
Land Use Mix	Average number of basic services (schools, shops) within walking distance of homes
Electronic communication	Portion of population with internet services
Vehicle Travel	Per capita motor vehicle-mileage
Transport Diversity	Variety and quality of transport options available in a community
Mode Split	Portion of travel made by non-automobile modes
Congestion Delay	Per capita congestion delay
Travel Costs	Portion of household expenditure devoted to transport
Transport Cost Efficiency	Transportation costs as a portion of total economic activity and per unit of GDP
Facility Costs	Per capita expenditure on roads, parking and traffic services
Freight Efficiency	Speed and affordability of freight and commercial transport
Delivery Services	Quantity and quality of delivery services
Commercial transport	quality of transport services for commercial users (tourists, businesses)
Crash Costs	Per capita crash costs
Planning quality	Comprehensiveness o the planning process
Mobility Management	Implementation of mobility management programs to address problems and increase transport system efficiency
Pricing Reforms	Implementation of pricing reforms such as congestion pricing etc.
Land Use Planning	Applies smart growth land use planning practices, resulting in more accessible, multi-modal communities

Table 2-4 Social Indicators of Sustainable Transportation (Litman 2008)

Indicator	Description
User rating	Overall satisfaction of transport system by disadvantaged users
Safety	Per capita crash disabilities and fatalities
Community livability	Degree to which transport activities support community livability objectives
Cultural preservation	Degree to which cultural and historic values are reflected and preserved in transport planning decision
Non-drivers	Quality of transport services and access for non-drivers
Affordability	Portion of budgets spent on transport by lower income households
Disabilities	Quality of transport facilities and services for disabled people
NMT transport	Quality of walking and cycling conditions
Children's travel	Portion of children' s travel to school and other local destinations by walking and cycling
Inclusive planning	Substantial involvement of affected people, with special efforts to insure that disadvantaged and vulnerable groups are involved.

Table 2-5 Environmental Indicators of Sustainable Transportation (Litman 2008)

Indicator	Description
Climate change emissions	Per capita fossil fuel consumption, and emissions of CO_2 and other climate change emissions
Other air pollution	Per capita emissions of "conventional" air pollutions
Air pollution	Frequency of air pollution standard violations
Noise pollution	Portion of population exposed to high levels of traffic noise
Water pollution	Per capita fluid losses
Land use impact	Per capita land devoted to transportation facilities
Habitat protection	Preservation of high quality wildlife habitat
Habitat fragmentation	Average size of roadless wildlife preserves
Resource efficiency	Non-renewable resource consumption in the production and use of vehicles and transport facilities

2.4.3 Congestion Measurement

A subset of transportation measurement is the measurement of congestion. This category of measurement specifically emphasizes the evaluation of congestion mitigation policies. There are various ways to describe a congestion phenomenon, for instance, in terms of travel speed, travel time, cost, or other elements. Traditional congestion indicators are generally traffic-oriented, using measures such as travel time, delay time and a set of travel time derivative indicators. In addition, reliability is often used in congestion measurement. Cambridge Systematic Inc. (2005) examines congestion mitigation strategies, emphasizing reliability

measurement. However, reliability does not exist independently. It is basically derived from travel time and defined by how travel times vary over time, calculating the average travel time and the size of the "buffer"—the extra time needed to ensure a high rate of on-time arrival. Reliability measurement ensures the ability to predict with a desired certainty what travel time will be. In practice, this is of even greater concern to operators and travelers than travel time itself (Daniela et al., 2004), as variability in travel times leads to uncertainty that travelers find frustrating and costly. Reliability measures generally include buffer index, planning time, and planning time index. Littman (2006a) provides a list of congestion indicators used to quantify and evaluate congestion (Table 2-6).

Table 2-6 Congestion Indicators (Littman, 2006a)

Indicator	Description
Roadway Level Of Service (LOS)	Congestion intensity on a particular roadway or at an intersection, rated from A (uncongested) to F (extremely congested).
Travel Time Rate	The ratio of peak period to free-flow travel times, considering only reoccurring delays (normal congestion delays).
Travel Time Index	The ratio of peak period to free-flow travel times, considering both reoccurring and incident delays (e.g., traffic crashes).
Percent Travel Time In Congestion	Portion of peak-period vehicle or person travel that occurs under congested conditions.
Congested Road Miles	Portion of roadway miles that are congested during peak periods.
Congested Time	Estimate of how long congested "rush hour" conditions exist
Congested Lane Miles	The number of peak-period lane miles that have congested travel.
Annual Hours Of Delay	Hours of extra travel time due to congestion.
Annual Delay Per Capita	Hours of extra travel time divided by area population.
Annual Delay Per Road User	Hours of extra travel time divided by the number of peak period road users.
Excess Fuel Consumption	Total additional fuel consumption due to congestion.
Fuel Per Capita	Additional fuel consumption divided by area population
Annual Congestion Costs	Hours of extra travel time multiplied times an travel time value, plus the value of additional fuel consumption. This is a monetized congestion cost.
Congestion Cost Per Capita	Additional travel time costs divided by area population
Average Traffic Speed	Average speed of vehicle trips for an area and time (e.g., peak periods).
Average Commute Travel Time	Average commute trip time.
Average Per Capita Travel Time	Average total time devoted to travel.

It is worth noting that although these measures are presented under the category of congestion measurement, they are quite similar to the measures used in mobility measurement. Congestion measurement is an essential component of mobility measurement, as the principles of mobility monitoring specify. So congestion and mobility are closely related, and the same metrics and concept can be used to monitor both (Cambridge Systematics Inc., 2005).

2.5 Performance Measurement and DEA

2.5.1 *Fundamentals of Performance Measurement*

Efficiency measurement DEA is actually founded on a production theory in microeconomics. To understand efficiency measures and DEA better, one needs to first understand a set of concepts related to a production function.

(1) Production technology and production function

Graphically, a static production technology is illustrated as in Figure 2-6. In a production technology, inputs are transformed into outputs. Inputs are resources that contribute to the production of any output, described in quantities and/or qualities. Outputs are resources that result from the transformation of the inputs. They are also described in terms of quantity and/or quality. Technically, a production technology is defined as all the feasible sets of combinations of inputs and outputs.
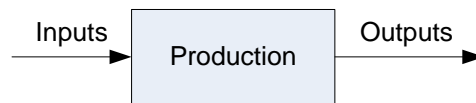
Figure 2-6 A static production technology

A production function differs from a production technology in that it assumes technical efficiency and states the maximum output obtainable from every possible input combination. Taking a simple production process with two variable inputs (x_1, x_2) and one single output (Q) as an example, the production function is the abstract mathematical relationship that describes how quantities of x_1 and x_2 combined to produce quantities of Q. Let us denote q as the production function. We have: $q = f(x_1, x_2)$.

The efficient production function is generally represented by an isoquant. It can be represented as a continuous function of Figure 2-7. The isoquant labeled as y^0 indicates all the possible combinations of X_1 and X_2 that give rise to the same output level, y^0. This isoquant is the standard by which one computes efficiency performance. It is also known as the production "frontier." The isoquant envelops all the inefficient decision-making units. There are various ways to obtain the frontiers. Farrell (1957) suggested a method of obtaining empirical piece wise convex efficient production function from observed data, since obtaining the theoretical production function is very complex, when possible. The method allows one to compare the observed firm with some ideally perfect performing firms. The piece wise isoquant is depicted in Figure 2-8. It is also often referred to as the best-practice frontier.
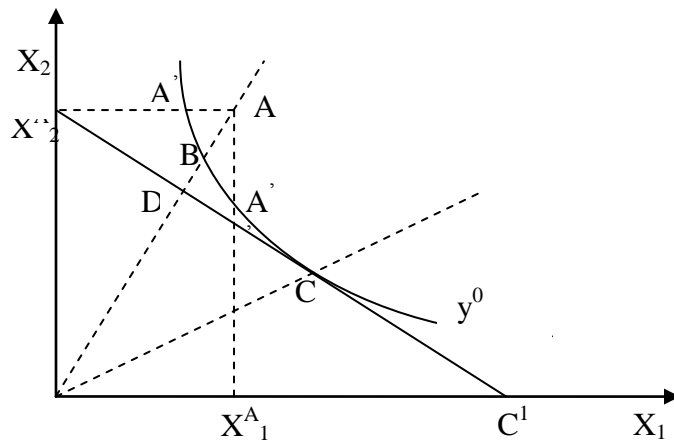
Figure 2-7 Production Isoquant (Input Oriented)
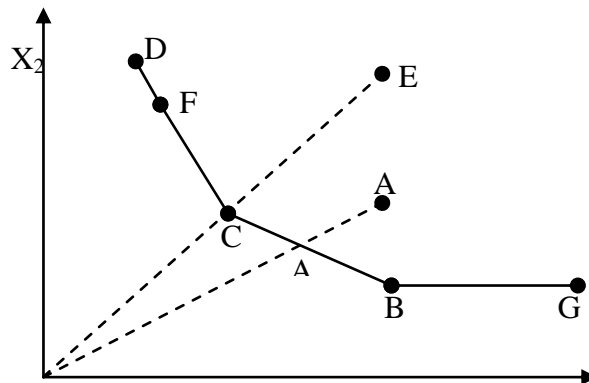
Figure 2-8 The Best-Practice Frontier (Input Oriented)

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(2) Definition of efficiency

Generally, the measure of efficiency is expressed as:

$$Efficiency = \frac{Output}{Input}$$

The measure takes a variety of forms, such as cost per unit, profit per unit, and so on. The measure of "productivity" is also expressed as a ratio of "output per worker hour" or "output per worker employed." These are considered as "partial productivity measures," which are used to measure the average productivity of labor as a measure of efficiency. However, these partial productivity measures cannot sufficiently capture multiple inputs and multiple outputs. Partial measurements can lead to serious misunderstandings. Hence Farrell (1957) provides new measures of productive efficiency, taking into account all inputs and outputs, moving the measurement from partial to total factor productivity measurement reformulated as:

$$Efficiency = \frac{Weighted\ Sum\ of\ Outputs}{Weighted\ Sum\ of\ Inputs}$$

Overall efficiency is decomposed into two components: technical efficiency and allocative efficiency. Allocative efficiency represents the degree to which a production unit minimizes cost when producing a specific level of output. Technical efficiency can be explained either in input-reducing or output-increasing orientation.

1) Input-Reducing Oriented

Input-reducing technical efficiency indicates the level of inputs used that can be reduced without altering the level of outputs produced. For instance, in Figure 2-7, assume that observations A, B and C represent firms that are producing the same level of output y^0. Clearly, observation A is inefficient with respect to B, since it is producing the same output level using more of both X_1 and X_2. Here, technical efficiency (TE) of A is given as:

TE=OB/OA

This measure can be explained as firm B produces the same level of output as A, but using only a fraction of OB/OA of each input.

On the other hand, the allocative efficiency (AE) is defined as:

$$AE=OD/OB$$

This measure expresses the cost difference if a firm had been allocatively efficient as a proportion of the firm's actual cost. Then the overall efficiency is:

$$Efficiency=TE*AE=OD/OA$$

2) Output-Increasing Oriented

Output-increasing technical efficiency gives the level of outputs produced that can be increased without altering the level of inputs used. In this case, we need to represent the production technology as an output correspondence (Figure 2-9). The technical efficiency of A is given by the ratio of OA/OB. The allocative efficiency is given by OB/OC. The overall efficiency is still the product of the technical efficiency and allocative efficiency, OA/OC. In general, the input-oriented and output-oriented technical efficiencies are not the same unless the production is experiencing constant returns to scale (Färe and Lovell, 1978).
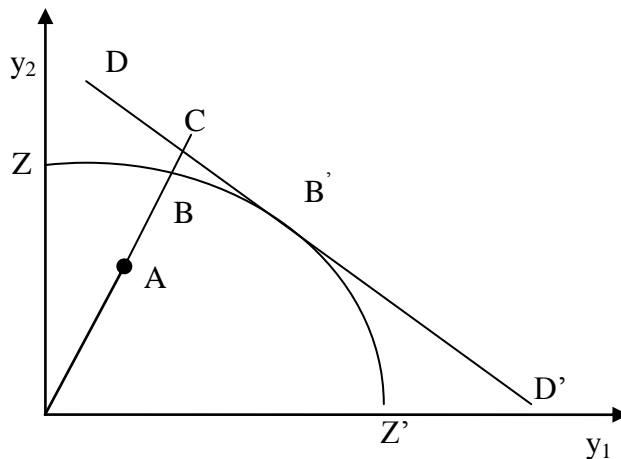
Figure 2-9 Production Isoquant (Output Oriented)

(3)   Returns to scale

Returns to scale reflect the degree to which a proportionate increase in all inputs increases output. Generally, there are three types of returns to scale:

Constant returns to scale

If a technology is experiencing constant returns to scale, a proportionately equal increase in all inputs leads to the same proportional increase in all outputs.

$$f(\alpha x_1, \alpha x_2) = \alpha f(x_1, x_2)$$

Increasing returns to scale

If a technology is experiencing constant returns to scale, a proportionately equal increase in all inputs leads to the greater (smaller) proportional increase in outputs.

$$f(\alpha x_1, \alpha x_2) > \alpha f(x_1, x_2)$$

Deceasing returns to scale

If a technology is experiencing constant returns to scale, a proportionately equal increase in all inputs leads to the greater (smaller) proportional increase in outputs.

$$f(\alpha x_1, \alpha x_2) < \alpha f(x_1, x_2)$$

(4) Production Technology Assumptions

In general, production technology is assumed to satisfy these properties:

1) It is not possible to produce positive outputs without using some inputs or to produce infinite outputs with finite inputs. However, it is always possible to produce no outputs.

2) There are two types of input disposability. Weak input disposability means that if all inputs are increased proportionally, production of outputs does not decrease. For strong input disposability, also known as free input disposability, if any input is increased, outputs do not decrease.

3) Equivalently, there are two types of output disposability: weak disposability and strong disposability. If proportional decreases in outputs remain producible with no change in

inputs, there is weak output disposability. Strong disposability allows any output to be costless disposed, which is not an appropriate assumption if undesirable outputs are produced.

4)   The correspondence between inputs and outputs is closed.

5)   Input and output sets are assumed to be convex. This indicates that, taking input convexity in a two-dimensional input space as an example, if two input bundles can each produce one unit of output, then so can the weighted average of them.

2.5.2 Data Envelopment Analysis

DEA is an analytical technique for measuring the relative efficiency of organizational units. It has been widely acknowledged for its strength in (1) capturing multiple inputs and outputs; (2) combining multiple dimensions (financial, throughput, safety, etc.); and (3) computing performance measures that integrate data/information across multiple dimensions and input/output resources (Gattoufi el al, 2004). Typically, production is always associated with some kind of transformation. The transformation units are called decision-making units (DMUs) in DEA. The DMU has a variety of forms. It can be a production line, a manufacturing factory, an industry sector, or other entity. It is not necessarily a concrete entity. As a result, DEA identifies the empirical frontier/best-practice units, and gives an inefficiency/efficiency score to each individual DMU. The CCR model (Charnes et al., 1978) is widely recognized as the birth of DEA. Since then, a collection of models have been developed based on the CCR model.

1)   The CCR Model (Charnes et al., 1978)

The CCR model adopts the measure of efficiency as the maximum of a ratio of weighted outputs to weighted inputs subject to the constraint that similar ratios for every DMU are less than or equal to unit. According to this definition, the model is represented mathematically:

$$Maxh_0 = \frac{\sum_{r=1}^{s} u_r y_{r0}}{\sum_{i=1}^{m} v_i x_{i0}}$$

Subject to:

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$$\frac{\sum\limits_{r=1}^{s} u_r y_{rj}}{\sum\limits_{i=1}^{m} v_i x_{ij}} \leq 1; \quad j=1,...,n$$

$$u_r, \ v_i \ \geq 0; \quad r=1,..,s; \quad i=1,...,m.$$

y_{rj}, x_{ij} are the known outputs and inputs of the jth DMU and u_r, v_i are the variable weights to be determined. The problem is to find a set of u_r, and v_i that maximizes the efficiency of DMU j_0 subject to the constraints. The constraints ensure that for all other DMUs, the ratio of "virtual output" vs. "virtual input" will not exceed 1 with the weights (v_i and u_r) maximizing the ratio of DMU$_0$. Similarly, we measure the efficiency for each DMU. The nonlinear programming formulation is replaced with linear programming equivalents for computation concerns.

$$\max h_0 = \sum_{r=1}^{t} u_r y_{rj0}$$

Subject to

$$\sum_{i=1}^{m} v_i x_{ij0} = 1$$

$$\sum_{r=1}^{t} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \leq 0, \quad j=1,...,n$$

$$u_r \geq \varepsilon, \quad r=1,...,t$$

$$v_i \geq \varepsilon, \quad i=1,...,m$$

If we consider this model as the primal, the dual can be obtained as follows:

$$\min \ z_0 = \theta - \varepsilon \sum_r s_r^+ - \varepsilon \sum_i s_i^-$$

Subject to

$$\theta x_{ij0} - s_i^- - \sum_{j=1}^{n} x_{ij} \lambda_j = 0, \quad i=1,...,m$$

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$$\sum_{j=1}^{n} y_{rj}\lambda_j - s_r^+ = y_{rj0} \quad r = 1,...,t$$

$$\lambda_j, s_i^-, s_r^+ \geq 0, \text{for all } j, r \text{ and } i$$

Comparing the dual with the primal, one can find that the primal has $n+ t + m +1$ constraints, while the dual has $t + m$ constraints. The number of DMUs (n) is generally considerably larger than the number of inputs and outputs together ($t + m$). Therefore, from a computation time point of view, the dual is more convenient than the primal. The dual problem is to find values of λ_j so as to construct a virtual unit with outputs $\sum_{j=1}^{n}\lambda_j y_{rj}$ r=1... t , and inputs $\sum_{j=1}^{n}\lambda_j x_{ij}$ i=1,2,...,m. This virtual unit outperforms the current measured DMU j^0, and is considered as the target for j^0. The DMU j^0 will be efficient if $\theta = 1, \sum_{r=1}^{t}s_r^+ = 0, \sum_{i=1}^{m}s_i^- = 0$. θ represents the maximum proportion of its input level that j^0 should be expending to secure at least its current output levels. Up to this point, the CCR model is elaborated as input oriented. Similarly, the output-oriented CCR model can be written as follows:

$$\max \ z_0 = \phi + \varepsilon\sum_r s_r^+ + \varepsilon\sum_i s_i^-$$

Subject to

$$\theta y_{ij0} + s_i^+ - \sum_{j=1}^{n} y_{ij}\lambda_j = 0, \quad i = 1,...,m$$

$$\sum_{j=1}^{n} x_{rj}\lambda_j + s_r^- = x_{rj0} \quad r = 1,...,t$$

$$\lambda_j, s_r^-, s_i^+ \geq 0, \text{for all } j, r \text{ and } i$$

2)   The BCC Model (Banker et al., 1984)

The CCR model is built on the assumption of constant returns to scale. In the BCC model this assumption is relaxed to allow variable returns to scale. The BBC model also admits input orientation and output orientation.

The input-oriented BBC Model is formulated as:

$$\min z_0 = \theta - \varepsilon \sum_{r=1}^{t} s_r^+ - \varepsilon \sum_{i=1}^{m} s_i^-$$

Subject to:

$$\theta x_{ij0} - s_i^- - \sum_{j=1}^{n} x_{ij} \lambda_j = 0, \quad i = 1,...,m$$

$$\sum_{j=1}^{n} y_{rj} \lambda_j - s_r^+ = y_{rj0} \quad r = 1,...,t$$

$$\sum_{i=1}^{n} \lambda_j = 1$$

$$\lambda_j, s_i^-, s_r^+ \geq 0, \text{ for all j, r and i}$$

Basically, the only difference in this model is the introduction of the constraint $\sum_{i=1}^{n} \lambda_j = 1$. It contracts the feasible region from the conical hull in the CCR model to the convex hull in the BCC model. The feasible region is a subset of the CCR model. This is illustrated with a single input and single output example from Cooper et al. (2000) (Figure 2-10).
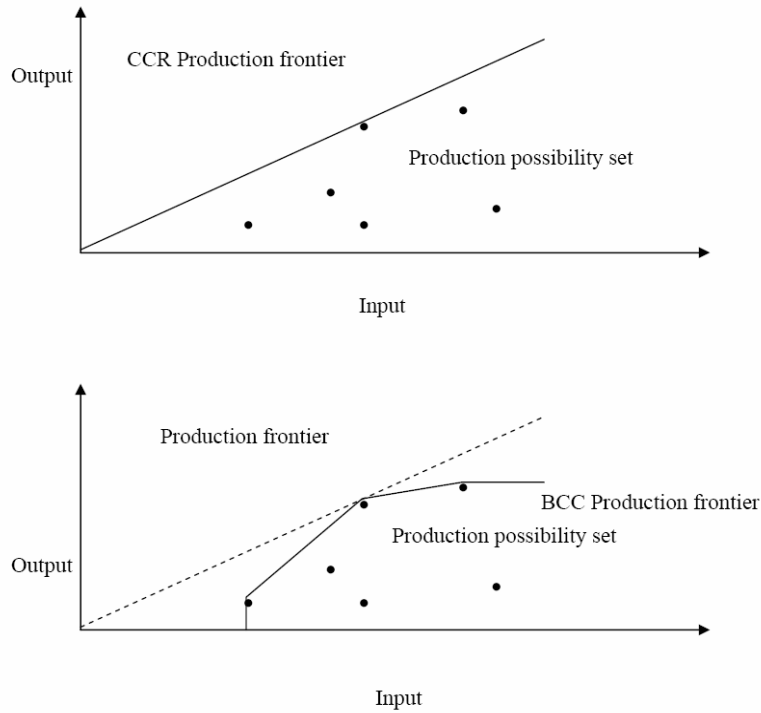
Figure 2-10 Production Frontiers in CCR and BCC

Similarly, the output-oriented BBC model is like:

$$\max \ z_0 = \phi + \varepsilon \sum_r s_r^+ + \varepsilon \sum_i s_i^-$$

Subject to

$$\theta y_{ij0} + s_i^+ - \sum_{j=1}^n y_{ij} \lambda_j = 0, \ \ i = 1,...,m$$

$$\sum_{j=1}^n x_{rj} \lambda_j + s_r^- = x_{rj0} \ \ r = 1,...,t$$

$$\sum_{i=1}^n \lambda_j = 1$$

$$\lambda_j, s_r^-, s_i^+ \geq 0, \text{ for all } j, r \text{ and } i$$

In both orientations, for a DMU to be efficient, it has to satisfy θ=1, with no slacks.

The CCR and BCC models are the basic DEA models. Various modifications have been developed, such as the additive model, the multiplicative model (Charnes, et al., 1982; Ahn et al., 1988), and the Go-DEA (Athanassopoulos, 1995). Many works also focus on the inclusion of different types of data. Cook and Zhu (2000), for example, developed a way of including rank order data into the DEA model. The combination of fuzzy theory with DEA is another popular research area (Kao and Liu, 2000; Guo and Tanaka, 2001; Lertworaasirikul et al., 2003). Many are devoted to the issue of incorporating undesired inputs/outputs (Scheel, 2001; Seiford and Zhu, 2002; Vencheh et al., 2005; Jahanshahloo et al., 2005; Amirteimoori et al., 2006) in the DEA models.

In general, DEA views each DMU involving an input and output transformation process. It is believed that there should be a production function associated with the process indicating how the inputs are transformed into outputs. The function can be theoretical or empirical. Most of the time, people do not know the theoretical function due to the complexity of the production process. However, DEA does not require specific information about its production function, since it adopts an empirical function based on the best results observed in practice. A minimum number of pre-assumptions are needed regarding its production function, including convexity of production function and non-positive slope (Farrell, 1957). This minimum requirement avoids imposing an a priori structure on the structure of the production function. On the other hand, it makes DEA performance measurement a "black box," as no information explicitly reveals how inputs are transformed into outputs.

For some circumstances, this "black box" may fit well; however, for others, one may need to look inside the "box" to provide greater insights into efficiency (inefficiency). This kind of issue has been addressed using network DEA. Network DEA allows one to explicitly model intermediate inputs or products in productivity measurement. In addition, the network approach allows for identifying misallocation of inputs among sub-processes and generating insights into sources of inefficiency within DMUs. Färe and Grosskopf (2000) developed a sequence of network models that can be applied to a variety of situations, including intermediate products (Figure 2-11), allocation of fixed resources (Figure 2-12), and dynamic systems (multi-period production) (Figure 2-13).
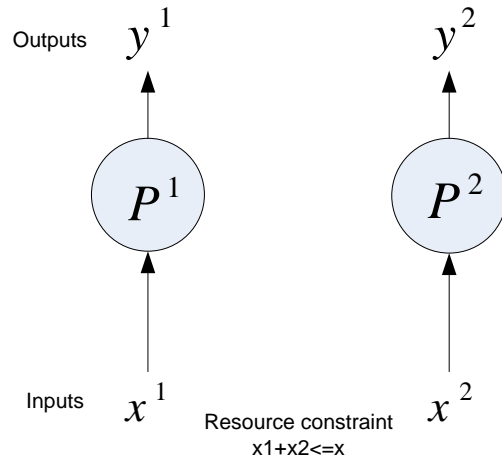
Figure 2-11 The Resource Constraint Technology
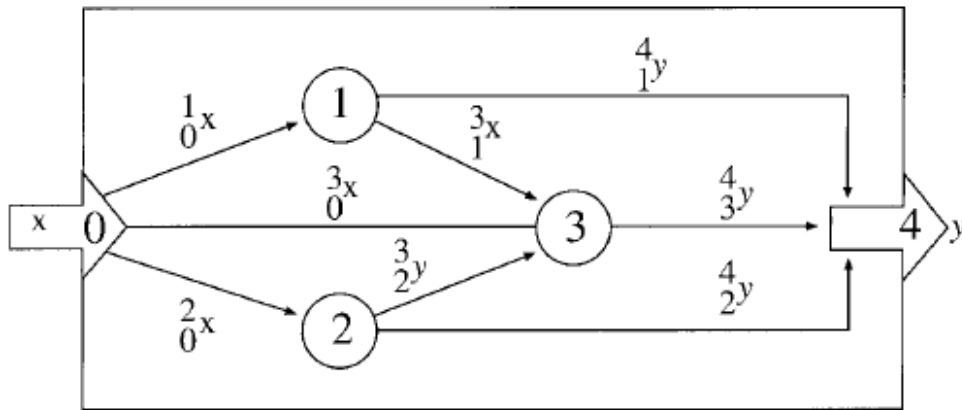
Figure 2-12 The Network Technology
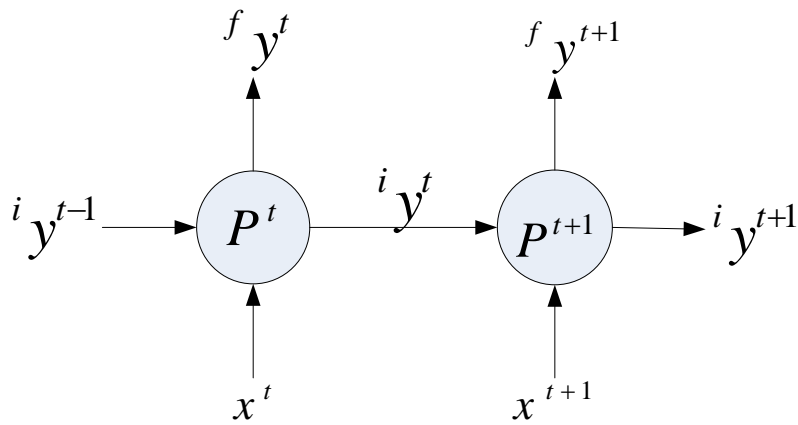
Figure 2-13 The Dynamic Technology

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CHAPTER 3 A Travel Demand Management Strategy: The Downtown Space Reservation System [5]

Abstract

In this paper, a Travel Demand Management strategy known as the Downtown Space Reservation System is introduced. The purpose of this system is to facilitate the mitigation of traffic congestion in a cordon-based downtown area by requiring people who want to drive into this area to make reservations in advance. An integer programming formulation is provided to obtain the optimal mix of vehicles/trips that are characterized by a series of factors such as vehicle occupancy, departure time, and trip length with an objective of maximizing total system throughput and/or revenue. Based upon the optimal solution, an "intelligent" module is built using artificial neural networks that enables the transportation authority to make decisions in real time on whether to accept an incoming request. An example is provided that demonstrates that the solution of the "intelligent" module resembles the optimal solution with an acceptable error rate. Implementation issues are addressed.

Keywords: Transportation; Travel demand management (TDM); Trip reservation; Integer programming; Neural networks

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[5] A shorter version of this chapter is under review by European Journal of Operational Research.

1.0   Introduction and Context

Various traffic management policies have been introduced to cope with the fast growth of congestion. In recent years, transportation engineers and planners have increasingly embraced strategies that deal with the management of existing facilities, rather than building new infrastructures on account of the investment and maintenance costs associated with these new infrastructures along with environmental considerations. These strategies are generally labeled as Travel Demand Management (TDM) strategies and involve managing travel demand by encouraging travel and land use patterns that lead to less congestion producing ways. In the report TTI prepared for the Federal Highway Administration (FHWA), "…… (TDM strategies) include putting more people into fewer vehicles (through ridesharing, increased public transportation ridership, or dedicated highway lanes for high-occupancy vehicles), shifting the time of travel (e.g., through staggered work hours), and eliminating the need for travel altogether (e.g., through telecommuting)" (TTI 2005, p. 87). As the popular press has indicated, many metropolitan cities have demonstrated a high interest in congestion management after reviewing the success of many congestion pricing implementations in Europe and Asia.

In response to the need of exploring the feasibility of providing innovative and effective solutions for traffic congestion, the design of reservation systems is being considered as an alternative and/or complementary TDM strategy (Edara, 2005). Reservation indicates that a user will follow a booking procedure defined by the reservation system before traveling so as to obtain the right to access a facility or resource (e.g., in this case, travel slots to visit the downtown area). This concept is relatively new to traffic congestion management. However, it is widely used in other domains (e.g. reserving in advance an airline seat, a hotel room, a rental car, etc.). From the provider's point of view, a reservation system can function as a control mechanism that oversees the sales of a resource given that traffic congestion, as an emergent phenomenon of individuals' actions, is hard to understand and predict. Moreover, from the consumer's perspective the reservation system ensures less uncertainty in obtaining the desired resource.

With the advent and deployment of advanced traveler information systems (ATIS), drivers' behaviors should be better understood. However, in the absence of appropriate control mechanisms, this information is still of relatively limited use (Levinson, 2003). Dynamic variations in utilization of transportation capacity can result in serious traffic congestion.

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Congestion pricing has tried to tackle the problem from an economic disincentive point of view, while a reservation system proposes to primarily address the problem from a rationing policy perspective. "Under rationing, automobile access to portions of the road network is allowed only to users with specific needs assessed by the Public Administration. While, on the contrary, under pricing, passage through some arcs of the network is permitted only to those users willing to pay" (Gentile et al., 2005, p. 3). It is apparent that congestion pricing is more flexible than a reservation strategy, in the sense that people are free to choose whether to travel, as long as they are willing to pay. However on the other hand, flexibility generates uncertainty in the demand patterns and thus variation in the road traffic. In this case, a reservation system can be introduced as an additional mechanism to cope with this uncertainty.

In this paper, we explore the application of a reservation concept within a traffic congestion management framework. The purpose of the paper is to provide an analytical model to allow the transportation authority to make decisions as to which requests should be accepted by the system. In particular, the reservation system will be introduced for a cordon based downtown road network, and hence it is called the downtown space reservation system (DSRS). We use the term "cordon" to define the physical boundary of the system. This means that the vehicles passing through the cordon will be the ones that will be managed by the system. In addition, considering the scope of this research, the current paper will not take into account problems related to dynamic reservation pricing since the price is assumed fixed and known for different types of vehicles and time slots.

This research contributes to the literature in two ways. First of all, it provides an analytical approach that demonstrates the way that a reservation system can potentially work within a congestion management context for a downtown area. Second, the proposed approach helps decision makers to consider congestion from a resource capacity limitation point of view, where the capacity of a road network is clearly defined. Furthermore, the design and implementation of this system borrows concepts from congestion pricing, especially cordon-based congestion pricing because of the commonality between the two approaches. It is the intention of this research to build on the considerable research and practical experience in the literature with respect to congestion pricing. However, the proposed TDM strategy is not intended to substitute congestion pricing, or any other existing TDM strategies. Instead, together

with other TDM strategies, it expands the solution domain for congestion management, especially for metropolitan areas.

The paper is organized as follows. The research context is provided in Section 1 whereas Section 2 presents a brief overview of the literature that covers earlier work on reservation systems. Section 3 provides the approach and methodology associated with the downtown space reservation system. To illustrate how the system would work in practice, a numerical example is provided in Section 4 along with a brief discussion of travel demand generation. Some implementation issues are provided in Section 5. Finally in Section 6, conclusions and future research recommendations are presented.

2.0   Background

Although reservation systems have been investigated for a number of industries such as airway transportation (McGill and Ryzin, 1999; Li, 2001) along with hotels (Badinelli, 2000), for railways (You, 2008), for sea cargo (Ang et al., 2007) and for parking (Teodorović and Lučić, 2006), it is not until the late 1990s that the concept was introduced into roadway transportation for travel demand management purposes. Nevertheless, very limited research is devoted to this topic. Wong (1997) illustrates the basic concepts of a new way to manage highway traffic by a highway reservation system, where he proposes a booking procedure to govern traffic by controlling the individual driver's departure time and associated routes by requiring the driver to reserve in advance. In this work, it is stressed that even with the most advanced driver information system, it is still necessary "to promote sustainable travel patterns and improve road system performance" (Wong 1997 p. 109). He defines the functions of a highway reservation system as follows: (1) controlling traffic flow by spreading peak demand over time and space; (2) responding to the predicted capacity reduction and avoiding associated congestion; (3) managing the operating time and route of certain specific types of vehicles; (4) providing more accurate travel information to travelers; (5) offering alternative ways for road pricing and priority schemes for different types of vehicles such as, high occupancy vehicles, trucks, etc. Although these functions were defined for a highway reservation system, they can be considered applicable for the downtown space reservation system as well. In the end, he suggests that this type of system is promising, even though it will take a long time before it could be successfully implemented.

Feijter et al. (2004) perform simulation experiments to justify the advantages of a reservation system by improving travel time reliability[6] and enhancing the effective use of road capacity. Akahane and Kuwahara (1996) explore the possibility of using a trip reservation system to mitigate traffic congestion at bottlenecks on holidays by adjusting driver departure times. The effects of this system are assessed based on a stated-preference survey that addresses travelers' attributes, the characteristics of trips and preferences associated with the conditions of trip reservations. The results were found to be promising.

This previously described work primarily focuses on conceptually discussing the merits of a reservation system without providing the details of an analytical approach, until Edara and Teodorović (2008) discuss a comprehensive model for a highway reservation system, where the system is capable of allocating highway space to a variety of potential users during different time intervals and accepting/rejecting driver travel requests. In this work, the highway allocation system is formulated as an integer programming problem maximizing passenger miles. Based on the optimization results, a real time highway reservation system is developed using neural network technology. The research methodology used in this work, as well as the reservation concept with respect to highway management, provides a viable foundation for the downtown space reservation system presented in this paper.

The existing literature emphasizes reservation systems for highways. The reason is understandable, as Wong (1997) claims that implementing a reservation system to a freeway should be simple, but it would be much more difficult to implement this type of system for an urban network considering the route choice and administration complexity. Nevertheless, as one explores the tradeoff between the first-best pricing strategies and second-best pricing strategies[7], it is not always necessary to cover all the streets in the reservation system, and each link within the network does not have to be managed individually. For example, more and more evidence has suggested that cordon-based control can be a viable option for congestion mitigation in a downtown area. London and Stockholm have both successfully implemented cordon-congestion congestion pricing schemes. Therefore, one can use the same principles associated with

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[6] Travel time reliability is defined as the percent of trips that reach a destination over a designated facility within a given travel time (or equivalently, at a given travel speed or higher) (Elefteriadou and Cui, 2007).
[7] In first-best pricing every individual road user is charged his/her exact marginal external congestion cost for each link, while second-best pricing is a mechanism that charges the user only for partial use of the network. Cordon-based congestion pricing is a second-best congestion pricing strategy.

implementing a cordon-based pricing scheme to address the complexity of a reservation system for an urban street network.

This research differentiates itself from the literature in two aspects. First, the proposed approach is developed for a downtown network characterized by its unique infrastructure and traffic attributes, while other reservation systems only consider a segment of a highway. Second, instead of emphasizing each origin-destination (O-D) trip and its route in the road network, the actual travel route of each vehicle is ignored, and vehicles are controlled only when passing the cordon boundary. In this way, the formulation of a downtown space reservation system is simplified.

3.0   The Downtown Space Reservation System

3.1   Introduction

Under the downtown space reservation system, people who want to drive downtown send their requests to the infrastructure manager before their trips occur. A trip request should include their desired entry time, exit time, associated reservation price and other necessary trip attributes. Only those who get permission from the transportation authority can drive in the downtown area. From a driver's perspective, what they need to do is to express their preference via some media, which could be the internet, phone etc. The transportation authority evaluates the request against the available resources on the road network and makes the decision on whether to accept an incoming request. If the current request meets the acceptance criteria set by the system, such as occupancy and/or reservation price, then the request is accepted, otherwise it is rejected.

The motivation of tackling the traffic congestion for downtown area in any metropolitan city is obvious. The downtown is typically the economic engine of the area, and it typically suffers from even worse congestion conditions than the rest of the city. At the heart of the area one finds a high concentration of businesses, government agencies, media and heritage enterprises, many departmental shops, large office buildings, pubs, cinemas, etc. There is very little, if any, open space left between buildings and infrastructure expansion and construction is difficult. Furthermore, the downtown area normally is the oldest part of the city. Transportation infrastructures were typically built long time ago and many of them have fewer and narrower lanes that have severely deteriorated over time. Consequently, these infrastructures do not have the ability to carry any excessive vehicles and maintenance is costly. Many people work in the

area and many of them own and use private cars. Shortage of off-street parking always means that people are parking on the roads or wandering to find a spot, which increases congestion.

When considering the road network characteristics, generally, such a network consists of a great number of short links and intersections. For any origin destination (OD) pair, there are many routes to travel along. The road network is rather dense, taking into account the size of the downtown area. Therefore, it is administratively prohibitive to control the traffic flow on each link individually. Furthermore, unlike a highway network that often exhibits bottleneck congestion, congestion in the downtown is typically area-wide. To solve area-wide congestion, it is not necessary to manage the traffic flow on each link individually. Therefore the cordon-based control can be a worthwhile approach to investigate, where the transportation authority selects a certain relatively small area, establishes a cordon around it, and controls vehicles crossing a specific boundary into the designated area. Every driver passing the cordon has to book in advance and pays the fee that is independent of the distance traveled and route followed before and after passing the cordon.

Generally, a road network consists of nodes, links. For a downtown network, a boundary can be included, which is a fictional closed loop that defines where the cordon is located. The loop can be defined by existing roads, bridges or other geographical marks. Questions about the location of the cordon and whether it is a single-loop cordon or multiple-loop cordon have been studied in the existing literature (May and Liu, 2002; May and Shepherd, 2002). Although they provide many theoretical guidelines to this problem, in practice, the answer highly depends on the circumstances the specific city is facing. Nodes where one can enter or leave the network are referred to as control points. Taking the Stockholm congestion pricing scheme as an example (Figure 3-1), the dotted line is the controlled cordon, and the numbered red dots denote control points, only through which vehicles can enter or exit the cordoned area.

The nature of the roadway network in this context is very similar to a rail system where passengers can board or detrain only at specific stations. The control points can be viewed as stations through where vehicles can access the roads within the cordon. The roads can be thought of as the railway. A vehicle can be compared with a passenger on a rail train. The optimal number of vehicles moving in the network is similar to the capacity of a train, which is the total number of seats in the train (Wong, 1997). Therefore, this number is defined as the capacity of the downtown network. In the Highway Capacity Manual (HCM) (1985), capacity is

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defined as the maximum flow of vehicles per hour that can be reasonably expected on a particular segment of a highway during a given time period under prevailing roadway, traffic, and traffic light control conditions.

In this research, the capacity of the network is assumed as the total capacity of the individual links that comprise the network. This is considered as an ideal capacity. However, if one considers the various interactions, the capacity is typically different than the ideal one. For instance, the traffic flow on a link may interact with the other links in the network. If traffic flow on one link is excessive, vehicles that are supposed to flow to this link are partially stuck on the other links, resulting in congestion on the other links. Methods and issues for downtown network capacity determination will be discussed in Section 3.3.1.
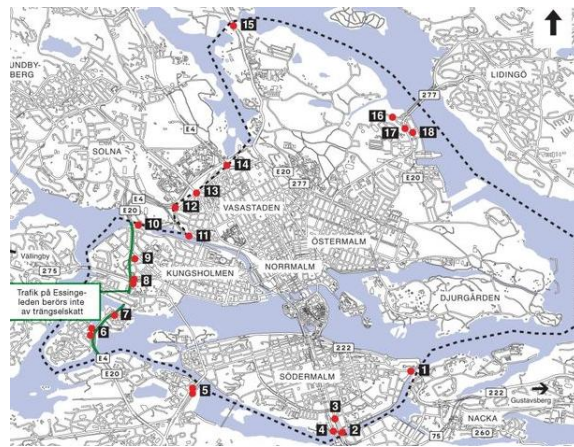
Figure 3-1 Stockholm Congestion Pricing Cordon
(Source: City of Stockholm, 2006)

From a hardware (for example, a toll collection system, radio communication devices, and automated vehicle occupancy monitoring etc.) view point, the feasibility of implementing this downtown reservation system should not be a problem given the recent advances in information-networks and road to vehicle communication technologies, especially various electronic toll collection techniques. These and other implementation issues will be discussed in Section 5.

3.2   Methodology

If customers are all homogeneous, with identical products, the reservation system would be rather simple. Customer requests would be accepted until resources (products) stored are consumed. However in many cases, both customers and products are heterogeneous. This

triggers a series of issues. How should the resources (products) be rationed among different customers? Are the products really differentiated and according to which criteria? How can the customer pool be segmented? Answers to these questions are required for the effective design of a reservation system. Each of these issues is worthy of substantial research. Yet, similar questions for airline reservation systems have been widely investigated in revenue management literature. Revenue management is defined as the art of maximizing profit generated from a limited capacity of a product over a finite horizon by selling each product to the right customer at the right time for the right price (Pak and Piersma, 2002). This perspective provides valuable insights for the design of the downtown space reservation system.

The fundamental reservation management decision is whether to accept or reject a request. We always want to accept those requests that are more preferable according to the reservation policy. As the example of airline reservations suggest, requests in higher tariff classes are preferred, while minimizing the chance of flying with vacant seats. This strongly supports the revenue maximization objective. If the demand is deterministic and known at any moment, there would no problem to achieve maximum revenue. Unfortunately, demand varies with time. For the downtown space reservation system, we also face the same problem, i.e., when to accept or reject a request facing unknown future demand. To solve this problem, we provide an initial formulation and solution by not considering the dynamic nature of demand. Then we will discuss how the dynamics of demand can be considered by the system when one later interfaces with the deterministic module that is called the offline optimization module. In this module, the problem is formulated as a multiple objective integer programming where different behavioral objectives are given appropriate weights. In order for the system to work in real time, artificial neural network technology will been used in an on-line module that deals with dynamic demand in real time.

3.3 The Offline Optimization Module-Model Formulation

Before presenting the module, some major assumptions are made as follows: Historical demand and reservation information is assumed attainable. This indicates one knows the exact number of trip requests days before the actual trips take place and along with their associated attributes, such as, vehicle occupancy, scheduled trip departure time etc. Examples of trip requests are provided in Table 3-1. However, since a reservation system does not yet exist, it is impossible to obtain the equivalent of "real" information as depicted in Table 3-1. Given this

situation, we will utilize some existing data and then simulate additional required information. The existing data that was used in this research include traffic flows, vehicle occupancy and classes from the Census Transportation Planning Package and Virginia Department of Transportation. The generation of the additional data will be discussed in detail along with the numerical example later in this paper.

<div align="center">Table 3-1 Travel Demand in Downtown Space Reservation System</div>

Request ID	Time of Making Request	Requested Entry Time (e_i^i)	Requested Departure Time (l_i^i)	Occupancy (psg_i^i)	PCU*	Price(p_i^i)
R_1^1	08/11	8:00	17:00	1	1	1
R_2^1	08/14	11:00	19:00	1	1	1
....		…	…	…	…	…
R_1^2	08/02	8:00	17:00	5	1.5	1
....		…	…	…	…	…
R_1^3	08/07	8:00	14:00	15	2.5	1
R_2^3	08/12	8:00	11:00	13	2.5	1
....		…	…	…	…	…

Note: *PCU, Passenger Car Unit, also called Passenger Car Equivalent, is a metric used in highway capacity analysis. It converts a mixed traffic flow into an equivalent passenger car flow. This allows one to deal with mixed traffic streams more accurately than if it had been assumed all vehicles were created equal. Highway capacity is measured in PCUs/hour.*

Travel demand market can be divided into various segments. This means not all the requests are same. Each trip has its own unique attributes. When decision makers allocate a common resource to them, their uniqueness and commonalities have to be acknowledged. The goal that a system intends to achieve plays an important part in the demand market segmentation. As in revenue management for the airline industry, profit is the primary goal. In this case, customers are classified into various classes, and customers in different classes have to pay different fares. For the downtown space reservation system, travel demand segmentation has to closely respond to its goal of alleviating traffic congestion and improving people's mobility. Because congestion results from excessive accumulation of vehicles using the same road network at the same time, a straightforward idea is to decrease the total number of vehicles. However as any demand management strategy, this is only one aspect of the problem since it is not the intent of the DSRS to compromise people's mobility, which could be achieved by increasing average vehicle occupancy (including encouraging public transit rides) while decreasing single occupancy vehicles.

In this research, people mobility is measured in terms of the total number of people going through the downtown area. Hence, vehicle occupancy could be chosen as one of the criteria to segment travel demand within a downtown area, which includes four categories, single occupancy vehicles, high occupancy vehicles, buses and trucks. A certain portion of the downtown network capacity needs to be allocated to each of them. Meanwhile, one notion needs to be kept in mind is that the objectives of the reservation system cannot be achieved without the help of solid public transportation network. The reservation price is assumed fixed and known for each type of vehicle. The price also depends on what time of the day a motorist enters and exits the congestion charging area. Travelling during peak hour intervals is assumed to be more expensive.

Because the major motivation of the downtown space reservation system is to reduce traffic congestion, reservation during low demand periods (e.g. midnight) is not necessary since the travel demand for those periods is low, and it can be well accommodated by the network. Therefore it is only necessary to control traffic during the time period for which travel demand exceeds the capacity of the road network in the downtown area. As in Stockholm, where congestion charging is in effect only on weekdays 6:30 to 18:30, a similar assumption is made for the DSRS.

The notation used in this paper is as follows: Decision variables

$$x_j^i = \begin{cases} 1, & \text{if } j\text{-th request of demand category } i \text{ is accepted} \\ 0, & otherwise \end{cases}$$

Parameters:

psg_j^i Total number of passengers in the vehicle of j-th request of demand category i

pcu_j^i The passenger car units of j-th vehicle of demand category i

p_m^i The reservation price of time slot m for demand category i

$$a_{jm}^i = \begin{cases} 1, & \text{if } j\text{-th request of demand category } i \text{ is included in the } m\text{-th time interval} \\ 0, & \text{otherwise} \end{cases}$$

e_j^i The entry time of j-th request of demand category i

l_j^i The departure time of j-th request of demand category i

Δt The length of each time slot

C Transportation network capacity

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U_m^i Upper bound of the demand category *i* in time slot *m*

L_m^i Lower bound of demand category *i* in time slot *m*

R_j^i *j-th* request in demand category *i*

I   Total number of demand categories

J   Total number of trip requests

M   Total number of time slot during the control period

Under the downtown space reservation system, traffic authority personnel make decisions on who can finally drive into the downtown at their desired time under the condition that, at any moment, the total number of vehicles (TV) within the cordon area does not exceed the capacity limit (C). The total number of vehicles is the accumulation of the vehicles entering minus those departing (flow over time). We denote the entering traffic flow as inflow (f_{In}), and departing flow as outflow (f_{out}). The total number of vehicles (TV) running within the cordon area equals:

$$TV(t) = \int_{t_0}^{t} f_{In}(t)dt - \int_{t_0}^{t} f_{out}(t)dt \le C \tag{1}$$

Equation (1) ensures the capacity is not violated. This means that the inflow and/or the outflow have to be managed continuously over time. The continuous assessment of the capacity violation Equation (1) is administratively prohibitive. Nevertheless, to make the problem manageable, let us consider dt as Δt, where $\Delta t \gg dt$. Equation (1) can be rewritten as:

$$TV(t) = \sum_{i=1}^{n} f_{In}(\varepsilon_i)\Delta t_i - \sum_{i=1}^{n} f_{out}(\varepsilon_i)\Delta t_i \le C \tag{2}$$

Therefore, instead of dealing with a continuous formulation, the system can be monitored in a discrete manner. The magnitude of Δt is determined by two factors, i.e., the variation of the traffic flow with time and the desired precision of the final results. Hereafter, Δt is called a time slot. For illustrative purposes, let us assume the control period starts at 7:00am in the morning and ends at 7:00pm in the evening, and the entire period is divided into one-hour intervals, which means $\Delta t = 1$ (Figure 3-2). To facilitate the expression of Equation (2) and make it more straightforward to understand, we introduce the parameter a_{jm}^i, indicating the status of a time slot respect to a specific request.

Each arrow in the Figure 3-2 represents a request submitted by users. For example, R_2^1 is the second request in class 1. For this specific trip, the driver desires to drive into the downtown area at 8:30 in the morning and leave the area around 1:30 during the same day. The time

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interval (8:30am to 1:30pm) when the vehicle is residing within the cordon intersects with time slots defined by m=2, 3, 4, 5, 6, 7. Hence, there are: $a_{2m}^1 = 1$ for $m = 2,3,...,7$, $a_{2m}^1 = 0$ for $m = 1,8,9,...,12$. And for each request there is a corresponding time slot vector expressed in a similar fashion as: $a_j^i = (011111100000)$

Then relation (2) can be reformulated as:

$$\sum_{i=1}^{I}\sum_{j=1}^{J} a_{jm}^i \le C \text{ for m} = 1, 2, ..., 11, 12.$$ (3)

As it has been stated that R_j^i is only a request. In other words, only if this request is accepted by the system, the associated requested trip will turn into an actual travel activity in the near future. Therefore, more precisely, what the decision maker is interested is:

$$\sum_{i=1}^{I}\sum_{j=1}^{J} a_{jm}^i x_j^i \le C \text{ for m} = 1, 2, ..., 11, 12.$$ (4)

Relation (4) is the primary constraint the system is subject to. Any objective function has to be accomplished under this condition.
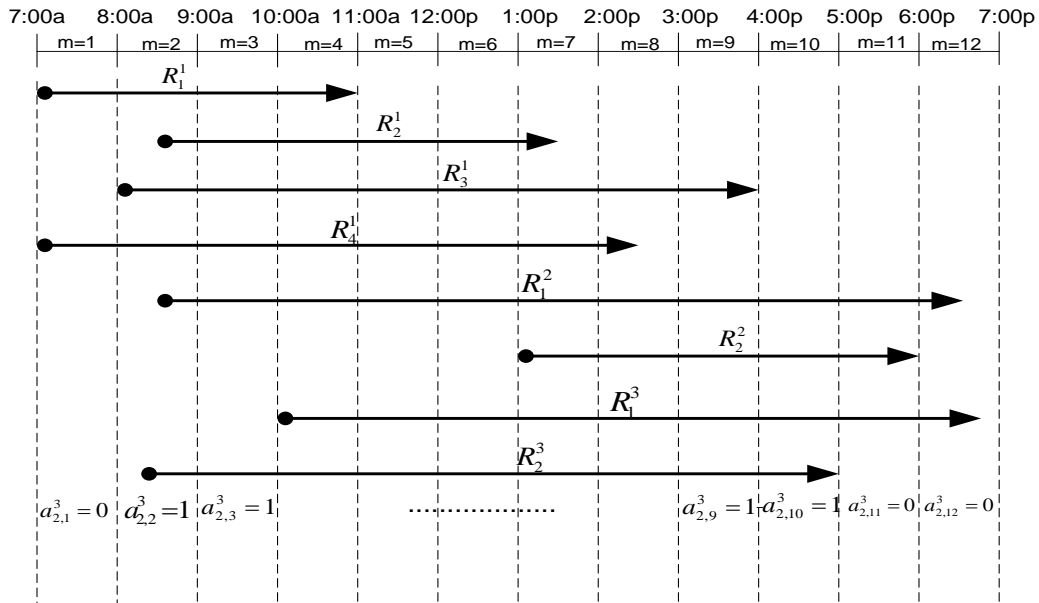
Figure 3-2 Reservation System Modeling

Two objectives are pursued for the reservation system. On one hand, the downtown space reservation system as a member of travel demand management strategy family, shares the common goal of any TDM, i.e., reducing traffic congestion. On the other hand, the revenue

maximization cannot be ignored. First of all, this is consistent with the road pricing philosophy – the price of using a road should be equal to the cost of using the road. Second the revenue generated provides a crucial funding source that can be used to improve roadway conditions and performance of public transportation. It is ideal to achieve both objectives simultaneously, but the two objectives might be conflict with each other. In this case, multi-objective programming is proposed.

The general form of multi-objective optimization problem with n decision variables, m constraints and p objectives is:

Maximize

$$\mathbf{Z}(x_1, x_2, \ldots, x_n) = [Z_1(x_1, x_2, \ldots, x_n), Z_2(x_1, x_2, \ldots, x_n), \ldots, Z_p(x_1, x_2, \ldots, x_n)] \quad (5)$$

Subject to: $\quad g_i(x_1, x_2, \ldots, x_n) \leq 0, i=1,2, \ldots, m$

$$x_j \geq 0, j=1,2, \ldots n$$

Where $\mathbf{Z}(x_1, x_2, \ldots, x_n)$ is the multi-objective objective function and $Z_1(x_1, x_2, \ldots, x_n)$, $Z_2(x_1, x_2, \ldots, x_n), \ldots, Z_p(x_1, x_2, \ldots, x_n)$ are the p individual objective functions (Cohon, 1978).

Therefore the objective function for the reservation system is denoted as:

$$\text{Maximize } \mathbf{Z} = [Z_1(X), Z_2(X)] \quad (6)$$

Where
$$Z_1(X) = \sum_{i=1}^{I} \sum_{j=1}^{J} \frac{psg_j^i}{pcu_j^i} x_j^i \quad (7)$$

$$Z_2(X) = \sum_{i}^{I} \sum_{j}^{J} \sum_{m}^{M} p_m^i a_{jm}^i x_j^i \quad (8)$$

$Z_1(X)$ stands for the objective of increasing people throughput, measured in persons, and $Z_2(X)$ is the revenue objective, measured in dollars. The two objectives are neither additive nor multiplicative in the sense that they represent different physical entities.

There are various solution techniques for a multi-objective programming problem, such as multi-attribute utility functions, minimum distance from the ideal solution, goal programming, prior assessments of weights, etc. For the details of each technique refer to Cohon (1978). Prior assessment of weights is adopted in this research. With this method, the multi-objective is actually reduced to a single-objective problem. The weight w is equivalent to the identification of a desirable tradeoff between Z_1 and Z_2.

Equation (6) becomes:

$$\text{Maximize } \mathbf{Z}(w) = Z_1(X) + wZ_2(X) \quad (9)$$

Where w is measured as people/dollar and indicates the tradeoff of serving additional people in relation to one additional dollar in revenue. Overall the model is expressed as follows, and it is transformed into a single objective integer programming.

$$Max \sum_{i=1}^{I} \sum_{j=1}^{J} (\frac{psg_j^i}{pcu_j^i} + w\sum_{m=1}^{M} (p_m^i a_{jm}^i))x_j^i \qquad (10)$$

$$s.t. \sum_{i=1}^{I} \sum_{j=1}^{J} x_j^i pcu_j^i a_{jm}^i \leq C_m \quad m = 1,...,T \qquad (11)$$

$$x_j^i = \{0,1\} \quad i = 1,..., I; j = 1,..., J \qquad (12)$$

The objective function (10) represents the total number of persons passing though the cordoned area over the defined control period along with the computed revenue. Each request is only permitted to make one reservation for one vehicle trip. Equation (11) is essentially the same as the capacity constraint equation (4), except for the inclusion of the number of PCUs. This assumes that capacity is measured in PCUs.

In addition, two auxiliary constraints (13) (14) can be introduced to take into account some practical issues. For instance, according to the solution from the above integer programming formulation, certain type of vehicles, such as trucks may be completely eliminated from the area. Although the solution maximizes the intended objective function, in order to ensure the necessary goods are supplied, a minimum portion of downtown capacity needs to be protected for trucks. Furthermore, to make sure certain special needs, such as ambulances, fire engines, are met, decision makers can always set aside a certain number of vacancies for emergency vehicles. The definition of the limits associated with these constraints is not determined by the reservation system but are pre-determined by the decision makers. Therefore, the following two constraints are not mandatory, instead, they are proposed as auxiliary.

$$\sum_{j=1}^{J} x_j^i pcu_j^i a_{jm}^i \leq U_m^i \quad i = 1,..., I; m = 1,...., T \qquad (13)$$

$$\sum_{j=1}^{J} x_j^i pcu_j^i a_{jm}^i \geq L_m^i \quad i = 1,..., I; m = 1,...., T \qquad (14)$$

3.3.1 Network Capacity Determination

In highway management, capacity has been measured in passenger car units (pcus)/hour for a highway segment. The actual capacity can be measured at a certain point of the highway by counting the number of vehicles passing through that location during the hour. For a

network with one origin, one destination, and one user class, the capacity is determined by the minimum of cut-set capacities[8] (Bell and Lida, 1997). However, for more general networks with multiple origins, destinations, there is no method for determining an area-wide road network capacity (Bell and Lida, 1997). Therefore, an open question is how to define the area-wide road network capacity. In this research, we propose an alternative method of dealing with capacity determination based on the fundamental traffic flow theory based on volume, density and speed.

Road traffic in a specific state is always characterized by flow (q), density (k) and speed (u). Flow rate is traditionally the most important quantity. It is important for the performance of the transportation network as a whole. Flow is labeled sometimes as throughput, and transportation engineers also use the term volume and it represents the number of vehicles that passes a certain cross section per unit of time. Maximum flow is also called capacity. Density reflects the number of vehicles per kilometer of road. Speed, flow, and density are related to each other. When the total number of vehicles operating on the link reaches a certain upper limit, the flow and speed fall to zero, and traffic stops. This point is known as jam density (k_j). On the other hand, when density is extremely low, a free flow speed (u_f) can be obtained. Both of the two extreme conditions are undesirable. Because when traffic flow is close to jam density, it may indicate network resource has been overused and congestion is imposed. However, when the density is extremely low, the resource could be underutilized. Several models that relate the variables q, u and k with each other have been developed based on various assumptions regarding the manner in which traffic streams flow. The most widely used of these is Greenshields equation developed in 1935 (Daganzo, 1997). Greenshields assumed that there is a linear relationship between speed and density. The fundamental relationships are used here to derive a maximum number of vehicles on a link, so that the traffic flow reaches its maximum at this point. The combination of this number for a set of links (A) is called as the network capacity hereafter. As shown in Appendix n^* is the number of vehicles that achieves maximum throughput is:

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[8] Cut-sets is a very important concept in network flow analysis. The definition of cut-set is:

Let X be any set of nodes in the network such that X contains node 1 but not node m. Let $\overline{X}$ = N –X where N is the total number of nodes in the network. Then $(X, \overline{X}) \equiv \{(i, j) : i \in X, j \in \overline{X}\}$ is called a cut-set separating node m from node 1. (Bazaraa et al., 1990)

$$n^* = \frac{lk_j}{2} \tag{15}$$

If the total number of vehicles moving along the link exceed n^*, the traffic condition deteriorates and dampens the throughput of the system. Assuming the interactions among various links are negligible, for a network consisting of a set of links (A), the maximum flow, thus the capacity of the network is calculated as:

$$n^A = \sum_{i \in A} n_i \tag{16}$$

For the downtown area, this only represents the capacity of the road network. Besides, the parking space also has to be incorporated, because it can accommodate a portion of the vehicles. At any time, there is certain portion of the vehicles in the downtown area parked somewhere, rather than running on the streets. If we take this into account, and denote the total number of parking places in downtown as P, the maximal number of vehicles in downtown equals:

$$C = n^A + P \tag{17}$$

In the above calculation, certain assumptions are made. One is homogenous density over the downtown network. It is true that in reality, some links may be more congested than others in many cases. However in a relative crowded downtown with area-wide congestion, the density over the road network is relatively close to homogenous. Second, the interactions between links are not considered along with the influence of intersection signals. When considering all these factors, the total maximum number of vehicles ought to be less than the value obtained using the stated approach. However, this approach still provides a basic reference point of downtown network capacity, and could serve as a basis for a further study of downtown capacity.

It is not the intent of this research to limit the methods of determining the downtown network capacity to this method only, but to provide this method as one many possible approaches. Several other directions could provide alternative methods regarding the determination of capacity. One direction is to derive capacity from the intersection capacity as transportation professionals argue that traffic speed and flow on urban streets are determined primarily by intersection capacity (http://www.vtpi.org/). Another way of dealing with the determination of capacity is to take into account the routing problem, which is essentially the traffic assignment model. However, the potential approaches are not confined to these. To evaluate which method would provide a more effective capacity analysis, further comparison research is needed.

3.4 On-line Decision Making Module-Neural Network Model

If we can precisely predict the cumulative demand of all the trips over the next day, making real time decisions would not be difficult by solving the integer programming formulation as it is presented in the Section 3.3. However, demand is uncertain. Even with the most sophisticated prediction technology, it is still hard to precisely predict the future. But the uncertainty does not mean intractable, given that various travel demand prediction tools exist, providing valuable insights when determining travel demand. In this research, in order to take into account the dynamic nature of demand, an artificial neural network will be used. Neural networks are highly capable of pattern recognition, classification and forecasting since they can approximate various functional forms. The purpose of the neural network is not to substitute for a sophisticated demand forecasting technology. Instead, it intends to provide a straightforward and readily available approach that can be used for the implementation of the proposed downtown space reservation system (DSRS). Inherently, neural network technology in this application, still utilize its strength in recognizing patterns in historical data and adapting itself to a new set of data.

A neural network is an adaptable system that can learn of relationships through repeated presentation of empirical data, and is capable of generalizing to new data. It consists of an array of processing elements (PEs) that can be organized in different architectures. A PE is also called neuron. Each PE multiplies the input flowing into it with a set of weights, and transforms the input into an output value. The connected PEs form a network and with the associated weights together the network is capable of providing a complex global function. Generally there are two basic phases in neural network operation. In the training phase, a set of examples are shown to the network, and the learning process is realized by changing the weights to adapt to the desired outputs. After training, knowledge embedded in the examples is stored in the neural network. In the testing phase, the neural network is frozen with the fixed weights obtained from the training phase, and a new set of data is fed into the trained network to produce network output.

The neural network model adopted in this paper is the multilayer perceptron (MLP). Typically, a multilayer perceptron network consists of three layers with feed forward and back propagation learning algorithm. Research (Trappenberg, 2002) shows that generally a three-layer can approximate any function arbitrarily well. The three layers include an input layer, a hidden layer, and an output layer. Each layer consists of a group of PEs. "Feed forward"

indicates information flows in one direction only, from the input layer to the hidden layer and to the output layer. The back propagation learning algorithm ensures the network learns from its mistakes. Neural Network computes the outputs with the current weights, and compares the outputs with the desired results, and adjusts the weights to minimize the difference between the computed and desired outputs. In this research, a well-known commercialized neural network software, NeuroSolutions[9], has been used. In fact, regardless of any particular kind of software used, the procedure of building an MLP neural network is similar. For the downtown space reservation system, the MLP neural network (Figure 3-3) is constructed as follows (Figure 3-4), following the eight-step neural network design methodology proposed by Kaastra and Boyd(1996).

Step 1: Variable Selection

Two classes of variables have to be selected – input variables and output variables. Both input and output variables are determined by the problem itself. In the downtown space reservation system, each trip request is characterized by several attributes, including the time interval within which the vehicle will be downtown, occupancy, and its associated price. The decision maker needs to evaluate the incoming request in conjunction with capacity availability as the request arrives. Two category inputs are included, specific trip attributes associated with the request, and the capacity availability status from the system. Only one output variable is needed, i.e. the acceptance/rejection indicator, indicating whether to accept or reject the request.

Step 2: Data Collection

Data for the neural network are obtained from the previous offline optimization module. In the offline module, we already simulated sets of travel demand data that are suitable for the reservation system. The neural network will be trained based on the original generated demand data and the corresponding optimal solutions obtained from the optimization module.

Step 3: Data Pre-processing

Preprocessing plays an indispensable role in building a successful neural network. The data from Step 2 may not be in the format that is supported by the neural network, and various data transformations are desired for a better performance of the neural network. First of all, the symbolical variables have to be transformed into numerical form. This is done fairly easily within the software itself. Meantime, the capacity availability at any time is not readily available

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[9] NeuroDimentions, Inc., http://www.nd.com

from the collected data. It has to be updated off-line when a new request is accepted, and then computed for each time slot.

Step 4: Training, Testing Sets

In accordance with the general neural network modeling process, the data are divided into two distinct sets called training, and testing sets.
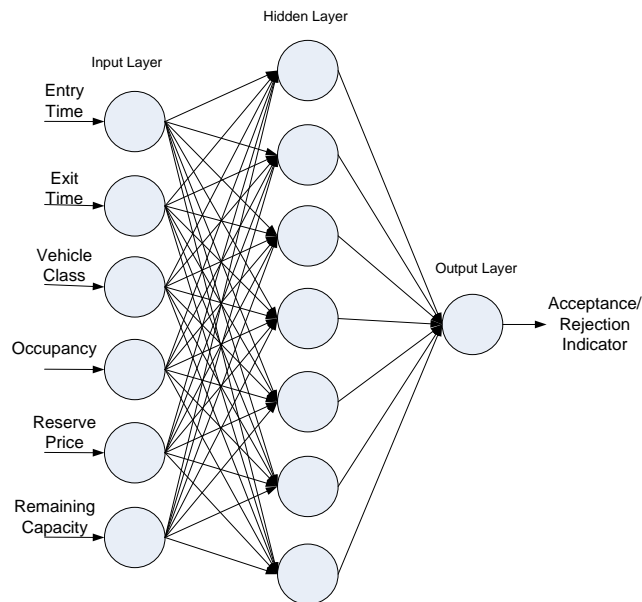
Figure 3-3 Neural Network Structure

Step 5: Neural Network Paradigms

A neural network can be constructed in numerous ways. The architecture of a neural network is mainly determined by the number of hidden layers, the number of neurons in each layer, and the transfer function used. The number of neurons in the input and output layer is determined by the number of input and output variables. There is no straightforward method to find the best number of neurons for a hidden layer. It is generally determined by trial and error. Theoretical results indicate that given enough hidden neurons, an MLP can approximate any reasonable function to any required degree of accuracy (Orr 1999).

A transfer function is basically the mathematical formulas used to produce the output of a neuron. It is often determined by the nature or the data and what the network is trying to learn. One very popular nonlinear transfer function is the sigmoid function. However, others, such as hyperbolic transfer functions, linear functions are also used. It is believed that activity of

biological neurons follows a sigmoid transfer function, but this is not the reason why sigmoid functions are widely used. Actually, the justification is mainly from a statistical point of view, since many neural network applications have shown that the sigmoid function should at least be a baseline model to measure results. A general rule of thumb is that the sigmoid will produce the most accurate model (Duch and Jankowski, 1999). In the current paper, we also started with a sigmoid transfer function, and compared the learning curve with a hyperbolic transfer function learning curve. The numerical example in Section 4 shows that the hyperbolic transfer function outperforms the sigmoid function. Therefore, the hyperbolic transfer function is chosen in this study.

Step 6: Evaluation Criteria

To evaluate how the neural network performs, the mean squared error (MSE) is minimized. The network takes the network's output and desired response, computes the cost as the squared error, and injects the error as derived from the cost into the back propagation plane until the training is stopped.

Step 7: Neural Network Training and Testing

In the training process, a set of examples are fed into the neural network iteratively. In terms of which is the best number of iterations, neural network researchers provide two general thoughts. One is stopping training when the network does not improve the results obtained. The second idea is stopping training after a predetermined number of iterations. The trained network is tested with the testing data sets. If the testing indicates that the neural network has generalized what it has learned from the examples, and capable of being used in practice, then one can start the implementation phase, which is the last step. If not, one may need to go back to the previous steps to find out where the problem lies, and repeat the steps. The degree to which a network learns the problem is best evidenced by a learning curve. Since MSE is used in our example, the curve should approach zero after successful training.

Step 8: Implementation

Although this is listed as the last step, it requires more consideration even before the first step, since implementation is the ultimate goal of any modeling work.
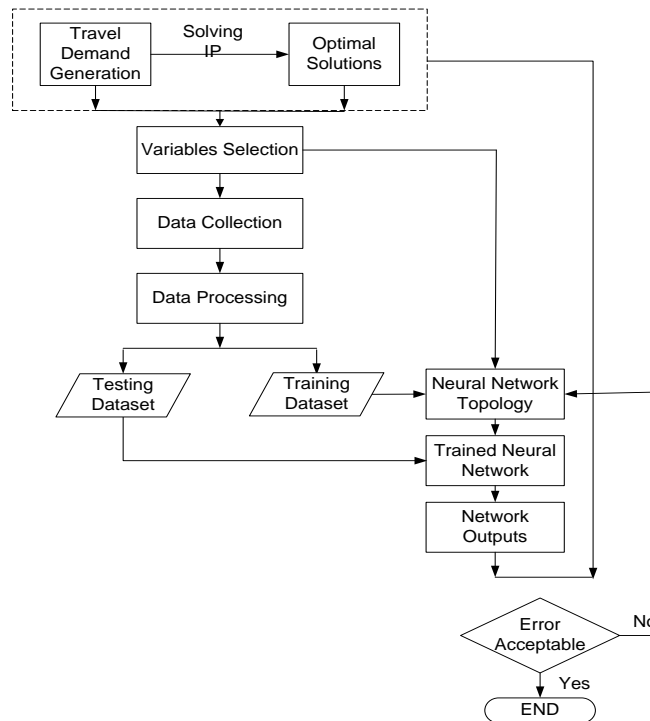
Figure 3-4 Neural Network Process Flow Chart

4.0   A Numerical Example

A numerical example is provided in this section. It is a hypothectical example, and illustrates the way the downtown space reservation system can work, together with a discussion of how to address travel demand data. For illustration purposes, we choose downtown DC as an example. Traffic data from the Advanced Interactive Traffic Visualization System (AITVS) (Spatial Data Management Laboratory, 2007), a web based traffic visualization system, provides a good platform of real-time and historical traffic pattern analysis for I-66 and I-95. However, this small example does not intend to replicate downtown DC to any extent considering the scope of the example (only 5000 trips were generated in this example). Instead, it is only an illustration of the overall methodology and its results.

First of all, let us illustrate how the demand data (Table 3-1) are generated for this example. Because a downtown space reservation system does not exist anywhere yet, it is difficult to obtain precise demand data in the form of individual trip entry time, departure time, vehicle types and occupancy. One possible way to deal with this problem is to generate demand data according to the available aggregate level transportation data.   Once the system is implemented, it would be fairly easy to collect the data for the reservation system. The major

task of demand data generation is to simulate vehicles entering and exiting a downtown area at any moment. Thereafter, cumulative number of vehicles residing in the area can be derived. This is an important parameter that the downtown space reservation system is aimed to control. Expanding on this notion, for a cordon-based TDM strategy, the traffic entering and exiting the area is the summation of the traffic over all the roadways that lead to the downtown (Figure 3-5), as equations (18) (19) below indicate where f_i indicates inflow along path i and f_i' represents the outflow along path i.
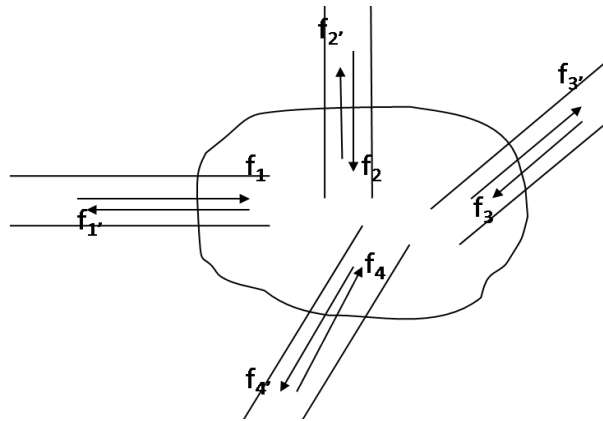
Figure 3-5 An Example Road Network

$$f_{In}(t)\Delta t = f_1(t)\Delta t + f_2(t)\Delta t + f_3(t)\Delta t + f_4(t)\Delta t \qquad (18)$$

$$f_{out}(t)\Delta t = f_{1'}(t)\Delta t + f_{2'}(t)\Delta t + f_{3'}(t)\Delta t + f_{4'}(t)\Delta t \qquad (19)$$

In this example, we propose to extract traffic information from the Advanced Interactive Traffic Visualization System (AITVS). The data generated attempts to simulate the basic demand trend rather than to replicate the exact numbers of the real demand. Taking downtown DC as an example, and assuming that traffic flow on I-66 at a location close enough to DC downtown, adequately represents the traffic inflow and outflow patterns for downtown DC, two traffic observation stations at milepost 51.2 are selected (Figure 3-6). Each station is for one direction. As the data from AITVS shows, generally, a relatively stable pattern exists for week days and weekends. The days that do not follow the general pattern are normally due to special events or accidents. The general traffic flow pattern is shown in Figure 3-7. For the inbound direction, there are two obvious peaks, the morning and evening peaks. However the morning peak is much higher than the evening peak. The outbound direction has a higher evening peak than a morning peak.

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Figure 3-6 Downtown DC Cordon and Traffic Observation Stations
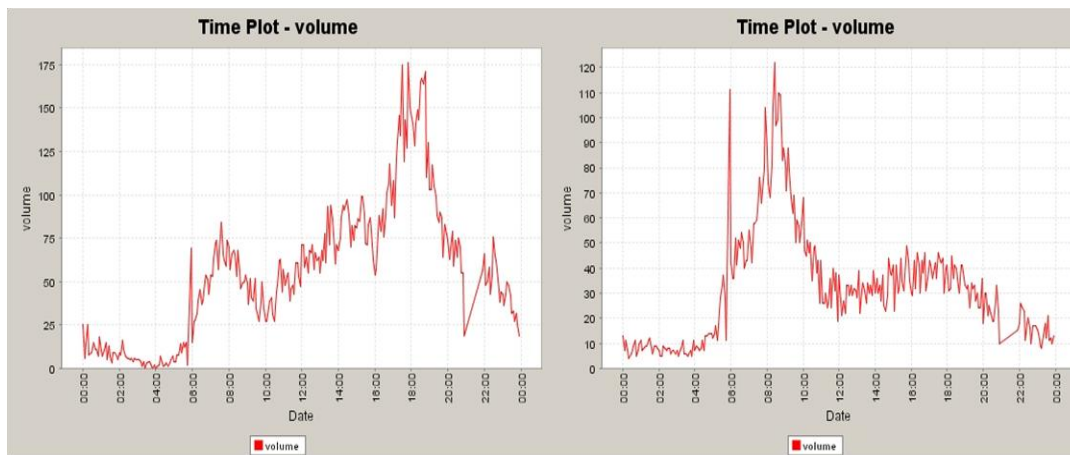
Figure 3-7 Traffic Flow Outbound and Inbound (Source: Spatial Data Management LAB)

Let us assume, in this example, the control period begins at 7:00am in the morning until 7:00pm in the evening on weekdays, and the period is divided into twelve small intervals. Therefore, only traffic data during this period needs to be generated. The generated data follows approximately the same traffic flow patterns as presented above. Traffic volume data are obtained through AITVS. Cumulative traffic volume (in percentage) is derived from the data for inbound traffic (entry). The generated demand has the same percentage distribution. The departure time for each trip depends on its entry time and staying length (departure time = entry time + staying length). Therefore, instead of generating departure time directly, staying length is generated assuming that vehicles entering during different time intervals follow different distributions. For example, for vehicles that enter the downtown area during time intervals in the

morning peak hours, 40% of them will stay a length of time that is normally distributed with $\mu=1$, $\sigma=0.1$, and 60% of them will stay a length of time that is normally distributed with $\mu=8$, $\sigma=0.8$. The parameters of the normal distribution are iteratively determined by comparing the generated outbound traffic volume (departure) with the real traffic flow data (outbound) from I-66. The set of parameters are chosen to approximate the demand distribution of real traffic. The more precise generation of demand data using trip generation models that are typically part of transportation planning is beyond the scope of this paper.

Knowledge regarding vehicle occupancy, vehicle classes, is approximated from two sources, the Census Transportation Planning Package (U.S. Census Bureau, 2005) and the Virginia Department of Transportation (VDOT) Daily Traffic Volume Estimates including Vehicle Classification Estimates (VDOT, 2005). The results are organized in Table 3-2.

Table 3-2 Traffic Composition by Travel Mode

Traffic Composition	
SOV	69%
HOV	23%
Truck	3%
Bus	5%

Apparently, pricing is a critical component of the reservation system. However, it will not be the emphasis in this research. Price varies for different time intervals and vehicle types, but remains fixed within the interval. These prices are only used for illustration purposes in this example (Table 3-3).

Table 3-3 Reservation Price

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
SOV	2	2	2	1	1	1	1	1	1	1.5	1.5	1.5
HOV	1	1	1	0.5	0.5	0.5	0.5	0.5	0.5	1	1	1
Truck	2	2	2	1	1	1	1	1	1	1.5	1.5	1.5
Bus	1	1	1	0.5	0.5	0.5	0.5	0.5	0.5	1	1	1

The generated data are shown in Table 3-4 [10]. The multi-objective optimization programming (Equations 10-13) is solved using AMPL/CPLEX with the data. The optimal results are shown in last column, where 0 indicates the corresponding request is rejected, and 1 indicates it is accepted.

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[10] For details of demand generation in the example, please contact the corresponding author.

Table 3-4 Travel Demand

Request ID	Request Arrival Time	Desired Entry Time	Desired Departure Time	Vehicle Class	Occupancy	PCU	Accept/Reject
R1	0.0107	8.7971	13.3839	SOV	1	1	0
R2	0.0233	7.8603	8.2572	SOV	1	2	1
R3	0.0258	17.3256	17.9646	SOV	1	2	0
….	…..	….	…..	….	….	….	
R4999	111.7941	7.3550	7.4659	Bus	8	3.5	1
R5000	111.8272	9.6205	10.3929	HOV	2	1	1

In the next step, solution from the optimization problem is used to train the neural network, for the DSRS to realize its real-time decision making capability.   In this particular example, 17 input variables are used including 12 capacity variables, one for each time slot, entry/exit times, reservation price, occupancy, and vehicle classes. With a series of trial and error experiments, the hidden layer is determined and it consists of 18 neurons. The network is trained with 2000 epochs. As stated in the section 3.4, the neural network is trained with the sigmoid transfer function first, and then with hyperbolic tangent function. As the learning curve shows in Figure 3-8, although the sigmoid function outperforms the hyperbolic tangent function at the beginning of the training, after about 150 epochs the average cost (computed as mean squared error) of hyperbolic tangent function is lower than that of sigmoid function. A lower average cost indicates a better performance for a neural network. Therefore, the hyperbolic tangent transfer function is adopted for this example.
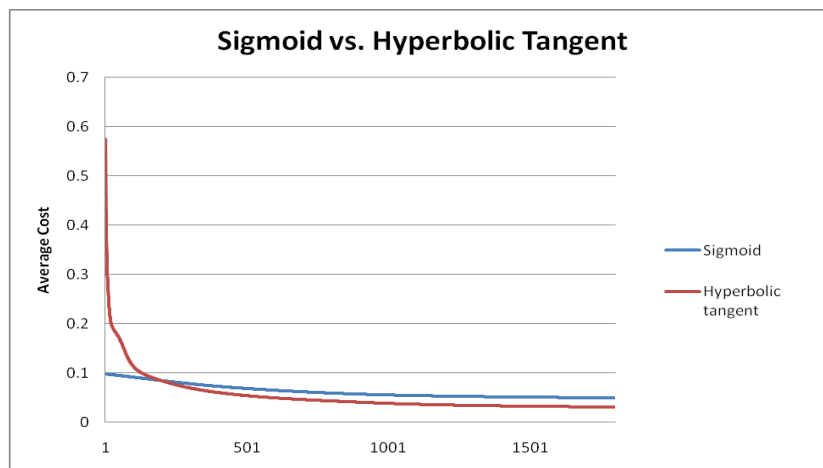
Figure 3-8 Neural Network Learning Curve

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To test the network, let us generate another set of demand data. First, we similarly solve the optimization problem using AMPL/CPLEX, and save the results for future use. Then, the data are fed into the trained neural network. The outputs produced are continuous numbers. However, when making a decision, either the request is accepted or rejected. The results are binary. There is no status between accept and reject. In this case, the continuous outputs from neural network have to be converted to a binary representation. For analysis purposes, we separate the data into two sets according to the optimal solution, one for accepted requests (1s), and the other for rejected requests (0s). Figure 3-9 represents the requests that are accepted by the optimization module. In terms of the neural network output, Table 3-5 indicates that about 92.7% output from the neural network fall in the interval of [0.8, 1], about 5% in between [0.6, 0.8]. Similarly, for the rejected requests, 71% are in [-1, 0], 15% in [0, 0.2], and about 9% in [0.2, 0.6]. We set the neural network output to one if the value of the output is greater than 0.5 then the associated request is accepted, otherwise rejected. Then the error rate, which represents the probability of a request being incorrectly accepted/rejected, is about 4.5%.

Table 3-5 Neural Network Output Intervals

NN Output Value	Rejected	Accepted
<0	70.98%	0.56%
0~0.2	15.01%	0.85%
0.2~0.4	6.63%	0.48%
0.4~0.6	2.14%	0.60%
0.6~0.8	2.98%	4.80%
0.8~1	2.26%	92.70%
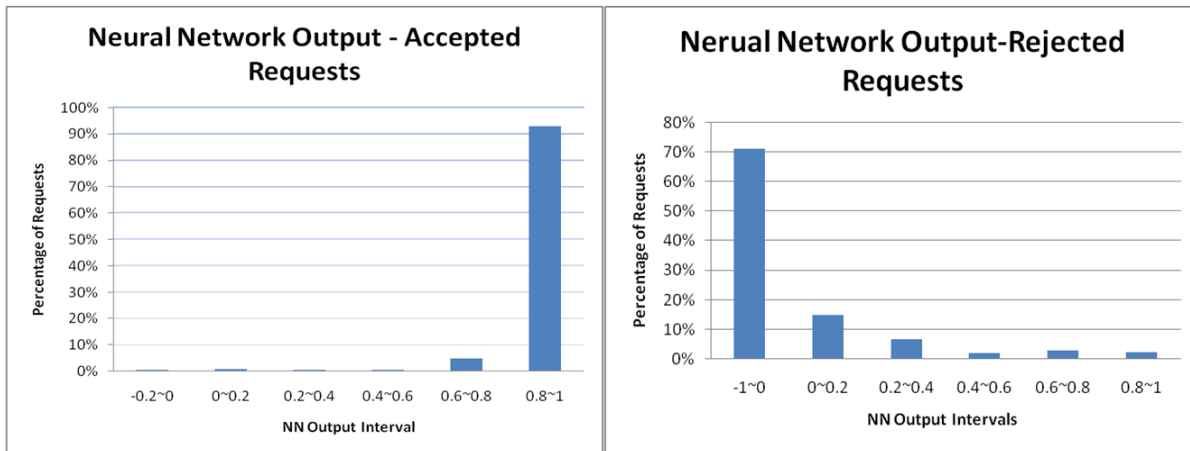
Figure 3-9 Neural Network Output Intervals for Accepted/Rejected Requests

As mentioned previously, this example is intended to demonstrate how the downtown reservation space system can be potentially configured. It is not the intent of this example to provide insights of how a downtown reservation system could impact traffic congestion. This is the focus of subsequent research work.

5.0   Implementation Issues

Although we are yet to reach the implementation phase of this system, it is still possible to identify some implementation issues that need to be considered. First of all, apparently, a downtown space reservation system is a novel strategy. Since the implementation of any significant TDM policy requires a fundamental life style adjustment, it is very important to obtain a public understanding and acceptance. Unfortunately, at the initiation phase, it is rather hard for the public to visualize the benefits. Public resistance and political pressures will always be key implementation barriers. For example, the initial implementation of the London congestion pricing system was fiercely criticized by various interest groups, including politicians, motorists and some business organizations. Nevertheless, after a while, people started to be positive about the program. Even many skeptics and opponents began to acknowledge that the direct costs were offset by the benefits of the congestion pricing policy. Therefore, an appropriate channel to convey the benefits of such a system would be helpful for public acceptance.

People may always argue the following case. What happens when one needs to go to the downtown area but has no reservation (for instance, in an emergency case)? As we have emphasized, the downtown space reservation system as a TDM strategy has to be accompanied with good public transportation. In this case, those trips without reservation (rejected trips) have three choices, e.g. using public transportation, shifting the time of travel, and eliminating the travel need (for example, instead of going to local store to shop, utilize on-line shopping). Special needs like emergency trips, disabled people, can be taken into account in the system design. For example, transportation authority can set aside slots for the emergency vehicles and disabled people.

Others may wonder how the transportation authority can enforce the system, such as if one were overstay in the downtown area. From a technological point of view, such technology already exists, considering the sophisticated tools used in automatic tolls these days, where the

system can exchange information by radio between a vehicle device mounted on a vehicle and a toll/monitoring station. For the downtown space reservation system, the exchanged information includes the actual entry and departure time of the vehicle, and whether they match its reserved schedule etc.

One can render more objections. As the system is still at its early stage, many aspects can be improved upon further study. For instance, the flexibility of the system can be improved through longer term reservation (such as monthly/annually permits) and to study whether to save certain number of slots for the "last minute show ups" that are accompanied with much higher fees etc.

Moreover, an effective TDM, like downtown space reservation system, is not only about designing the program itself. It involves a variety of participants within the community. Pedestrian improvements, transit improvements, alternative work schedules often enhance the synergistic result of a TDM program. One critical point is that motorists have to be provided enough opportunity to take alternative transportation modes. In London, the congestion pricing policy along with improved transit services has played an indispensable part in assuring the success. Similarly for the downtown space reservation system, it is essential to make alternative transportation modes, especially public transit, attractive. This is one of the most valuable insights learned from the experience of both the London Congestion Pricing and Stockholm Congestion pricing schemes.

Various political, ethical, social, economical issues can be obstacles for effective implementation. Downtown space reservation system is still in its infant stage, and this is only an initial research study in this field. It is not the intent of this paper to tackle all of these issues yet exploration of these issues is expected in the future. Finally, an approach that can lead to the consideration of all implementation requirements as well as the life-cycle design of the downtown space reservation system is the systems engineering process discussed by Blanchard and Fabrycky (2006).

6.0   Conclusions and Future Research

In this paper, we explore the applicability of reservation concept for congestion mitigation, particularly focused on the downtown of a city. Although it is called downtown space reservation system, its application is not rigorously restricted to a downtown area. Streets

of a central business district resembling an area could use a similar approach. The proposed downtown space reservation system consists of two modules, an offline optimization module and an online decision making module. In the offline module, an optimization problem is solved based on historical travel information. Multiple objectives are incorporated into the optimization problem. From travel demand management point of view, the mobility of people is improved by restraining the excessive amount of automobiles entering the area. From an economic point of view, revenue is maximized. This revenue can be used to finance public transportation systems. Eventually, the optimization solutions show that under known demand patterns, the system is able to pick the "best" trips and achieve the "best" system performance in terms of congestion mitigation and revenue generation. Needless to say the tradeoff between these two objectives needs to be explored further. Furthermore, HOV and high value trips could be accepted with a greater possibility.

Based on the optimal results from the offline module, an "intelligent" system is developed using neural network technology, a powerful learning approach. Not only is the system able to learn and generalize from the optimal solutions, but the system is also able to update itself, as the new information arrives. With an extensive training, the "intelligent" system can facilitate decision makers to make real time decisions on whether to accept/reject a reservation request. The intelligent system may not guarantee the optimal results compared with the results from the off-line module. However, for a known traffic pattern, it does show a significant consistency. In the numerical example, one can catch a glimpse of the way the in principle works and to what extent the neural network resembles optimality in the offline module. At this initial stage, it may be too risky to test the system for any downtown area. However, in the future it may be worth to develop a prototype and test it in a simulation environment. Leaving aside the implementation aspects, the system can be promising.

Nevertheless, the proposed approach is based on fundamental assumptions concerning the relative importance of revenue generation versus congestion mitigation, the calculation of downtown capacity, the configuration of the neural network, and the consideration of static versus dynamic pricing. All of these issues need to be explored in more depth especially given the implementation challenges discussed in the previous section. Finally, a more comprehensive performance evaluation framework needs to be defined to assess the relative merits of the downtown space reservation system.

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Spatial Data Management LAB, http://spatial.nvc.cs.vt.edu/traffic_zhh/

NeuroDimention, Inc., http://www.nd.com

Appendix

Greenshields assumed a number of fundamental relationships among speed (u), density (k) and flow (q) (See Figure 3-10). The fundamental relationships are used here to derive a maximum number of vehicles on a link, so that the traffic flow reaches its maximum at this point. The combination of this number for a set of links (A) is called as a network capacity hereafter.
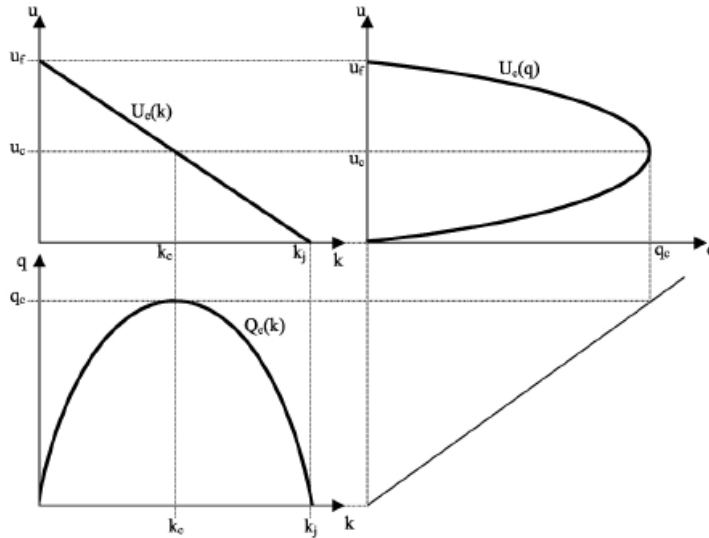
Figure 3-10 Fundamental Relationships

The flow (q) by definition is number of automobiles (n) passing a point over time (t). We denote speed and density respectively by u and k.

$$q = \frac{n}{t}$$

(20)

Travel time along observed link l equals:

$$t = \frac{l}{u}$$

(21)

After substituting (21) into (20) we get:

$$q = \frac{n}{\frac{l}{u}} = \frac{n}{l}u = ku$$

(22)

Speed-density relationship in Greenshields model is denoted as:

$$u = u_f (1 - \frac{k}{k_j})$$

(23)

Combining relations (22) and (23), we get:

$$q = kv = kv_f(1 - \frac{k}{k_j}) \tag{24}$$

According to the definition of density, $\qquad k = \frac{n}{l}$ (25)

Relation (24) can be written as:

$$q = q(n) = kv_f(1 - \frac{k}{k_j}) = \frac{n}{l}v_f(1 - \frac{\frac{n}{l}}{k_j}) = \frac{v_f}{l}n - \frac{v_f}{l^2 k_j}n^2 \tag{26}$$

In relation (26), traffic flow rate is a function of total number of vehicles in the link at that time. For any link, a maximum throughput is desired from a system view of point. To achieve this objective, maximum flow rate needs to be reached. The first order derivative of q(n) is:

$$\frac{dq}{dn} = \frac{v_f}{l} - 2n\frac{v_f}{l^2 k_j} \tag{27}$$

The second order derivative:

$$\frac{d^2 q}{dn^2} = -2\frac{v_f}{l^2 k_j} <= 0 \tag{28}$$

Relation (28) indicates the concavity of function q(n). Therefore we can obtain optimal solution at:

$$\frac{dq}{dn} = \frac{v_f}{l} - 2n\frac{v_f}{l^2 k_j} = 0 \tag{29}$$

Solving equation (29) for n, we can get:

$$n^* = \frac{lk_j}{2} \tag{30}$$

This is the maximum flow rate the link can reach. Under the maximum flow rate, the link achieves its maximum throughput. If the total number of vehicles moving along the link exceeds n^*, the traffic condition will deteriorate and dampen the throughput of the system.

CHAPTER 4 Evaluation of the Downtown Space Reservation System: A Microscopic Traffic Simulation Approach[11]

Abstract

This research investigates the design and impact of a Downtown Space Reservation System (DSRS) presented by Zhao *et al.* (2008) using a microscopic traffic simulation approach executed in VISSIM. The DSRS is part of a Travel Demand Management (TDM) strategy that is designed to mitigate traffic congestion in a downtown urban setting. The simulation is conducted according to an experimental design procedure for a revised road network representing downtown Boise, Idaho. The issues that are tested in the simulation include: (1) whether the DSRS improves traffic performance when compared with the case without the DSRS; (2) how the DSRS performs compared with a reservation system that uses a First Come First Serve (FCFS) principle; and (3) how specific DSRS parameters (such as, the relative importance of throughput versus revenue generation) influence network system performance. Conclusions and future research recommendations are provided based on the insights from the simulation modeling work.

Keywords: Travel Demand Management; Trip reservation; Traffic simulation; Transportation performance; Urban network.

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[11] The paper is under review by Transportation

1.0 Introduction

Various Travel Demand Management (TDM) strategies have been proposed to tackle congestion problems, and trip reservation is one of them. Zhao *et al.* (2008) developed a trip reservation system, named the Downtown Space Reservation System (DSRS). It is a transportation strategy developed for the purpose of congestion mitigation, especially for the center of a city or Central Business District (CBD). Building upon the initial development of the DSRS, this paper will present a microscopic traffic simulation model together with a simulation experimental design scheme for the purpose of evaluating performance of this TDM strategy.

The DSRS is a rather new concept in the realm of TDM strategies and has not yet been implemented in practice. A transportation system is a complex system involving different stakeholders including the government, transportation agencies and the public. To implement the DSRS, research is needed with respect to how well the DSRS will work and additional research is needed to find out what is needed to gain support from various stakeholder groups. So far research has only proposed basic concepts when defining reservation systems as mechanisms to mitigate traffic congestion. This research builds a simulation model to address the evaluation issues of such a system. Multiple experiments conducted within the context of the simulation model show the effects of different system parameters and policies on network performance, and assist decision makers and analysts in gaining more insights about the relationships among various system components and predicting system performance under various conditions.

This research contributes to the literature in two ways. First, from a transportation planning point of view, the proposed simulation approach provides a mechanism to illustrate advantages of the DSRS. It facilitates the promotion of the system and communicates the possible impacts of the system to potential stakeholders. Second, it also facilitates the DSRS design process. Findings and insights derived from simulation results can be used for further modification and improvement of the DSRS.

The remainder of this paper is organized as follows: Section 2 presents a literature review of typical microscopic simulation applications in transportation, indicating the possibilities and challenges in our application. The DSRS is briefly introduced in Section 3. Section 4 describes simulation experiments and the simulation network used in this paper. The results of the simulation experiment are discussed and analyzed in Section 5. Implementation

issues of the DSRS are discussed in Section 6. Finally, in Section 7, conclusions are drawn and future research recommendations are provided.

2.0   Simulation in Transportation Studies

Simulation is widely used in transportation. There are various traffic simulation applications including (1) evaluation of signal control strategies, (2) analysis of equilibrium in dynamic assignment, (3) analysis of corridor design alternatives, and (4) testing new concepts (Lieberman and Rathi 1992). This work falls under the fourth area of testing a new concept. The idea of using simulation to test a new concept is not new. Rathi and Lieberman (1989) used traffic simulation model to test metering control along the periphery of a congested urban area to mitigate the congestion within the area. This early work illustrated the value in testing new "high risk" ventures with simulation without exposing the public to possible adverse consequences. Similarly, Ben-Akiva *et al.* (2003) evaluated four types of traffic control strategies - access control, route control, lane control and integrated control - using a microscopic simulation approach. Simulation is also used in the evaluation of intelligent transportation systems (ITSs) (Barcelo and Codina 2005; Boxill and Yu 2000).

Microscopic simulation related to an urban transportation network is more complicated than modeling an ordinary isolated intersection or a road segment due to the high level of detail and the combination of different kinds of intersections and road network links. Micro-simulation models are limited in scope and scale (i.e., in terms of the network size with respect to links, nodes, and number of vehicles). Although Rakha *et al.* (1998) demonstrated the feasibility of constructing and calibrating a large scale network at the microscopic level in the Salt Lake area, the authors acknowledge the challenge of building such a large network. They emphasized that the data collection and coding exercise is substantially intensive. The successful use of micro-simulation is commonly limited to relatively small size networks (Kitamura and Kuwahara 2005). Nevertheless, due to the development of computer technology and the growing popularity of the micro-simulation, the effort needed to run a micro-simulation will be reduced in the near future.

3.0   The Downtown Space Reservation System (DSRS)

With the DSRS, travelers who want to drive in a designated downtown area have to book their time slots before they make their trips. Reservation requests can be submitted through

different channels, i.e. internet, phone, and local stores. The transportation authority, who administers and supervises the DSRS, allocates the time slots to different travelers based on the availability of resources (i.e., road network capacity) and other criteria such as vehicle classes and reservation revenue. Only those who get permission from the transportation authority can drive in the downtown area during the requested time period. The rejected trips are assumed to be accommodated by other modes such as walking, biking or public transit. The DSRS process is depicted in Figure 4-1. Figure 4-2 illustrates how the monitoring system would work in the field and how traffic data could be collected.

A similar monitoring system has been successfully implemented in Stockholm (IBM, 2007). The system works in the following way:

1. The vehicle breaks the first laser beam, triggering the transceiver aerials in step 2;

2. The transceiver signals the vehicle's onboard transponder, capturing the time and date;

3. At the same time, a camera photographs the vehicle's front license plate;

4. The vehicle breaks the second laser beam, triggering the second camera in Step 5;

5. The second camera photographs the rear license plate without the vehicle slowing down;

6. The vehicle information (including time, date, and license number) is fed back to the central computer and is confirmed with the stored reservation data to see whether the current vehicle is in the booking system.
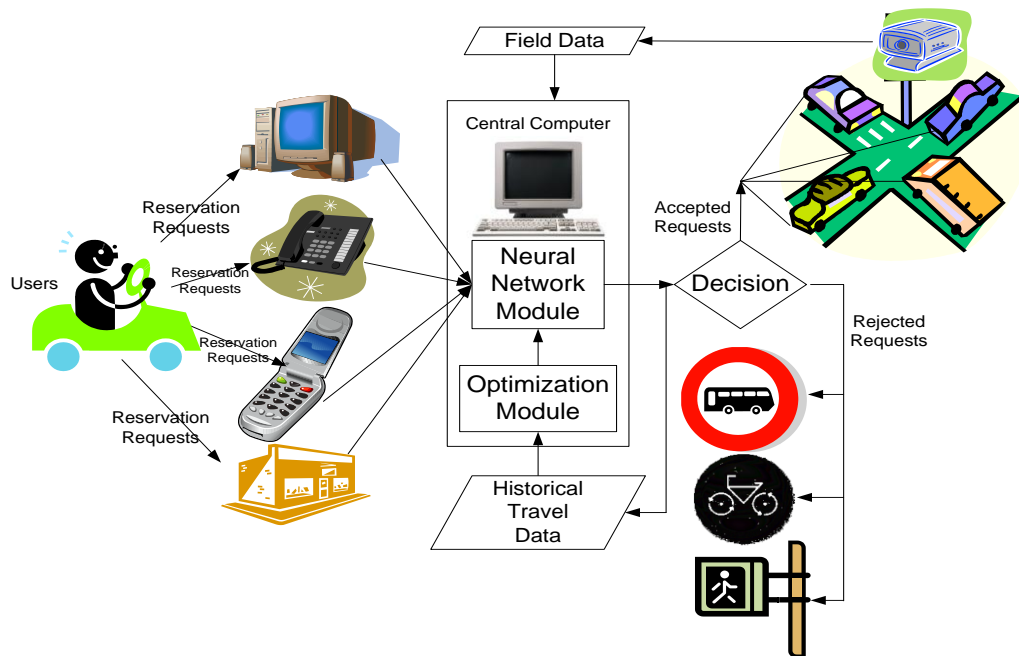
Figure 4-1 The Downtown Space Reservation System

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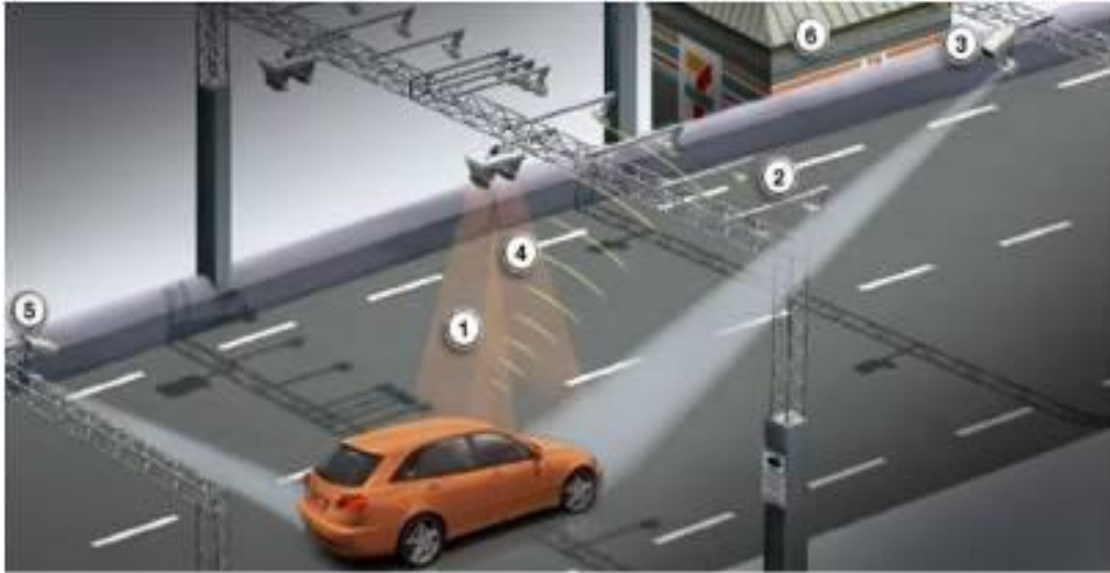
Figure 4-2 The Monitoring System in Field (IBM Corporation, 2007)

The proposed DSRS consists of two modules, an offline optimization module and an online decision making module (neural network module). In the offline module, an optimization problem is solved based on historical travel information. Multiple objectives are incorporated in the optimization problem, i.e. the total number of people that the transportation system handles during a certain time period and the revenue obtained from the reservation system. From a travel demand management point of view, the mobility of people is improved by restraining the excessive amount of automobiles entering the area. From an economic point of view, revenue is maximized. This revenue can be used to finance public transportation systems.

Table 4-1 provides the general data format used in the reservation system. The first seven columns are the reservation request information submitted by drivers, and the last column is the decision solution provided by the system. The "Time of Making Request" shows how long in advance of the trip they make the request, and the "Entry Time" and "Departure Time" show the time the driver wants to enter and exit the area. We assume that people can make request one month in advance of their trips. If people make reservation 3 weeks in advance, they will be charged $0.2 per time slot for HOV, SOV, and $0.4 per time slot for other vehicle classes (Table 4-2). The price is arbitrary and it is only used for experimental purposes in this paper. The passenger car unit is assigned to different vehicle classes according to the general guidelines from Victoria Transport Policy Institute (VTPI, 2008).

Table 4-1 Travel Demand Data in the DSRS

Request ID	Time of Request	Entry Time	Departure Time	Vehicle Class	Vehicle Occupancy	PCU	Accept/ Reject
R1	Week 1	8:05	13:30	SOV	1	1	0
R2	Week 4	7.35	9:35	Bus	8	3	1
R3	Week 2	9:15	10.30	HOV	2	1	1
….	…..	….	…..	….	….	….	

Table 4-2 Reservation Price ($/time slot) and PCU

	Time of Making Request					PCU
	>=4 weeks	>=3 weeks	>=2week	>=1 week	<1 week	
SOV	0.1	0.2	0.3	0.4	0.6	1 or 1.4
HOV	0.1	0.2	0.3	0.4	0.6	1 or 1.4
TRUCK	0.2	0.4	0.6	0.8	1	4
BUS	0.2	0.4	0.6	0.8	1	3

The optimization module is formulated as:

$$\text{Maximize } \mathbf{Z} = [Z_1(X), Z_2(X)] \tag{1}$$

$$Z_1(X) = \sum_{i=1}^{I}\sum_{j=1}^{J} \frac{psg_j^i}{pcu_j^i} x_j^i \tag{2}$$

$$Z_2(X) = \sum_{i=1}^{I}\sum_{j=1}^{J} p_m^i a_{jm}^i x_j^i \tag{3}$$

$Z_1(X)$ stands for the people throughput objective and $Z_2(X)$ is the revenue objective. The multi-objective problem is reduced to a single-objective problem using prior assessment of weights. The weight w is equivalent to the identification of a desirable tradeoff between Z_1 and Z_2, and it takes into account normalization of scales.

Equation (1) becomes: $$\text{Maximize } \mathbf{Z}(w) = wZ_1(X) + (1- w)Z_2(X) \tag{4}$$

Subject to the capacity constraints: $$\sum_{i=1}^{I}\sum_{j=1}^{J} x_j^i pcu_j^i a_{jm}^i \le C \quad m = 1,...,T \tag{5}$$

psg_j^i Total number of passengers in the vehicle of *j-th* request of demand category *i*

pcu_j^i The passenger car units of *j-th* vehicle of demand category *i*

p_m^i The reservation price of time slot *m* for demand category *i*

C Transportation network capacity (Section 4.3)

$a_{jm}^i = \begin{cases} 1, & \text{if j-th request of demand category } i \text{ is included in the m-th time interval} \\ 0, & \text{otherwise} \end{cases}$

$$x_j^i = \begin{cases} 1, & \text{if } j\text{-th request of demand category } i \text{ is accepted} \\ 0, & \text{otherwise} \end{cases}$$

Each time slot is assumed to be a five-minute interval in this paper. The online module is based on the optimization module. Assuming we have hundreds of historical demand scenarios, we obtain optimal solutions using the above optimization module. Given that artificial neural networks have the ability to "learn from experience" (Teodorović and Vukadinović, 1998), they can learn from the historical demand scenarios and the optimal solutions. From this learning process, the system will be able to recognize a situation characterized by the number of reservations made by each vehicle class for particular time period and reservation revenue. Neural networks are able to provide a real-time solution decision, the so called on-line module.

4.0   Simulation Experiments

4.1   Experimental Purposes

In the optimization module, people throughput and revenue maximization are explicitly included in the optimization objective whereas measures like travel time and travel speed are not. However, these measures are important for examining how the newly-introduced system meets congestion mitigation goals. Additionally, measures such as these are easily communicated to and understood by the public and transportation professionals. Traffic simulation package VISSIM (PTV America, 2007) is used to provide these measures for system evaluation purposes.

4.2   Simulation Test-bed – the VISSIM Network

4.2.1   Description of the Network

The VISSIM network used in this research is part of the Downtown Boise Simulation Study, which is provided in the VISSIM Software package. The network is modified to meet the needs of this research. The reason for using an existing network rather than coding a new one is that, the DSRS is developed for any general downtown network, and the network in the Downtown Boise Simulation Study has the characteristics of a typical downtown area with many intersections and short links (Zhao *et al., 2008)*). It is a reasonable representation of typical urban road network. The modified VISSIM network is shown in Figure 4-3, composed of 33 intersections and 14 urban streets.
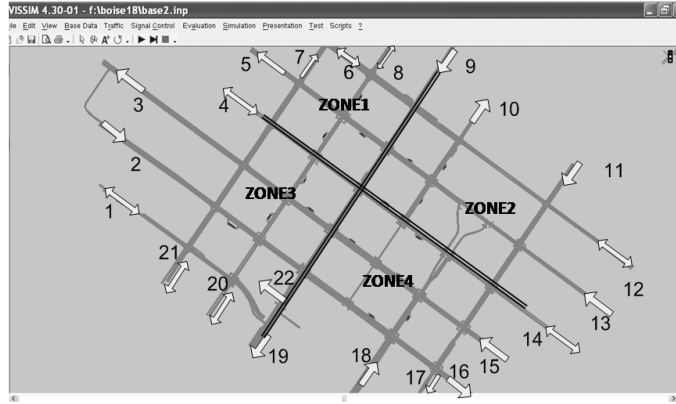
Figure 4-3 VISSIM Network

The DSRS is proposed as a cordon-based strategy. The cordon indicates the boundary of the reservation system. Only the vehicles driving into the cordon area are affected by the reservation system. Along the cordon, there are 22 entry/exit points that vehicles can enter/exit the area. In Figure 4-3, each arrow indicates whether the point is an entry point and/or exit point. Considering the network size, the area is divided into four zones. Each vehicle will go to one of the four zones, and park in the zone for a period of time, and then leave the area through one of the exit points. Each zone has more than one parking lot, and each vehicle will park in a parking lot of the zone. All these parking lots have no capacity constraints. They are only needed for traffic assignment in VISSIM. They do not represent actual parking lots in the area. In addition, it is worth noting that the behavior related to finding a parking lot impacts traffic considerably in practice. However, since in our case the parking lot has no capacity limitation at any time, such impacts are not considered in our analysis.

4.2.2 *VISSIM Traffic Demand Inputs*

The experiment in this research based on a VISSIM network of downtown Boise, which was originally developed by PTV America, Inc. (PTV America, 2007). We adopted the existing signal timing and roadway geometry. Travel demand distribution is generated by taking into consideration the vehicle inputs originally used by PTV. The column "Production" contains the "Vehicle Inputs (vehicles/hour)" from the original Boise VISSIM network. "Production Percent" is computed as the ratio of entry points "Production" to the total production trips, for example for entry point 1, 100/6484=1.54%. In our experiment, trips are distributed across the entry points according to the "Production Percent" values, and trips are evenly distributed among the four zones according to the "Attraction Percent" values (Table 4-3). In addition, a sensitivity

analysis with respect to trip attraction rates where trips were not evenly distributed among the four zones yielded similar results to the ones reported in this paper.

Table 4-3 Trip Generation

Entry Points	ZONE1	ZONE2	ZONE3	ZONE4	Production	Production Percent (Production/Total Trips)
1	25	25	25	25	100	1.54%
2	191	191	191	191	764	11.78%
4	46	46	46	46	184	2.84%
6	167	167	167	167	668	10.30%
8	23	23	23	23	92	1.42%
9	200	200	200	200	800	12.34%
11	242	242	242	242	968	14.93%
12	121	121	121	121	484	7.46%
13	65	65	65	65	260	4.01%
14	75	75	75	75	300	4.63%
15	116	116	116	116	464	7.16%
18	225	225	225	225	900	13.88%
22	57	57	57	57	228	3.52%
20	25	25	25	25	100	1.54%
21	43	43	43	43	172	2.65%
Attraction	1621	1621	1621	1621	6484	
Attraction Percent	25%	25%	25%	25%		

Each vehicle stays in a zone for a period of time, and then chooses one of the exit points to leave the downtown area. Figure 4-4 shows all the combinations of the entry and exit point pairs. In this paper, we assume that people prefer to depart from the same point of entry or the closest exit point to its entry point (Table 4-4). According to this assumption, for instance, vehicles that enter through entry point #1 will leave through departure point # 1.
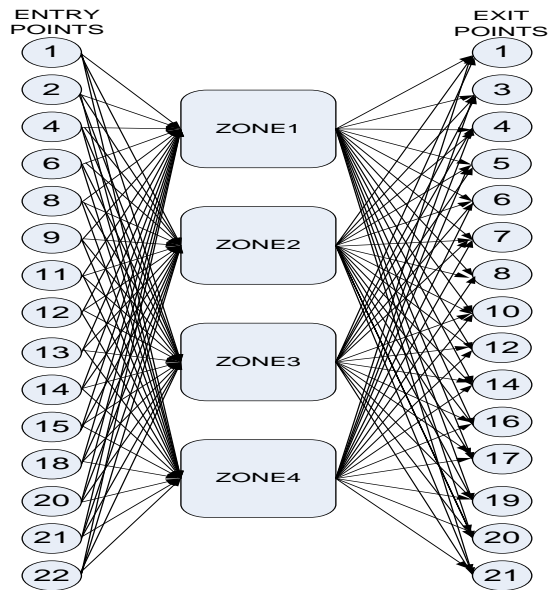
Figure 4-4 Vehicles Flow Chart

Table 4-4 Entry/Departure Pairs

Entry Points	Departure Points
1	1
2	3
4	4
6	6
8	7
9	8
11	10
12	12
13	5
14	14
15	16
18	19
22	17
20	20
21	21

4.2.3   Network Capacity Determination

According to Zhao, *et al.* (2008) capacity of the road network (Figure 4-3) is computed as:

$$n^A = \sum_{i \in A} n_i = \sum_{i \in A} \frac{l_i k_{ij}}{2} \tag{6}$$

Where n^A is the network capacity and link i belongs to the network A; l_i is the length of link I ;k_{ij} is the jam density of link i. Jam density is the condition of extremely high density that brings the traffic on a roadway to a complete stop. In this research, we assume that under jam density road conditions, vehicles stop in the road and are bumper-to-bumper. Therefore, the jam density of a link can be formulated as:

$$k_{ij} = \frac{\frac{l_i}{AvgLen}}{l_i} = \frac{1}{AvgLen} \tag{7}$$

Where AvgLen denotes the average vehicle length for a standard car.

Equation (6) is rewritten as:

$$n^A = \sum_{i \in A} n_i = \sum_{i \in A} \frac{l_i \frac{1}{AvgLen}}{2} = \sum_i \frac{l_i}{2AvgLen} \tag{8}$$

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Average vehicle length is computed from the data from Klaus Parking Systems, Inc. (2008). The length of 87 different types car models is averaged, AvgLen = 196 (ft). Then the capacity of the network (of Figure 4-3) is computed as 2550 PCUs.

4.3   Experimental Design

4.3.1   Experimental Hypotheses

The major hypothesis is that congestion will be mitigated and transportation performance will be improved with the reservation system according to performance measures such as travel time, congestion delay time and average speed. It is also worthwhile to look at the change of total vehicle miles traveled as a system throughput. If there is no congestion, this measure could be reduced with the DSRS, because without the DSRS more vehicle trips can be accommodated by the network. On the other hand, if serious congestion exists, even if more vehicles are allowed to travel in the network, the total miles they can travel could be less than the case with the DSRS within the same time period. Furthermore, it is expected that with the DSRS, transportation performance is more stable than it is without the DSRS.

The DSRS is different from the first come first serve (FCFS) reservation system. The DSRS is expected to outperform FCFS in terms of people throughput and revenue maximization. In addition, it is expected that changes in the relative importance of the throughput and revenue objectives in the optimization module will also affect the network performance.

4.3.2   Experimental Procedure

Three experiments are set up according to the hypotheses:

- With and without the DSRS at different demand levels

Multiple demand scenarios are generated. These scenarios are controlled by the parameter of average arrival rate λ. The arrival rate indicates the intensity of the travel demand of the particular scenario. The process of vehicles entering the designated network is assumed as a Poisson process with a known average rate λ. In this case, six arrival rates are chosen indicating different levels of traffic demand (Table 4-5). These six arrival rates represent the traffic conditions ranging from low, to moderate, and to extreme congestion. For each demand scenario, simulation runs twice, i.e., simulation without the reservation system (Figure 4-5) and simulation with reservation system in place (Figure 4-6).

Table 4-5 Travel Demand Levels

Parameter	I	II	III	IV	V	VI
Arrival rate λ [Vehicles/3Hours]	7000	7200	7400	7600	7800	8000

- Reservation System: DSRS vs. FCFS

The major objective in this analysis is to compare performance of the DSRS versus the reservation policy of FCFS. In the DSRS, decision-makers make sure that the capacity is available first, and then check whether the current request maximizes system objectives. It is still possible that the request will be rejected even if capacity is available because decision-makers may expect that saving the current slot for a later request could maximize the system objective. Under FCFS reservation, the total network capacity must still be considered and reservation requests are honored on a first come first serve basis. However, a request will be accepted as long as there is vacancy regardless of the future possible trip requests.

- People throughput vs. revenue

As was stated previously, two objective function components (people throughput and revenue) are involved in the DSRS and there is a tradeoff between the two components. In the DSRS, weights are assigned to the two components indicating their relative importance. To reflect how the weights affect the system performance, an experiment is conducted for one demand scenario ($\lambda=7000$), where different weights are assigned to the two components.
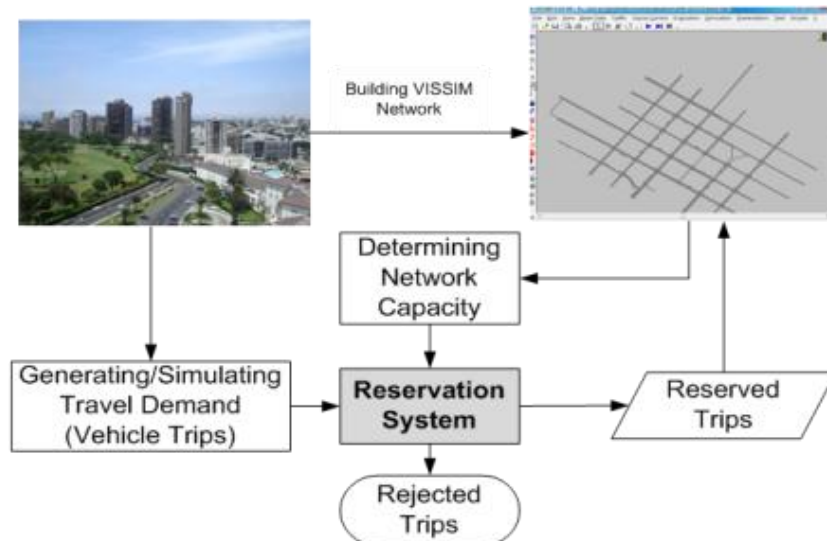
Figure 4-5 Simulation Process with Reservation System

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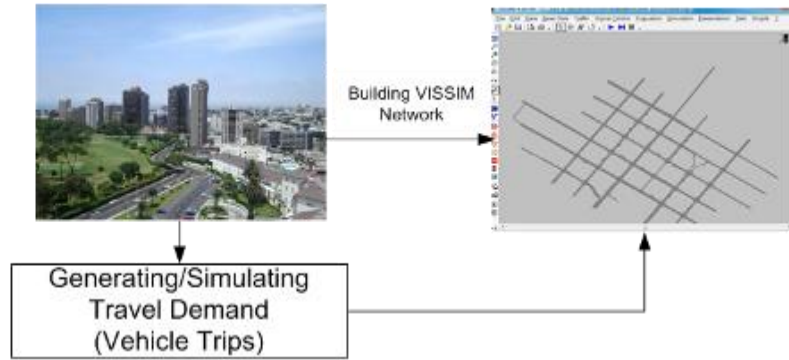
Figure 4-6 Simulation Process without Reservation System

4.3.3   Other Simulation Parameters

In this experiment, the DSRS is assumed to be operating only during the AM peak period, when heavy traffic enters a downtown region. Some of the trip chains will fall out of this AM peak period window. In such cases, only the portion of the trip chain that occurs during the reservation period (in this case AM peak period) determines the available allocation capacity and the reservation fees.

The stochastic nature of traffic flow is very important in the context of microscopic traffic simulation. In VISSIM, many parameters are assumed to follow a distribution rather than have a fixed value, such as the desired speed distribution. In order to capture the stochastic nature of traffic flow, each demand input should be run multiple times with different random seeds to obtain stochastically sound MOE values. A simulation run with one random seed is called a simulation replication. The number of replications for each demand input depends on two factors, i.e., the desired level of accuracy and simulation output variation across multiple runs. We use the standard deviations of MOEs to illustrate the output variation in the simulation experiment. All results presented in this paper are based on ten random seeds for each demand scenario.

5.0   Simulation Outputs Analysis

5.1   Measures of Effectiveness

Outputs provided by VISSIM allow a wide range of MOEs at various levels of detail. The selected measures in this paper are mostly defined at the network level, since our intention is to improve the overall traffic condition for the entire network rather than a single intersection or link. Delay time is one of the most important measures. In VISSIM, delay time is determined

by comparing the actual travel time with the ideal travel time. The ideal time is the time with free flow speed and no signal control. The total delay is computed by subtracting the ideal travel time form the real travel time. Meanwhile, average speed is used to indicate the average traffic flow condition. Dwell times at stop signs and signals are included in the calculation of average speed and delays. The measure of total path distance is essentially the total vehicle miles traveled in the entire network during the simulation time horizon.

5.2 Simulation Convergence Test

Convergence is a key notion in dynamic traffic assignment. Since there is no agreement among simulation experts whether dynamic assignment convergence is needed for the simulation run with each random seed for the same demand input, this research starts with conducting a convergence test before running the experiments proposed in Section 3. A demand scenario with arrival rate λ =7000 is generated.

First, the dynamic assignment algorithm (DA) is run until it converges for a single random seed (R1). The obtained routes are then entered into the simulation model and the model is run for random numbers R2 to R10. These results are shown in Table 4-6. Next, the DA algorithm is independently run for each random seed (R1 to R10) and allowed to converge. These results are shown in Table 4-7.

Table 4-6 Convergence of One Random Seed

MOEs	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
Average delay time per vehicle [s]	562	565	574	560	546	572	566	574	573	571
Average speed [mph]	13	13	13	13	13	13	13	13	13	13
Total travel time [h]	325	323	329	322	320	326	324	328	331	325
Total Path Distance [mi]	4200	4181	4204	4196	4177	4179	4207	4201	4192	4179
Total delay time [h]	167	166	171	164	163	169	166	170	174	168

Table 4-7 Convergence of All Random Seeds

MOEs	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
Average delay time per vehicle [s]	562	558	561	555	553	595	558	581	562	564
Average speed [mph]	13	13	13	13	13	13	13	13	13	13
Total travel time [h]	325	321	325	321	322	333	323	330	327	324
Total Path Distance [mi]	4200	4186	4207	4195	4177	4177	4202	4209	4208	4192
Total delay time [h]	167	164	167	163	165	176	165	172	169	167

The t-test (Table 4-8) suggests that the results of the two tables are very close, when comparing the MOEs in the two tables (Tables 4-6 and 4-7). There is no significant difference between the two cases. Therefore, in the following experiments, for any given demand input, we

conduct DA until it converges starting with any random seed. From there we test the stochastic impacts on the MOEs by changing the random seeds.

Table 4-8 Convergence t-test (α=0.05)

	Average delay time per vehicle [s]	Average speed [mph]	Total travel time [h]	Total Path Distance [mi]	Total delay time [h]
t Statistic	0.41	-0.40	0.13	-1.69	0.26
t Critical	2.26	2.26	2.26	2.26	2.26

5.3   Simulation Analysis I: With and Without the DSRS

Scenarios S1 through S6 show how the system performs under different demand scenarios indicated by the traffic arrival rate (λ). To compare the system performance with and without DSRS, measures such as average delay, average speed, total path distance and total travel time are chosen and plotted in Figure 4-7. Under DSRS the system exhibits a more stable trend according to the MOEs in Figure 4-7.

Total path distance without DSRS is indeed higher than it is with DSRS for the first five scenarios. This is because under DSRS, fewer vehicles are allowed to travel within the network (Table 4-9). If we consider the total path distance as the system throughput (indicating how many vehicle miles will travel at this level of demand), we would arrive at the conclusion that the system produces more vehicle miles without DSRS. In this sense, we might be better off without DSRS. Nevertheless, one may also observe that starting with S5, the number of vehicle miles begin to decline   When the demand level increases where λ =8000 vehicles/3 hours (demand scenario S6), the total path distance without DSRS begins to drop to a lower level than it is with DSRS. The degradation of total path distance is due to the higher congestion level, indicated by the extremely high average delay (1776 seconds) and low average speed (3mph). For example, in demand scenario S6, 4812 vehicles trips entered the network in the case of the DSRS implemented, and 6284 vehicles entered the network without the DSRS. However, the total path distance (3936) without the DSRS is lower than the distance (4114) with the DSRS. This is because even if there are more vehicle trips when there is no DSRS, but many of them are stuck in the network and not able to complete their trips.

On the other hand, average delay and average speed are observed to represent the traffic flow conditions. Comparing the average delay time per vehicle, it is obvious that vehicles experience less average delay under DSRS. Especially in the case where travel demand level λ increases, the average delay under DSRS does not vary very much, but the average delay without

DSRS increases sharply. In addition, the average speed drops from 12 mph to 3 mph indicating severe congestion.

Table 4-9 VISSIM Results

Parameters		Entering Volume	Average delay time per vehicle [s]	Average speed [mph]	Total travel time [h]	Total Path Distance [mi]	Total delay time [h]
S1	WR[a]	5602	524	13	309	4057	155
	WO[b]	6886	721	12	404	4859	220
(λ=7000)	%[c]		-27%	9%	-24%	-17%	-29%
S2	WR	5794	485	13	285	3754	142
	WO	6934	808	11	470	4841	287
(λ=7200)	%		-40%	24%	-39%	-22%	-51%
S3	WR	5685	517	13	303	3947	153
	WO	6295	834	11	441	4917	255
(λ=7400)	%		-38%	17%	-31%	-20%	-40%
S4	WR	5673	520	13	301	3913	153
	WO	5746	987	10	504	5185	308
(λ=7600)	%		-47%	26%	-40%	-25%	-51%
S5	WR	5724	532	13	305	3933	155
	WO	6752	1367	6	950	4581	777
(λ=7800)	%		-61%	124%	-68%	-14%	-80%
S6	WR	4812	645	12	342	4114	187
	WO	6284	1776	3	1507	3936	1359
(λ=8000)	%		-64%	348%	-77%	5%	-86%

In order to illustrate the magnitude of the change of the selected MOEs with the DSRS compared to the same network without DSRS, the percentage differences are plotted in Figure 4-8. It is clear from this Figure that the average speed increases from 9 percent to 348 percent across the six scenarios from the DSRS scenarios to the non-DSRS scenarios. Total travel time and average delay consistently decrease as demand increases. This is due to the way in which VISSIM computes delay. The delay is the difference between the ideal travel time and the actual travel time. The two MOEs are highly correlated.

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[a] *VISSIM measurements with DSRS*
[b] *VISSIM measurements without DSRS*
[c] *Increase of measurements comparing WR with WO*
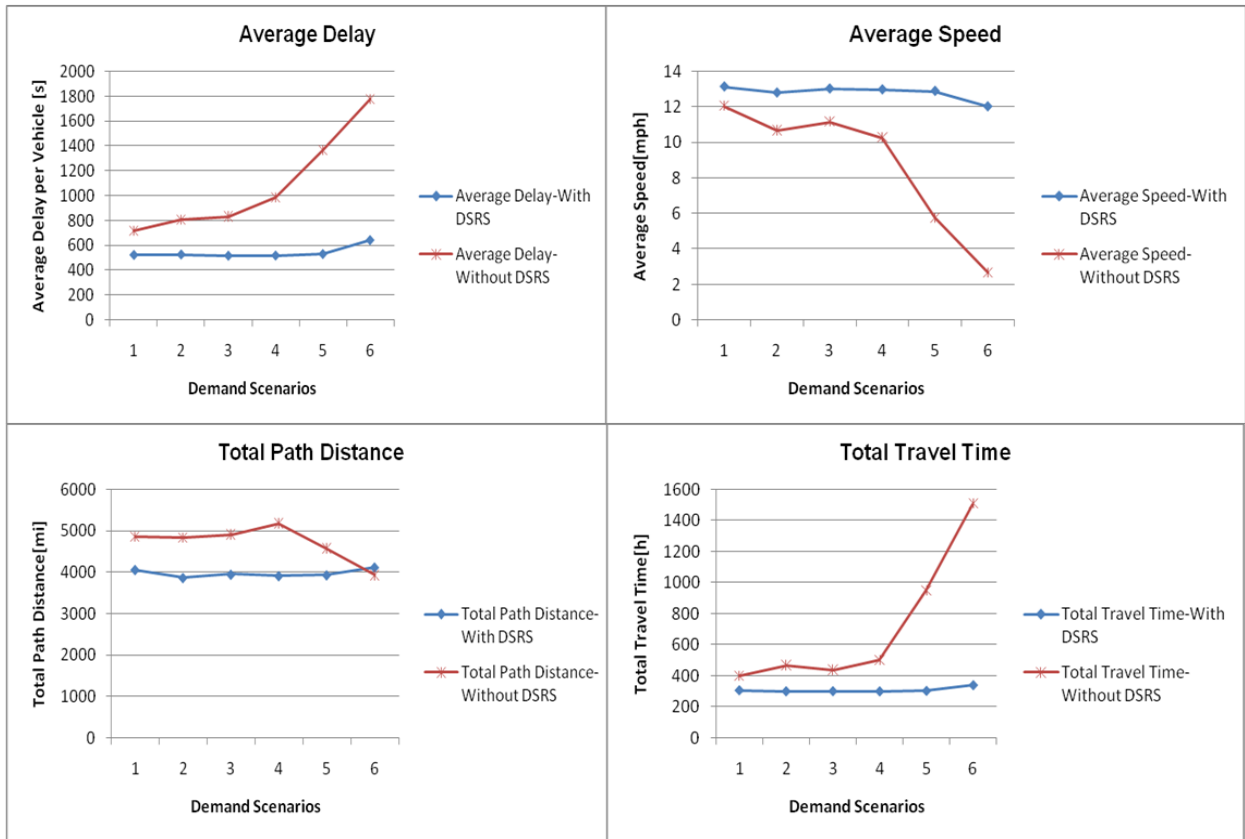
Figure 4-7 Performance Comparison with and without the DSRS (S1-S6)
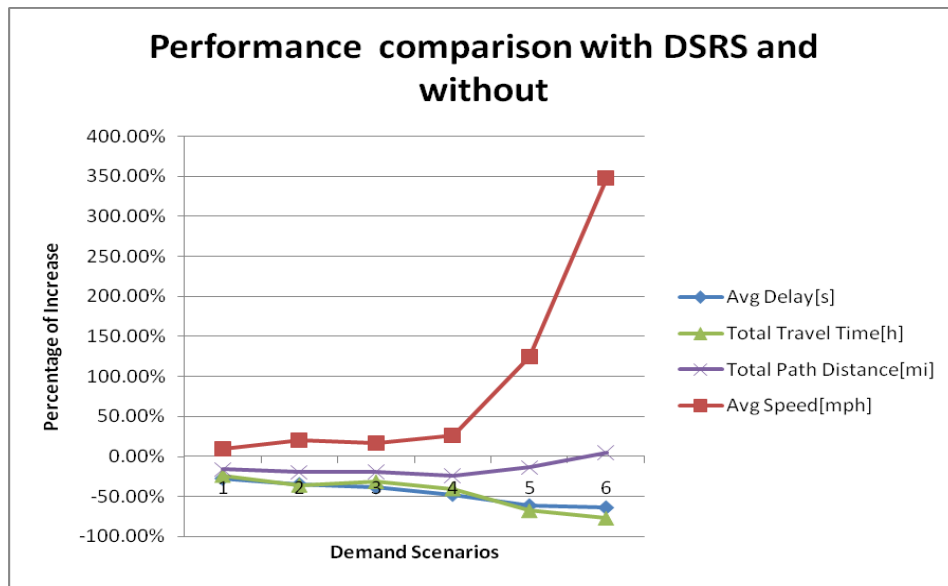
Figure 4-8 Performance Comparison with and without the DSRS

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5.4 Simulation Analysis II- DSRS vs. FCFS

The intention of this set of simulation runs is to compare the performance of the DSRS versus the FCFS reservation system. The ten demand instances with the same average arrival rate (λ =7000 vehicles/period) are simulated. The travel demand instances are differentiated from each other because of the stochastic nature associated with the arrival rate, entry/exit time, and occupancy. As shown in Table 4-10, the total revenue obtained from the DSRS is significantly higher than the revenue from the case of FCFS (17 percent), and the throughput (total number of people served) also improves about 10 percent.

Table 4-10 People Throughput and Revenue DSRS vs. FCFS

	# of trips	DSRS_$	DSRS_p	FCFS_$	FCFS_p	$%	P%
i1	5949	22210.9	17522	19123	15945	16.15%	9.89%
i2	5953	21888.4	17826	18943.8	16615	15.54%	7.29%
i3	5913	21898.9	17306	18603.1	15870	17.72%	9.05%
i4	5840	22824	17642	19068.8	16039	19.69%	9.99%
i5	5889	21976.6	17765	18822.5	14708	16.76%	20.78%
i6	5888	22376.8	17811	18896.4	16172	18.42%	10.13%
i7	5938	22706.3	17822	19150.5	16303	18.57%	9.32%
i8	5914	22322.6	17210	18898	15966	18.12%	7.79%
i9	5963	22081.2	18211	19482.5	16561	13.34%	9.96%
i10	5871	22143.3	17622	19046.4	16362	16.26%	7.70%
Mean	5912	22243	17674	19004	16054	17.06%	10.19%

In terms of the traffic performance, we still consider the following MOEs: average delay per vehicle, average speed, total travel time/distance, and total delay time (Table 4-11). According to the results of the t-test (α=0.05), differences between these two cases are not significant, and this indicates that there are no significant improvements of traffic conditions (Table 4-12). This phenomenon is consistent with the fact that under both the DSRS and FCFS, traffic flow is subject to the same capacity constraints. Therefore, the total number of vehicles accepted is similar. However, even if the traffic conditions are similar, from the revenue maximization and people throughput point of view, the DSRS still outperforms the case of FCFS.

Table 4-11 VISSIM Results DSRS vs. FCFS

	i1	i2	i3	i4	i5	i6	i7	i8	i9	i10
DSRS										
Average delay per vehicle	566	579	571	552	574	558	563	547	669	548
Average speed	13	13	13	13	13	13	13	13	11	13
Total travel time	325	329	326	318	325	319	321	318	405	318
Total Path Distance	4192	4245	4218	4124	4181	4126	4157	4167	4142	4159
Total delay time	168	170	167	162	168	164	165	160	249	162
FCFS										
Average delay per vehicle	548	543	542	529	571	561	550	548	568	550
Average speed	13	13	13	13	13	13	13	13	13	13
Total travel time	320	316	315	308	327	323	321	321	330	321
Total Path Distance	4173	4122	4099	4026	4193	4145	4157	4167	4242	4174
Total delay time	162	160	159	155	168	166	163	162	169	163

Table 4-12 t-test Results DSRS vs. FCFS ($\alpha=0.05$)

	Average delay per vehicle [s]	Average speed [mph]	Total travel time [h]	Total Path Distance [mi]	Total delay time [h]
t Stat	2.21	-1.06	1.36	0.95	1.36
t Critical	3.25	3.25	3.25	3.25	3.25

5.5   Simulation Analysis III-The Relative Importance of Throughput vs. Revenue

As mentioned previously, the objective function of the DSRS contains two components, i.e., people throughput and revenue. The two components are assigned different weights indicating their corresponding importance (Table 4-13). For example, when the weight is equal to 0.5, this indicates that the two elements are equally important, and 1 indicates the case that only people throughput is considered while assigning a zero weight to revenue. Theoretically, as the weight for people throughput increases, the total number of people should increase as well. The second column of Table 4-13 shows this behavior. However, the increases are not very noticeable until the weight is increased to 1. The revenue follows a decrease trend. However, the degree of decrease of revenue (10 percent) is higher than the increase of the people throughput (4 percent). This result indicates the compromise between the two criteria of people throughput and revenue (Figure 4-9). To test the significance of the changes in people throughput and revenue with respect to weights w, additional t-test was conducted to compare results for weights 0.5 and 0.89, and 0.89 and 1 as shown in Table 4-14. The results indicate that the differences in results for the three weights are statistically significant.

On the other hand, the resulting performance measures from the simulation runs (Table 4-15) demonstrate that the differences among the various weight configurations are not intuitively

obvious. This is a reasonable finding. Different weights may only influence which vehicle will be accepted, while the total number of vehicles is mostly constrained by capacity. Thus, with the same amount of travel demand in the network, the traffic conditions should perform similarly. Therefore, it may not be necessary to impose a higher weight on the people throughput even if one aims at increasing the people throughput, because the network improvement is limited. By increasing the weight on the people throughput, we may not get much improvement, but lose much more revenue. In this case, it may be not worthwhile to sacrifice the revenue in order to gain a limited increase of the people throughput.
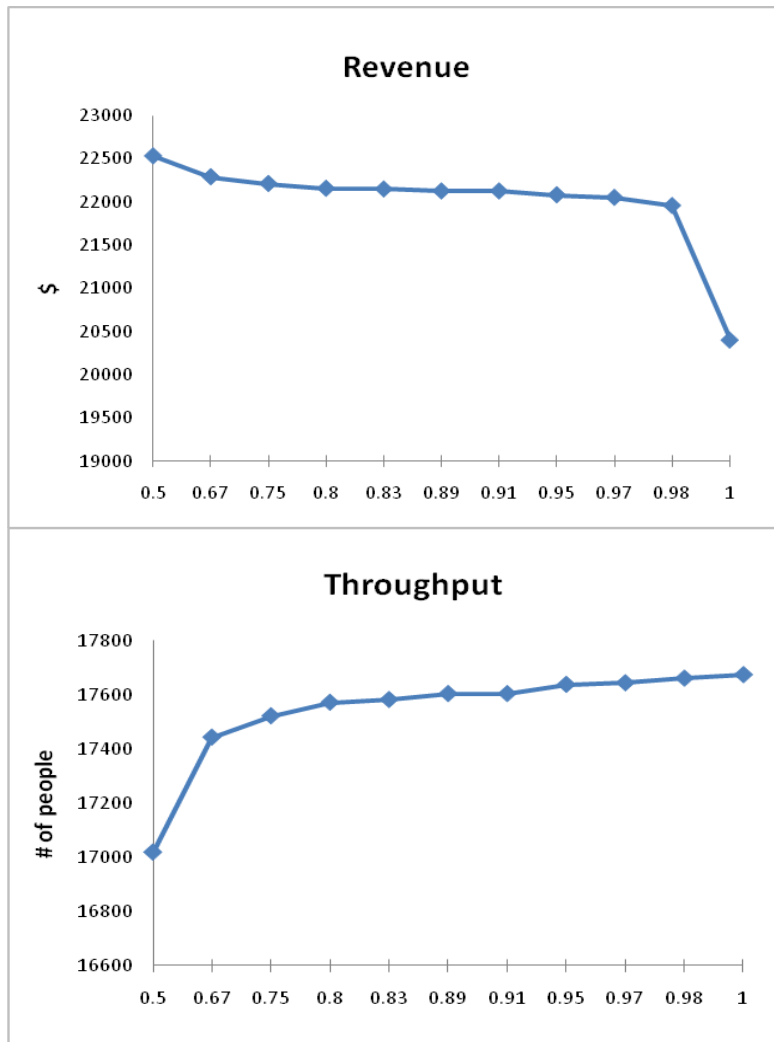
Figure 4-9 People Throughput and Revenue

Table 4-13 People Throughput and Revenue

Weight w	# of people	Revenue $	# of accepted vehicles
0.50	17018	22529.5	5908
0.67	17443	22288.7	5937
0.75	17522	22210.9	5949
0.80	17572	22155.3	5946
0.83	17582	22147.4	5944
0.89	17604	22124.2	5940
0.91	17604	22124.2	5940
0.95	17638	22080.5	5939
0.97	17644	22050.3	5945
0.98	17661	21956.3	5953
1	17674	20401.7	5966

Table 4-14 t-test Results of W=0.5, 0.89, 1

	Revenue				# of people			
	w=0.89 vs. w=1		w=0.5 vs. w=0.89		w=1 vs. w=0.89		w=0.89 vs. w=0.5	
	w=0.89	w=1	W=0.5	w=0.89	w=1	w=0.89	w=0.89	w=0.5
Mean	22066	20101	22520	22066	17775	17678	17678	17020
Df	29		29		29		29	
t Stat	16.41		30.74		17.87		41.56	
P(T<=t) one-tail	1.62E-16		5.51E-24		1.7E-17		1.06E-27	
t Critical one-tail	1.70		1.70		1.70		1.70	
P(T<=t) two-tail	3.24E-16		1.1E-23		3.4E-17		2.13E-27	
t Critical two-tail	2.05		2.05		2.05		2.05	

Table 4-15 Performance Results for Different Weights

Weight w	0.50	0.67	0.75	0.80	0.83	0.89	0.91	0.95	0.97	0.98	1
Average delay per vehicle [s]	579	586	566	582	586	585	577	592	598	598	611
Average speed [mph]	13	13	13	13	13	13	13	13	13	13	13
Total travel time [h]	330	336	325	334	335	334	331	337	339	339	345
Total Path Distance [mi]	4230	4316	4192	4315	4306	4297	4288	4326	4330	4326	4367
Total delay time [h]	171	174	168	172	173	173	170	175	177	176	181

6.0   Implementation Issues Associated with the DSRS

To implement the proposed DSRS many implementation issues need to be addressed. Some of the relevant issues are discussed below.

- Reserving spaces: The communication channel (s) via which travellers can make reservation requests could include, telephone, internet, text messaging, among others. The time window available to make a request also is a key variable. For example, the reservation

system can be opened 24 hours in advance and closed 1 hour prior to the actual departure times. The size of this window depends on the request processing capabilities of the DSRS server.

- Early/Late arrivals: In the event that a vehicle arrives at its entrance (say freeway ramp) before or after its scheduled arrival time the DSRS needs to have sufficient slack in the system to accommodate such vehicles. This can be accomplished by setting aside a certain portion of the entrance capacity to such arrivals. The early arriving vehicle can be issued a warning in the first violation with repeat offenders being ticketed and/or preventing them from making reservations for a certain number of days.

- Late departures: It may happen that the departure plans of travellers change after entering the downtown region. This could happen for a variety of reasons – for example, a meeting running late. Again, in such situations where drivers violate their original departure times may be treated the same way early/late arrivals are treated.

- Enforcement: License plate numbers provided by motorists while reserving spaces can be used for enforcement purposes. These numbers can be read at highway speeds with the current technology and processed in milliseconds. If the number does not match the system accepted number for that time interval then a violation ticket is issued. To detect the number of occupants inside the vehicle, technology such as infrared and laser can be used (e.g. Forth road bridge in Scotland has tested such equipment for use in a variable pricing project in 2007. The system gives discounts to car pools based on the number of occupants.)

- Daily commuters: People who work in downtown and commute on every week day could be treated in a different way. A portion of the total capacity can be devoted to drivers that are willing to make reservations for a longer period of time (e.g., few months to up to a year). Since they help reduce the uncertainty in demand, such requests can be given preferential treatment, for example, reducing the reservation price.

- Trip cancellations/No-shows: The DSRS should also establish a policy on treating trip cancellations and drivers that don't show up for their trips. Assigning penalties on future reservations is one way of dealing with it. Drivers missing their reservations for valid reasons such as a medical emergency may be allowed to show the necessary proof to get the penalty waived. It is to be noted that these are just potential ideas of how to deal with such violations. It is entirely up to the agency implementing the DSRS to develop such a policy.

- Request rejections and re-requests: Travellers whose travel requests are turned down for a certain time interval may keep checking (re-requests) in hope of someone cancelling their trips or may choose to reserve for the next available departure time. The number of re-requests is an important factor for the design of the reservation server and should be taken into account to avoid service outages due to the overloading of the server.

- Privacy issues: Travellers may be asked to provide their license plate numbers during reservations. The agency should take sufficient care not to disclose the identity of drivers. This situation is very similar to the automated tolling applications around the world and may not be a major implementation issue.

7.0   Conclusions and Future Research

The new TDM strategy, the Downtown Space Reservation System is evaluated using microscopic traffic simulation. Three sets of simulation analyses are presented. According to the simulation experiment in this paper, the DSRS can markedly improve traffic conditions as compared to the no-control case, especially in an area with high congestion levels. Congestion is highly sensitive to the total number of vehicles in the network after the total demand reaches a certain level (about 7600 vehicles in the case presented in this research). A small amount of extra vehicles could lead to great degradation in network performance. Meanwhile, the magnitude of the improvement in performance increases with increasing demand levels. This indicates that when demand level is low, the improvement of introducing the DSRS is negligible. In this situation, the DSRS is not needed. This further suggests that decision makers should first set a critical point beyond which they would like to introduce the DSRS. Furthermore, the DSRS increases the total people served and revenue when compared with FCFS reservation. However, when balancing the two objective function components (people throughput and revenue), the analysis indicates that the people throughput is not very sensitive to the relative importance that is ascribed to this component. If decision makers attempt to improve the people throughput by increasing its associated importance, they must be cautious that the loss in the revenue may counteract the gain in the people throughput.

Future research could improve the current work with respect to three aspects. First, we use a relatively small size network. Variation in performance could exist for an actual larger size network. To evaluate and minimize the effects of the network size, further research could start

with a larger network built for an urban downtown area, such as downtown Washington DC. In addition, it is preferred to have accurate travel demand data for the area under consideration. Simulation with an actual sized network and real travel demand data may provide more insights with respect to network system performance and the system design.

There is an interesting observation encountered during the simulation. One of the assumptions the DSRS is built on is that the downtown area exhibits area-wide congestion rather than bottle network congestion. However, during the simulation we notice that the area-wide congestion often starts from certain intersections. The congestion at intersections quickly transforms itself to an area-wide congestion. This suggests that for a larger network, it could be problematic to have coverage of a large downtown area by a single DSRS. In this case, one could further investigate whether dividing the whole area to several sub-areas would improve the performance of the DSRS.

Also, in the current work, we assume that the trips rejected by the DSRS are either removed from the network or are accommodated by public transportation, and the current public transportation has sufficient capacity. In the future work, one may take into consideration the public transportation effect, for example, what if the public transportation is not adequate and more buses are needed. The additional buses to some extent will also create congestion.

Finally, we do not consider trial and error driver behavior when looking for parking as a major contributor of traffic congestion when evaluating the DSRS. However, one could consider the impact of having a DSRS in conjunction with an intelligent parking reservation system (Roper and Triantis, 2009) as a more comprehensive approach to mitigating congestion.

This experiment provides a test platform for the DSRS, demonstrating its effects in a virtual transportation network. This is a useful precursor to the implementation of the system in the future. Furthermore, the simulation results in this work enable one to develop a systematic and macro performance evaluation framework before the system is actually implemented. Despite of the limitations in this work, the basic experimental approach is meaningful.

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CHAPTER 5 Transportation Network Performance Measurement – The Impact of the Downtown Space Reservation System: A Network-DEA Approach

Abstract

A transportation network is a multiple input/output system. Transportation service providers are interested in transportation system efficiency and effectiveness. Transportation users are concerned with their mobility. The community may care more about environment and safety issues. To represent these multiple perspectives in a performance evaluation framework, network-DEA is used. The perspectives are inter-related through the intermediate inputs/outputs in the network-DEA approach. In this paper, two different types of network-DEA were compared and an illustrative example is provided using the data propagated from a microscopic traffic simulation model of the Downtown Space Reservation System. Thus, the network-DEA model complements the micro level simulation performance evaluation by accounting for a macro level measurement consideration.

Keywords

Data Envelopment Analysis (DEA), Network DEA, Transportation Network Performance

1.0 Introduction

Transportation systems play an essential role in our daily life. Not only are travelers impacted by these systems but people living in the community are also impacted by safety and environmental issues. At the same time, transportation service providers are striving to meet their financial constraints. These conflicting interests make the traditional transportation economic evaluation method such as Benefit-Cost analysis inadequate to capture the complexity and the underlying structure of the transportation system. Therefore, an effective measurement tool is necessary for a comprehensive evaluation of transportation systems. Especially, since many transportation agencies have begun to support Travel Demand Management (TDM) strategies to facilitate congestion reduction, environment protection, energy conservation and economic considerations. Conventional transportation evaluation approaches tend to undervalue TDM strategies by ignoring and understating costs associated with automobile usage and the benefits of more efficient and diversified transportation systems. The need for a more comprehensive performance measurement approach has emerged for TDM strategy evaluation.

In order to address this need, this research develops a transportation performance measurement framework with an application of a new efficiency measurement methodology, namely network-DEA. This proposed framework expands on Färe and Grosskopf's network DEA approach (2000) and captures the perspectives of transportation system providers, the users and the community, as well as the interrelationships among these views. It also provides an overall performance (efficiency) measure for a transportation network. Our approach is to compare and contrast various instances (scenarios) that occur in the transportation network under the execution of a TDM strategy, namely the Downtown Space Reservation System (DSRS). The scenarios constitute the production possibility set for our analysis. Traffic flow of a downtown area, where the DSRS is implemented, is simulated with microscopic simulations. The data that support the analytical framework is obtained from the execution of the simulation.

This research contributes to the extant performance measurement literatures in four aspects: (1) Network DEA application in transportation performance measurement is relative immature. Very few researchers have attempted to focus on such applications. This research presents a demonstration of a potential practical application of network DEA in transportation system and TDM strategy evaluation. (2) This paper combines the network DEA technique with traffic

simulation in performance measurement. It utilizes the outputs from the microscopic traffic simulation models as inputs data to the DEA models. Thus, the network-DEA model complements the micro level simulation performance measurement by accounting for a macro level performance measurement considerations. (3) Furthermore, the current research compares two different types of network DEA models, the original network DEA model proposed by Färe and Grosskopf (2000) and the slacks based network DEA model proposed by Tone and Tsutsui (2008). To the authors' knowledge, this is the first attempt to compare the two approaches. (4) Finally, the authors extend the current research to connect the DEA performance measurement with the design of the system. The illustrative example in this paper is used to imply how the assessment can help in terms of the system design by detecting potential improvement directions and including requirements into the design at the early stage.

The paper is organized as follows. The introduction is provided in Section 1. Section 2 presents a brief background of the DSRS and the microscopic traffic simulation. Overview of transportation performance measures and the three-perspective conceptual performance measurement framework are provided in Section 3. Section 4 introduces the DEA and Network DEA at the beginning, following mathematic descriptions of the original network DEA and the slacks based network DEA with inclusion of undesirable outputs in both models. In Section 5, an illustrative example is presented together with the comparison between the two different network models. Finally, conclusions and future research are addressed in Section 6.

2.0 Background

The transportation network evaluated in this research is characterized by the implementation of the TDM strategy, namely the DSRS. It is developed for the purpose of congestion mitigation, especially for the center of a city or Central Business District (CBD). With the DSRS, travelers who want to drive in a designated downtown area have to book their time slots before making their trips. The transportation authority, who administers and supervises the DSRS, allocates time slots to travelers based on the availability of resources (i.e., road network capacity). Only those who get permission from the transportation authority can drive in the downtown area during the requested time period. The system intends to alleviate traffic congestion by reducing excessive vehicles on the road (Zhao and Triantis, 2008).

The core of the DSRS is an optimization module that is maximizing two objectives, i.e., people throughput (the total number of travelers that the transportation system serviced) and revenue obtained from reservation, subject to the transportation network capacity constraint. In the optimization module, decision maker assigns weights on the objectives reflecting their relative importance in the system. Starting from the initial optimization formulation development of the DSRS, a microscopic traffic simulation model was built to evaluate performance of this TDM strategy, to help obtain a better understanding of the system behavior, and to evaluate the impact of changes in the system. The simulation model provides a means to test the DSRS before it is implemented by providing a range of effectiveness measures. The simulation was run under different scenarios characterized by varying travel demand levels and reservation policy specifics. The TDM policy was varied by changing the relative importance of the people throughput and revenue in the reservation system. The simulation provides essential data to the network DEA model.

3.0 Conceptual Framework

3.1 Transportation performance measurement

Selecting appropriate performance measures[12] is crucial in performance measurement. Different perspectives of stakeholders and the achievement of their expectations are reflected by performance measures. The relationship among the measures and perspectives is depicted by the structure of the performance measurement framework. Hence, measures and the corresponding structure are the two major components to develop a performance measurement framework. There is a substantial amount of literature that provides the common performance measures used by different transportation agencies. Oregon Department of Transportation (Reiff, 2005) compiled a list of 750 performance measures which encompasses different policy areas including mobility, accessibility and sustainability. Texas Transportation Institute (TTI, 2005) emphasizes on monitoring a family of mobility measures, such as travel delay, travel time index and buffer index. These measures essentially are similar with the measures used for congestion

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[12] Performance measure is defined as a metric used to quantify the efficiency and/or effectiveness of an action (Neely et al., 1995). Performance indicator is defined as the logical variables (criteria) which measure the attainment of objectives, such as travel time. Performance measures provide the precise metrics by which a particular indicator is measured. There are might be more than one performance measure (metric) for a given indicator (Falclcchio 2004).

measurement purpose (Cambridge Systematics, 2005). In addition, sustainability has been advocated in order to take into account the environmental issues. According to a set of working definitions of sustainability in transportation, Jeon (2005) recommended a three-dimensional sustainability framework including economic development, environment preservation and social development, and provided a list of performance measures for each dimension. Litman (2008) also suggested a list of economic, social and environmental indicators for assessing sustainable transportations. Based on the literature, this research categorizes the measures into inputs, outputs and outcomes for the transportation system in this research as depicted in Figure 5-1, where inputs are what invest, outputs are what we reach directly, and outcomes indicate the differences or effects that the outputs fundamentally make to the user and the community. This performance measures mapping is the foundation for developing the transportation network structure later.
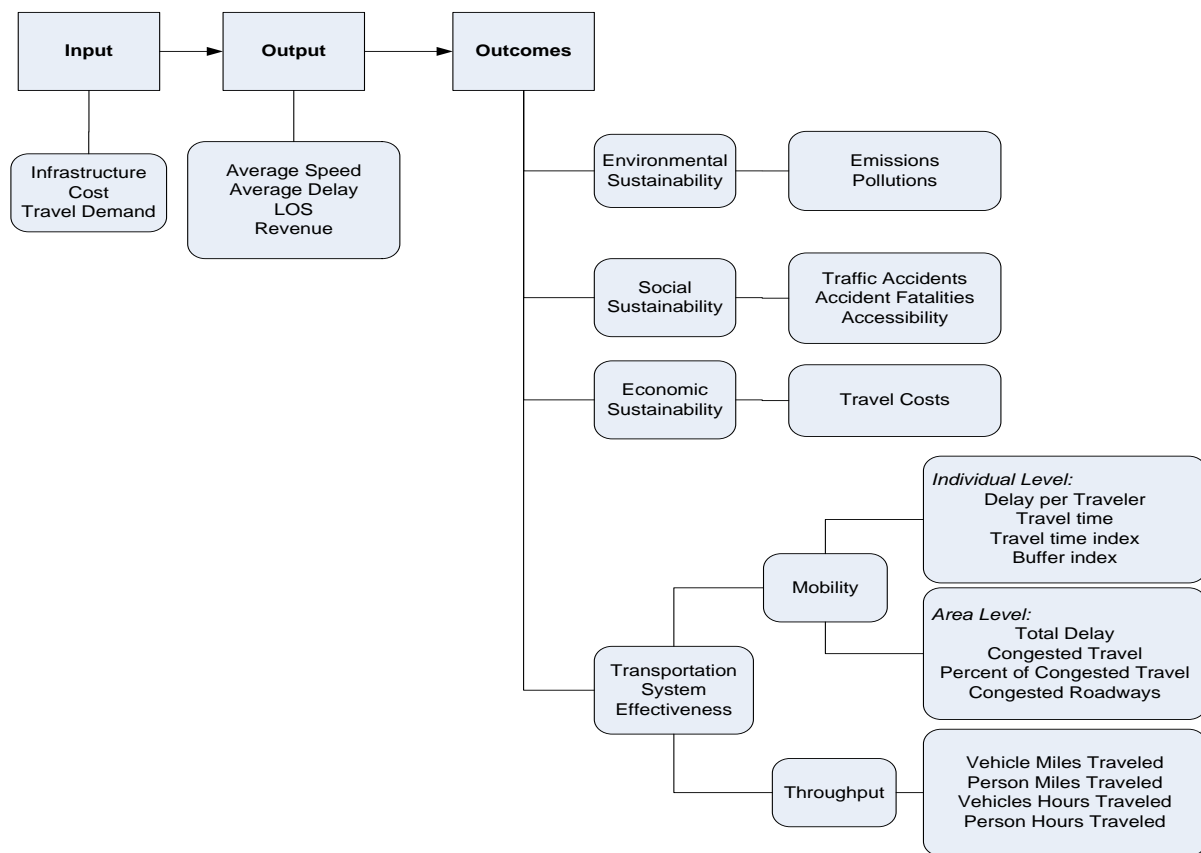
Figure 5-1 Transportation Input-Output-Outcome System

3.2 Transportation Network Structure

Researchers and practitioners developed various frameworks for demonstrating the underlying relationships between the performance of the transportation system and multiple stakeholders' benefits and expectations. Tsolakis and Thoresen (1998) suggested a four-dimension performance framework, which accommodated a range of community values and viewpoints including economic, social, safety and environmental concerns, stressing the importance of community participation and public openness in road performance evaluation. Falcocchio (2004) presented a conceptual framework for more effective development and application of performance measures in transportation systems evaluations, where the interests of customers, community, transportation providers and professional societies are included. Sheth et al. (2007) proposed a transit performance evaluation framework in conjunction with Data Envelopment Analysis (DEA). It combines the views of transit provider, consumer and society.
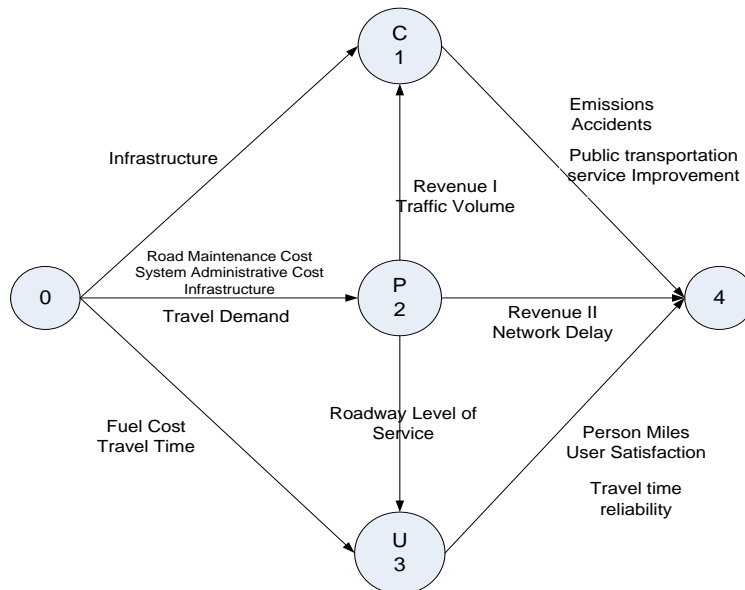
Figure 5-2 Three-Perspective Performance Network Structure

Expanded on the literature, this research adopts a three-perspective framework, i.e. provider, user and community perspectives. These three perspectives represent the most important stakeholders in transportation systems. Their perspectives and interactions determine the overall performance of the transportation system. Users and community stakeholders are more likely outcome oriented whereas providers are output oriented. Furthermore, we assume that travelers are more concerned about their mobility. This is reflected with the travel time

related measures. Transportation service providers are mostly interested in the system efficiency and effectiveness, which is reflected by revenue, roadway level of service and vehicle miles traveled etc. Last but not least, the community typically cares more about environment and safety issues that are associated with the traffic. Therefore, sustainability oriented measures are more appropriate to reflect their interests.

The performance network of Figure 5-2 represents the underlying structure of transportation system with respect to different perspectives and the interrelationship among them. The network consists of five nodes. Node 0 and Node 4 are dummy nodes. The major function of these nodes is to distribute inputs to and collect outputs from the intermediate nodes (Node 1, Node 2 and Node 3). Node 1 represents the community's viewpoint. The community is directly impacted by the transportation system in their territory. Node 2 represents the perspective of the transportation service provider. Node 3 is transportation user's perspective. The connection between nodes is directed, indicating the information and/or material transformation from inputs to outputs. The framework reflects the interrelationship among the three viewpoints.

For instance, from providers' point of view, the inputs to the transportation system include different categories of cost, infrastructure and the unfulfilled travel demand; the outputs include revenue, traffic volume, Level of Service (LOS), and network delay. From the community's point of view, the inputs are the infrastructure, the revenue from transportation service and the traffic volume; the outputs are the emissions, accidents resulted from traffic flow and public transportation improvements benefited from the transportation related revenue. From the users' perspective, the inputs are the fuel cost, travel time and reservation fee spent on the trips; the outputs are the person miles traveled, user satisfaction and travel time reliability. Among the variables, there are two types of inputs/outputs – intermediate inputs/outputs and final outputs. The final outputs are the outputs that are finally fed into Node 4, such as emissions, accidents, and person miles etc. The intermediate outputs, LOS, traffic volume and revenue, are the outputs from providers' point view, while they are also the inputs to Node1 and Node3.

4.0   Methodology

4.1   Overview of DEA and Network DEA

DEA is an analytical technique for measuring the relative efficiency of organizational or production units. It has been widely acknowledged by its strength of (1) capturing multiple inputs and outputs, (2) combining multiple dimensions, and (3) computing performance measures that integrate data/information across the multiple dimensions and input/output resources (Gattoufi el al, 2004). DEA identifies the empirical frontier/best practice units, gives an inefficiency/efficiency score to each individual decision making unit (DMU). Since the initial work by Charnes et al., (1978), DEA has been used in many public sectors, e. g. education, agriculture, healthcare, and banking industry (Anderson et al. 2007; Cherchye and Puyenbroeck, 2007; O'Neill et al., 2008; Cheng et al., 2007). Although DEA may not be one of the most popular tools used in transportation performance measurement, several applications are found in public transit system evaluation (Chu and Fielding, 1992; Kerstens 1996; Nakanishi and Norsworthy 2000; Karlaftis, 2003, 2004), airline routes/networks performance evaluation (Adler and Golany, 2001; Chiou and Chen 2006). Other applications in transportation include: evaluating the improvement resulted from a TDM strategy (Nozick et al.,1997), using DEA approach to find efficient paths in a road network taking into account the user mobility (Cardillo and Fortuna, 2000), and the evaluation of public sector investments in Intelligent Transportation Systems (Nakanishi and Falcocchio, 2004).

Meanwhile, various modifications have been developed, such as the additive model, the multiplicative model (Charnes, et al. 1982, Ahn, et al. 1988), the Go-DEA (Athanassopoulos, 1995) and the network DEA. The network DEA highlights itself by providing detail for management to indentify inefficiency sources embedded in interactions among various components of the evaluated unit. The improvement allows one to further investigate the structure and processes inside the unit. In addition, the network approach also allows for indentifying misallocation of inputs among sub-processes and generating insights of sources of inefficiency within the DMU. Färe and his colleges (Färe and Whittaker 1995, Färe and Grosskopf 1996) first proposed a DEA model with inclusion of intermediate production using network theory. Building on this earlier work, Färe and Grosskopf (2000) summarized a sequence of network models that can be applied to a variety of situations including intermediate

products, allocation of fixed resources and dynamic systems (multi-period production). They are acknowledged as the forerunner of network DEA study. Following their pioneering work, other researchers begin to extend the network DEA in various directions. Some remarkable applications and methodological publications are briefly reviewed here.

Löthgren and Tambour (1999) applied the network DEA model by representing pharmacy production process and consumption process with two separate nodes in a network model. Lewis and Sexton (2004) apply the network model to major league baseball to identify the extent of inefficiency within each Sub-DMU (sub-process). Their work departure from the work of Färe and Grosskopf in that they "define reference set for the DMU based on the hypothetical Sub-DMUs indentified for each Sub-DMU" (P.1366), while Färe and Crosskopf "define the reference set as the set of all convex linear combinations of DMUs as is the common practice in DEA" (p1366). The DEA evaluation framework is described as "…(we) begin by solving a DEA problem for each Sub-DMU to obtain its efficiency score. Then we use the acyclic structure of the underlying graph to indentify a partial order of the Sub-DMUs based on the dependence of each Sub-DMU on the output of other Sub-DMU in accordance with the partial order, assuming that all Sub-DMUs that precede the Sub-DMU under analysis are efficient." (p.1367). Prieto and Zofio (2007) conceived a national economy as a set of interdependent technologies, and these technologies, or sub-technologies, represent different sectors, like agriculture, manufacturing, construction, services. Each sector transforms incoming primary and intermediate inputs into flows of intermediate and final outputs. Lotfi et al. (2007) developed a network DEA model on interval inputs and outputs. Hua and Bian (2008) expanded Färe and Crosskopf's network model to explicitly incorporate undesirable factors that can exist internally as intermediate inputs/outputs, or as final outputs of the network DMUs. Chen (2009) developed a new network-DEA model to incorporate the dynamic effect in production networks for the reason that the previous studies "ignore an important fact that the production processes of DMUs and Sub-DMUs often have a temporal dimension, without considering this dimension it would easily lead to distorted efficiency measurement" and "confine their analysis to the dynamics of a single production process linked over multiple time periods". Hence, they did not "provide a clear guideline as for how to incorporate dynamic effects in production networks into efficiency measurement". To solve the issues, he proposed a performance measurement framework for a dynamic production network by analytically stratifying the structure of the network (DMU) into

layers according to the production characteristics of sub-DMUs. Then the efficiency of the networks is measured by first estimating the efficiency of sub-DMUs, then of layers, then finally of the entire DMU. Kao (2009) built a relational network DEA model to measure the efficiency of the system and component processes at the same time. As a first study of its kind, Avkiran (2009) illustrated a non-oriented slacks based network DEA application in domestic commercial banks. Among the existing network DEA applications, only two groups of researchers used network DEA in assessing transit systems and railway systems. Sheth et al. (2007) combine the network DEA with goal programming and measured the performance of bus routes by combining the perspectives of provider, user and society. Yu and his college (Yu, 2008; Yu and Lin, 2008) investigate the efficiency and effectiveness of a group of global railways using network DEA. Network DEA is distinctive because of its ability of addressing efficiency with consideration of the internal structure and the interactions among network components.

4.2   Original Network DEA Model

According to Färe and Crosskopf (2000), the network model is formalized as the constraint sets or reference technologies of DEA model, and the network DEA model consists of a set of sub-technology or activities. In this research, the equivalent sub-technologies or activities are different stakeholders. The network DEA model is essentially a family of models by formulating a classic DEA model for each node.

Since the community is assumed to bear the adverse effects of traffic congestion, i.e. emission, the output is expected to be minimized whereas the other desirable outputs are to be maximized. Efficiency measurement with the incorporation of undesirable outputs in production models has been widely studied. Färe et al. (1986) first modeled the effects of environmental controls restricting the disposal of undesirable outputs with the classic radial efficiency measurement approach. Following this approach, Färe et al. (1989) modified the efficiency measures to allow for asymmetric treatment of desirable and undesirable outputs using hyperbolic efficiency measurement approach. For illustration purpose, here we use the same variable notation of their paper, where θ is the efficiency score; q_k is the undesirable output; Q is the undesirable output vector; z is the intensity variable; $\bar{z}$ is the intensity variable vector. The hyperbolic efficiency measurement requires solving a nonlinear programming problem. The authors converted the nonlinear problem to a linear programming problem by taking a linear

approximation to the nonlinear constraint $\frac{q_k}{\theta} \leq Q\bar{Z}$. The linear approximation is $2q_k - \theta q_k \leq Q\bar{Z}$.

However, Zofio and Prieto (2001) suggested computing the hyperbolic measure by converting the nonlinear constraint to $\theta q_k^{-1} \geq (\sum_{k=1}^{K} q_{tk} z_k)^{-1}$ for computational purposes. However, our analysis has shown that this constraint is still nonlinear with respect to the intensity variables z_k. The computational benefit from replacing nonlinear constraint $\frac{q_k}{\theta} \leq Q\bar{Z}$ with the constraint $\theta q_k^{-1} \geq (\sum_{k=1}^{K} q_{tk} z_k)^{-1}$ is very limited, if any. Therefore, this paper uses the linear transformation proposed by Färe et al. (1989). Nevertheless, other methods of treating undesirable variables are available, such as indirect ways which transform the values of the undesirable outputs by a monotone decreasing function such that the transformed data can be included as desirable outputs (Scheel, 2001), slacks-based efficiency measure which has been adopted in commercial DEA software (http://www.saitech-inc.com/index.asp), and an index number approach (Färe et al., 2004).

Assuming there are K DMUs and the kth DMU (k=1……K) uses i inputs and provides j outputs or intermediate outputs. The formulation will evaluate the efficiency of k_0th DMU by computing the efficiency measures $\theta_{k0,}$ and N sets of intensity variables $\lambda_n^{k_0}$. N equals the number of nodes (not including the dummy nodes). The network DEA model with k=1, … , K observations is written in terms of output increasing as:

Max θ

s.t. $\quad {}^n x_i \geq \sum_{k=1}^{K} {}^n \lambda_k \, {}^n x_i^k \quad n = 1,...,N; i = 1,...,I_n$ \hfill (1)

$\quad {}_n^m y_j \geq \sum_{k=1}^{K} {}^n \lambda_k \, {}_n^m y_j^k \quad m = 1,...,N, n = 1,...,N, m \neq n; \; j = 1,..., {}_n^m J$ \hfill (2)

$\quad \theta \cdot {}^n y_j \leq \sum_{k=1}^{K} {}^n \lambda_k \, {}^n y_j^k \quad n = 1,...,N; j = 1,...,J_n$ \hfill (3)

$\quad {}_m^n y_j \leq \sum_{k=1}^{K} {}^n \lambda_k \, {}_m^n y_j^k \quad m = 1,...,N, n = 1,...,N, m \neq n; \; j = 1,..., {}_m^n J$ \hfill (4)

$$^{n}q_{r}\Big/\theta = \sum {}^{n}\lambda_{k}.{}^{n}q_{r}^{k} \quad n = 1,...,N; \; r = 1,...,R_{n} \qquad (5)$$

$$^{n}\lambda_{k} \geq 0 \quad n = 1,..,N; k = 1,...,K \qquad (6)$$

Where

$^{n}x_{i}$, input i to node n

$^{m}_{n}y_{j}$, intermediate output j from node m as an input to node n

$^{n}y_{j}$, final output j of network from node n

$^{n}_{m}y_{j}$, intermediate output j from node n, meanwhile it is the internal input to node m

$^{n}q_{r}$, undesirable outputs from node n

I_{n}, the number of inputs to node n

J_{n}, the number of desirable outputs from node n

R_{n}, the number of undesirable outputs from node n

$^{m}_{n}J$, the number of intermediate outputs from node m as an input to node n

Expressions (1) to (5) are considered as the basic model formulations. The objective is to find out a set of intensity variables $\lambda_{n}^{k_{0}}$ for each node. Each node follows the basic DEA technology $\{ \; y_{m} \leq \sum_{k=1}^{K} \lambda_{k} \; y_{kj}, j = 1,...,J, \; \sum_{k=1}^{K} \lambda_{k} x_{ki} \leq x_{i}, \; i = 1,...,I, \; \lambda_{k} \geq 0, k = 1,...,K \; \}$. It allows us to identify an efficient hypothetical DMU that serves as a reference point for each DMU. Expressions (1) and (2) guarantee that the hypothetic DMU consumes no more of each input and each intermediate inputs as does DMU k_{0} at node n. Expression (3) and (4) ensure that the hypothetic DMU produce at least as much as each product (i.e. final outputs and intermediate outputs) as does DMU k_{0} at node n. Expression (6) indicates the non-negative property of intensity variables. Compared with Färe and Crosskopf's model (2000), the difference is the inclusion of the undesirable output constraints (5). The equality of the constraints reflects the weak disposability of the undesirable outputs. Additionally, we assume that only the final

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outputs are scaled by factor θ. Similar to the standard DEA model, if the network model satisfies the variable return to scale (VRS), $\sum_{i=1}^{K} {}^{n}\lambda_k = 1 \ (\forall n)$.

4.3   Slacks-Based Network DEA Model

In DEA, excesses in inputs and shortfalls in outputs are called slacks. Hereafter, the slacks based network DEA model will be referred as the SBMN model. The slacks-based measure of efficiency (SBM) is augmented from the additive models, and it makes the efficiency evaluation invariant to the units of measure for inputs and outputs (Cooper et al., 2000). Furthermore, it directly provides a ratio efficiency score which helps gauge the depth of inefficiency, similar to the ratio efficiency in the classic CCR model. Expanding on the basic SBM model proposed by Tone (2001), Tone and Tsutsui (2008) developed a slacks-based network DEA model. Färe and Grosskopf (2000) use radial efficiency measurement in their network DEA model. In contrast, the SBM model uses a non-radial approach. The radial approach assumes proportionate reduction/increase in inputs/outputs. The SBM model relaxes the proportionate change assumption and aims at obtaining maximum rate of reduction/increase in inputs/outputs. Therefore, the SBM model captures the non-radial slacks directly (Avkiran, et al., 2008).

According to the selected orientation, three different models, input-oriented, output-oriented and non-oriented, have been proposed by Tone and Tsutsui (2008) as follows:

$$\theta_0^* = \min_{\lambda^k, s^{k-}} \sum_{k=1}^{K} w^k [1 - \frac{1}{m_k} (\sum_{i=1}^{m_k} \frac{s_i^{k-}}{x_{i0}^k})] \tag{7}$$

$$\frac{1}{\tau_0^*} = \max_{\lambda^k, s^{k+}} \sum_{k=1}^{K} w^k [1 + \frac{1}{r_k} (\sum_{r=1}^{r_k} \frac{s_r^{k+}}{y_{i0}^k})] \tag{8}$$

$$\rho_0^* = \min_{\lambda^k, s^{k-}, s^{k+}} \frac{\sum_{k=1}^{K} w^k [1 - \frac{1}{m_k} (\sum_{i=1}^{m_k} \frac{s_i^{k-}}{x_{i0}^k})]}{\sum_{k=1}^{K} w^k [1 + \frac{1}{r_k} (\sum_{r=1}^{r_k} \frac{s_r^{k+}}{y_{i0}^k})]} \tag{9}$$

Subject to the same constraints:

$$x_0^k = X^k \lambda^k + s^{k-} (k = 1,..., K) \tag{10}$$

$$y_0^k = Y^k \lambda^k + s^{k+} (k = 1,..., K) \tag{11}$$

$$\lambda^k \geq 0, s^{k-} \geq 0, s^{k+} \geq 0, (\forall k) \tag{12}$$

The intermediate inputs/outputs are called link flows. As regard to the link flow constraints, two cases are proposed[13]:

(1) Discretionary intermediate inputs/outputs constraints

$$Z^{(k,h)} \lambda^h = Z^{(k,h)} \lambda^k, (\forall (k,h)), \tag{13}$$

(2) Non-discretionary intermediate inputs/outputs constraints

$$Z_0^{(k,h)} = Z^{(k,h)} \lambda^h (\forall (k,h)),$$
$$Z_0^{(k,h)} = Z^{(k,h)} \lambda^k (\forall (k,h)). \tag{14}$$

Where

θ is the input-oriented efficiency.

τ is the output-oriented efficiency.

ρ is the non-oriented efficiency;

w^k is the relative weight of node k that is determined corresponding to its importance. It is assumed the same importance in our example.

x^k is the external input to node k.

y^k is the final output from node k.

$z^{(k,h)}$ is the intermediate products produced from node k and consumed by node h.

s^{k-} is the input excess in node k.

s^{k+} is the output shortages in node k.

λ^k is the intensity variable of node k.

m_k is the number of inputs in node k.

---

[13] In this example, the discretionary case is adopted. It assumes that the link flow or the intermediate products can be increased or decreased in the optimal solution of the programming.

r_k is the number of outputs in node k.

Similarly, $\sum_{j=1}^{n}\lambda_j^k = 1(\forall k)$ if variable return to scale is hold.

To take into account the undesirable output, this paper adopts the approach implemented in the DEA-Solver Pro software (http://www.saitech-inc.com/index.asp). In the presence of bad outputs, a DMU is efficient if there is no vector (x, y, b) ϵ P such that $x_0 >= x$, $y_0 <= y$, $b_0 >= b$ with at least one strict inequality. In accordance with this definition, the SBM is modified as follows.

$$\rho_0^* = \min \frac{1 - \dfrac{1}{m}(\sum_{i=1}^{m_k} \dfrac{s_i^{k-}}{x_{i0}^k})}{1 + \dfrac{1}{s}(\sum_{r=1}^{s_1} \dfrac{s_r^g}{y_{i0}^k} + \sum_{r=1}^{s_2} \dfrac{s_r^b}{y_{i0}^b})} \qquad (15)$$

Subject to

$$\begin{aligned}
x_0 &= X\lambda + s^- \\
y_0^g &= Y\lambda - s^g \\
y_0^b &= Y\lambda + s^b \\
s^-, s^g, s^b, \lambda &\geq 0
\end{aligned} \qquad (16)$$

The superscript "g" indicates desirable outputs, and "b" indicates undesirable outputs.

5.0   An Illustrative Example

Because of the limited number of demand scenarios (DMUs) available from the microscopic simulation, the DEA network has been simplified in this example (Figure 5-3), keeping the vital and representative variables of the network of Figure 5-2.

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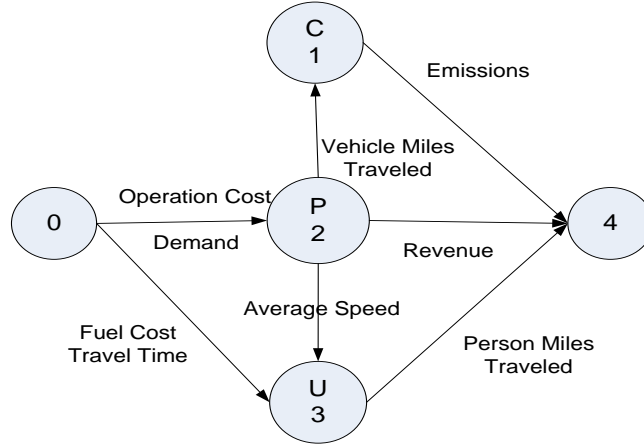
Figure 5-3 The Simplified Network

As the example, the network DEA model is written in terms of output increasing as:

$$\text{Max } \theta$$

Subject to:

Node 1 (community's perspective):

$$y_{vmt} \geq \sum_{k=1}^{K} \lambda_c^k \, y_{vmt}^k \tag{17}$$

$$\frac{y_e}{\theta} = \sum_{k=1}^{K} \lambda_c^k \, y_e^k \tag{18}$$

Node 2 (providers' perspective):

$$x_c \geq \sum_{k=1}^{K} \lambda_p^k \, x_c^k \tag{19}$$

$$y_{as} \leq \sum_{k=1}^{K} \lambda_p^k \, y_{as}^k \tag{20}$$

$$y_{vmt} \leq \sum_{k=1}^{K} \lambda_p^k \, y_{vmt}^k \tag{21}$$

$$\theta . y_r \leq \sum_{k=1}^{K} \lambda_p^k \, y_r^k \tag{22}$$

Node 3 (users' perspective):

$$x_f \geq \sum_{k=1}^{K} \lambda_u^k \, x_f^k \tag{23}$$

$$x_{tt} \geq \sum_{k=1}^{K} \lambda_u^k \, x_{tt}^k \tag{24}$$

$$y_{as} \geq \sum_{k=1}^{K} \lambda_u^k \, y_{as}^k \tag{25}$$

$$\theta.y_{pm} \leq \sum_{k=1}^{K} \lambda_u^k \, y_{pm}^k \tag{26}$$

$$\sum_{i=1}^{K} \lambda_n^k = 1 \; (n = u, p, c) \tag{27}$$

y_{vmt}: Vehicle miles traveled (VMT), intermediate outputs from node 2 and intermediate input to node1;

y_e: Emission, output from node 1;

x_c: System operation cost (maintenance cost and administrative cost) incurred by the system provider;

y_{as}: Average speed, intermediate output from node 2 and input to node 3;

y_r: The total revenue obtained from the reservation system, an output of node 2;

x_f: Fuel consumption, input consumed by transportation users;

x_{tt}: Average travel time used by transportation users;

y_{pm}: Person miles traveled (PMT), final output from users' perspective.

$\lambda_p^k, \lambda_u^k, \lambda_c^k$ are non-negative intensity variables associated with each node.

Expressions (17) – (18) are associated with community node, (19) to (22) are associated with provider node, and (23) to (26) are associated with user node. The model allows us to identify an efficient hypothetical DMU that serves as a reference point for each DMU. Per the consultation with transportation experts, VRS is assumed here. However, constant return to scale (CRS) is presented for comparison purpose.

5.1 Data Description

The unit of analysis is the demand scenario with the DSRS implemented in the transportation system. Data associated with the demand scenarios are obtained from the simulation model. The scenarios are varied in terms of the total demand level (i.e. average arrival rate), the reservation policies (i.e. the weights assigned to people throughput and revenue in the objective function of the optimization model) and the inherent uncertainty of the traffic assignment and the traffic flow in the simulation (Table 5-1). The demand level varies from 6000 to 7000 (vehicles/control period). It is selected according to the transportation network size of the traffic simulation model. The weights are arbitrarily assigned due to the lack of practical

references. Table 5-1 shows that DMU 6 to DMU 16 have the same demand level and weights. They are different because of the stochastic nature of the traffic assignment and the traffic flow. Altogether, there are 28 scenarios, thus 28 DMUs. Operational cost is assumed constant for all 28 DMUs. Table 5-2 shows the statistical summary for the data set.

Table 5-1 Demand Scenarios

DMU	Demand Level	Weights	DMU	Demand Level	Weights
1	6000	3 (3:1)	15	7000	3 (3:1)
2	6200	3 (3:1)	16	7000	3 (3:1)
3	6400	3 (3:1)	17	7000	1 (1:1)
4	6600	3 (3:1)	18	7000	2 (2:1)
5	6800	3 (3:1)	19	7000	3 (3:1)
6	7000	3 (3:1)	20	7000	4 (4:1)
7	7000	3 (3:1)	21	7000	5 (5:1)
8	7000	3 (3:1)	22	7000	8 (8:1)
9	7000	3 (3:1)	23	7000	10 (10:1)
10	7000	3 (3:1)	24	7000	20 (20:1)
11	7000	3 (3:1)	25	7000	30 (30:1)
12	7000	3 (3:1)	26	7000	40 (40:1)
13	7000	3 (3:1)	27	7000	50 (50:1)
14	7000	3 (3:1)	28	7000	$+\infty$ (1:0)

Table 5-2 Summary statistics of the inputs and outputs data

	Fuel Consumption	Avg. Travel Time	Revenue	Avg. Speed	Emission	Vehicle Miles Traveled	Person Miles Traveled
Mean	349.12	216.11	22251.7	12.83	34807.9	4179.25	14325.75
Minimum	299.91	176.96	20401.7	11.38	29901.1	3743.16	11385.04
Maximum	370.65	268.83	23679.8	13.21	36954.13	4366.56	16862.95
Standard Deviation	16.46	18.63	526.56	0.35	1639.837	151.25	1562.631
STD %	4.71%	8.62%	2.37%	2.72%	4.71%	3.62%	10.91%

5.2   Analysis I: Network Models vs. Separation Models

In this section, the analysis is based on the assumptions of output maximization and variable return to scale. This section focuses on exploring the relationship between the nodes and the entire network. To show how the node efficiency affects the network efficiency, we first ran standard DEA models for each node individually (Figure 5-3), and then ran the network model. The present analysis does not include the separation DEA model for community node because the way the undesirable output (emission) is treated in the network DEA model pose a computation problem if the node only has one undesirable output and no desirable output. According to the efficiency scores obtained from the separation and network DEA models (Table

5-3), following observations are obtained: (1) if one of the two nodes is efficient (technical efficiency), then the network is efficient (technical efficiency); (2) the network efficiency score equals the efficiency score of one of the two nodes; (3) the network efficiency is dominated by the provider node; generally speaking, it is dominated by the more efficient node (lower node efficiency score); (4) the DMU is mix efficient only if both of the nodes are efficient[14]; (5) the standard deviation in Table 5-2 suggests that the variation of the input and output data across the 28 DMUs is not significant. Therefore, it is not surprising that the efficiency scores may not differ much.
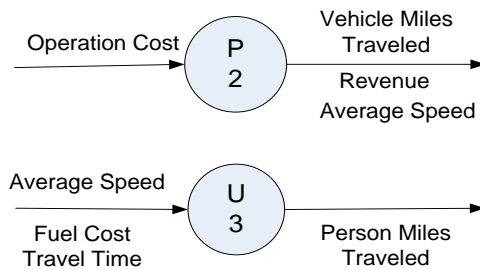
Figure 5-4 Separation Models for Provider Node and User Node

Table 5-3 Nodes efficiency of the separation models and network efficiency (VRS)

DMU	Provider	User	Network	DMU	Provider	User	Network
1	1.0208	1.0850	1.0208	15	1.0368	1.0000	1.0000
2	**1.0000**	**1.0000**	**1.0000**	16	1.0152	1.0000	1.0000
3	1.0190	1.1581	1.0190	17	1.0026	1.0394	1.0026
4	1.0127	1.0360	1.0127	18	1.0000	1.1491	1.0000
5	**1.0000**	**1.0000**	**1.0000**	19	1.0218	1.0507	1.0218
6	1.0271	1.0000	1.0000	20	1.0000	1.2581	1.0000
7	1.0218	1.2381	1.0218	21	1.0068	1.1802	1.0068
8	1.0279	1.1854	1.0279	22	1.0105	1.0000	1.0000
9	1.0281	1.1667	1.0281	23	1.0042	1.0626	1.0042
10	1.0000	1.1362	1.0000	24	1.0000	1.1353	1.0000
11	1.0356	1.1014	1.0356	25	1.0000	1.0522	1.0000
12	1.0216	1.0081	1.0081	26	1.0142	1.0000	1.0000
13	1.0022	1.2502	1.0022	27	1.0077	1.0952	1.0077
14	1.0000	1.0744	1.0000	**28**	**1.0000**	**1.0000**	**1.0000**

As the network model shows, each node has one set of intensity variables and each node has its own reference set. The reference set for DMU k_0 at node n is $R_n^{k_0}=\{j \mid \lambda_n^j>0\}$. For provider node, DMU2, 5, 10, 14, 18, 20, 25and 28 are considered as reference peers for the

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[14] For the separation models in this example, if the DMU is technical efficient, it is also mix efficient.

inefficient DMUs (Figure 5-5). Among them, DMU5, 18 are the most frequent ones. DMU 18 has the highest VMT. It makes the DMU more efficient from provider's perspective. DMU 5 has the highest revenue. Even if it has a relative low VMT, from maximizing revenue aspect, it outperforms others in terms of provider's perspective. Other DMUs could improve performance through increasing revenue if referring DMU5 as reference point. DMU10 has high revenue (3rd). DMU14 has moderate revenue (10th), but has very high average speed (2nd). For user node, DMU16 and DMU28 are the reference peers for all the other DMUs (Figure 5-5). DMU 28 has the highest person miles traveled. Therefore, from users' perspective, others are more likely to improve efficiency compared with DMU 28. DMU 16 is the second highest person miles traveled. All these reference DMUs are technically efficient. However, for community node, it shows that DMUs do consider some inefficient DMUs as reference peers. This is because that the network efficiency is mainly dominated by the provider node, and the community node plays the least part in the network efficiency. Therefore even though those DMUs are more efficient in community node and can be considered as reference in that perspective, they still have inefficient network scores due to the dominance of the inefficiency in the provider node.
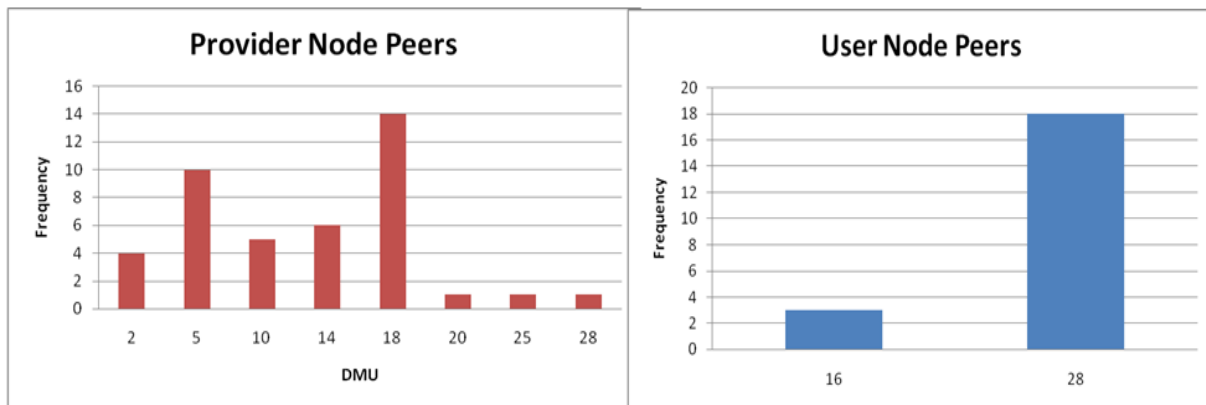
Figure 5-5 Reference DMUs for Provider and User Node

The inefficiency associated with the nonzero slacks is referred as mix inefficiency (Cooper et al., 2000). In this example, only DMU 28 is mix efficient under both VRS and CRS according to this definition. DMU 28 represents the demand scenarios with maximum weight on people throughput. In this scenario, decision maker makes decision whether to accept the incoming request based on the goal of maximizing total number of people throughput, and does not take into account the factor of revenue maximization. The associated revenue is the lowest among the 28 DMUs, but person mile is the highest among the 28 DMUs. The people throughput is

reflected mainly by the node 3 (User Node). Therefore, for that node, 18 out of the 28 DMUs refer that DMU as reference point (Figure 5-5).

Table 5-4 shows that the slacks mostly occur to the user node from travel time and person miles traveled[15]. For those radial efficient but mix inefficient DMUs, such as DMU10, 14, 18, 20, they could be improved by reducing the travel time and/or increasing the person miles traveled without compromising other inputs and outputs. Because the operational cost for all demand scenarios is assumed the same, there are no operational cost slacks in provider node. The inefficiency associated with provider node is mainly technical inefficient, while the inefficiency in user node is mainly mix inefficient. The undesirable output emission is assumed weak disposable, thus no slacks for this node.

Table 5-4 Slacks

DMU	(I) cost	(O) revenue	(I) Fuel	(I) travel t.	(O) PM	(O) Emission
1	0	0	2.15	10.58	0.00	0
2	0	0	0	0	0	0
3	0	0	0	36.84	655.35	0
4	0	0	0	6.58	0	0
5	0	0	0	0	0	0
6	0	603.62	0	0	0	0
7	0	0	0	19.78	1704.07	0
8	0	0	4.42	0	1884.33	0
9	0	0	0	21.60	761.59	0
10	0	0	0	10.35	1102.29	0
11	0	0	0	1.69	796.82	0
12	0	0	0	4.54	0	0
13	0	0	0	27.00	1791.69	0
14	0	0	0	7.44	522.91	0
15	0	0	0	0	0	0
16	0	163.37	0	0	0	0
17	0	0	4.72	8.41	590.38	0
18	0	0	0	34.63	1323.60	0
19	0	0	0	19.01	174.69	0
20	0	0	0	28.31	2166.45	0
21	0	0	0	10.63	2094.44	0
22	0	230.06	0	0	0	0
23	0	0	0	19.46	913.01	0
24	0	0	0	1.21	1832.93	0
25	0	0	0	5.41	662.55	0
26	0	291.96	0	0	0	0
27	0	0	0	21.98	1023.64	0
28	0	0	0	0	0	0

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[15] This statement will also be supported by the results of the SBMN model in the next section

5.3 Output Maximization vs. Input Minimization

Comparison between input and output oriented models shows that output oriented model provides higher discriminating power among the 28 DMUs (Figure 5-6). Especially under VRS assumption, all the 28 DMUs of the input oriented model are technically efficient. It is expected that the homogeneousness comes from the assumption of the same operational cost to the DMUs. The (in)efficiency is mainly driven by the outputs. Furthermore, if we take into account the fact that operation costs are all the same for the demand scenarios, decision maker may have less motivation to focus on reducing cost in this case. Therefore, operation costs are not minimized in the second input orientation model (M2). Figure 5-6 show that the input oriented results (M2) are more discriminated in this case. This further suggests that in case if input minimization is more desired for the system, decision maker should emphasize on minimizing users' travel time and fuel consumption. It would reveal more information about the DMU by differentiating itself from other DMUs. This also emphasizes the importance of users' perspective in assessing the network performance.
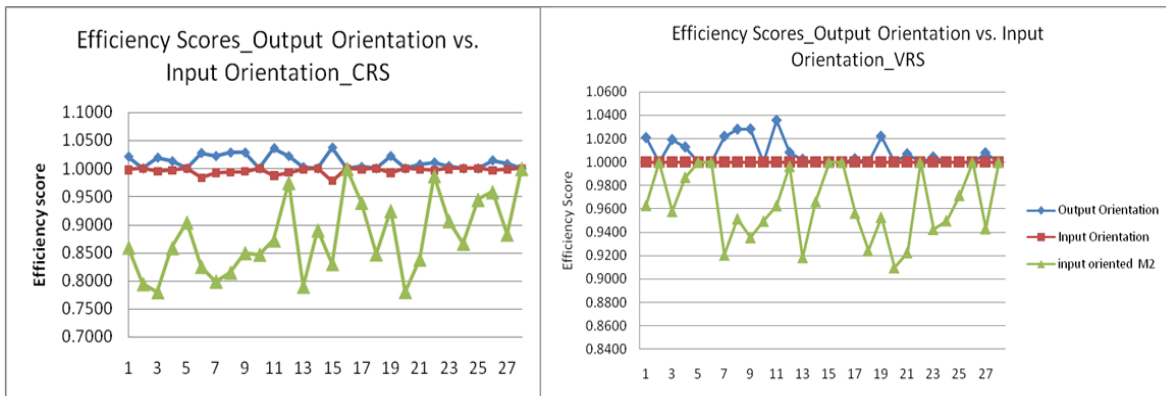
Figure 5-6 Output Oriented vs. Input Oriented

5.4 Analysis II: Original Network Model vs. SBMN Model

Compared with the network DEA model, the SBMN models have a higher discriminating power (Figure 5-7). More DMUs are efficient in the Network DEA model. This indicates that if the proportional (radial) reduction/increase assumption is relaxed, some DMUs are inefficient, whereas are efficient in network DEA.
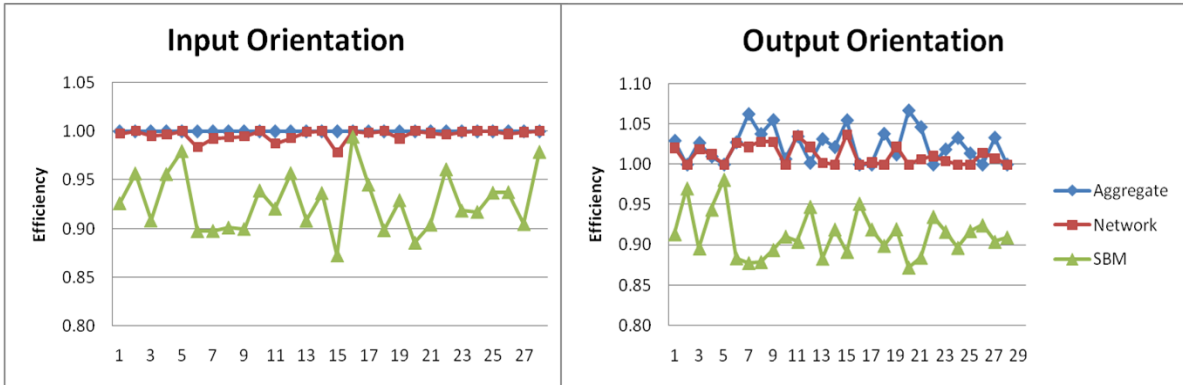
Figure 5-7 Efficiency Comparison

Comparing the reference sets in Network DEA models (Figure 5-5) and SBMN models (Figure 5-8), DMU2 and 5 are reference DMUs for the inefficient ones at the provider node in the network DEA models. In SBMN models, DMU 2 appears in the reference sets of all the three nodes with much higher frequency. Although the referring frequency for a DMU may be different in the two different network DEA approaches, the majority of the referenced DMUs are the same. This indicates that the two approaches should provide similar frontiers. In SBMN models, the reference peers can be inefficient themselves, but the reference peers should have at least one node SBM efficient, so even if the DMU is not efficient because of the other nodes, it still can be a benchmark for other DMUs in that efficient node.
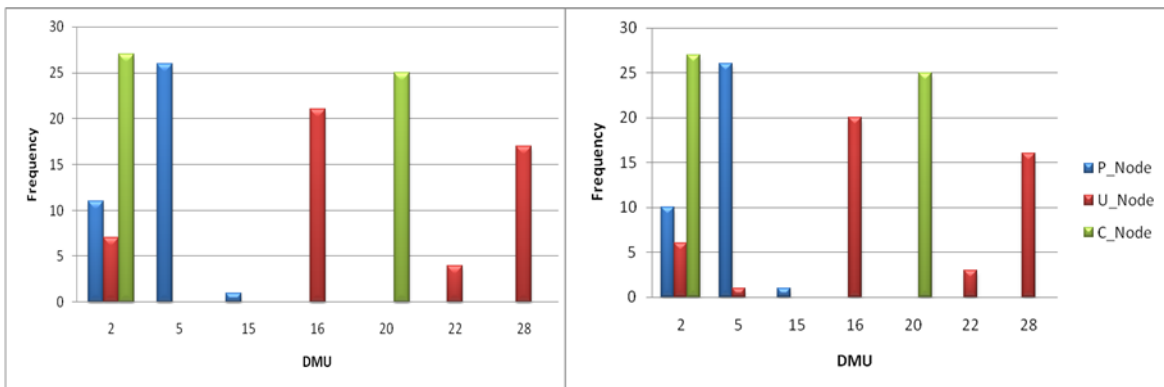
Figure 5-8 Reference Sets SBM_NO (left) and SBM_O (right)

Let us take DMU 2, 5, 28 as examples (Table 5-5) that are efficient in network DEA model. DMU 2 is efficient in all of the models in all the three perspectives (nodes). It is a reference point for most of the other DMUs. The input and output measures associated with the demand scenario show that this scenario has a low demand level (λ=6200), relative high revenue from the provider's perspective, low fuel consumption and travel time from the user's

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perspective, and low emission from the community perspective. Therefore, this DMU is the global efficient one in this example. It can be considered as a benchmark for the other DMUs. DMU 5 is efficient in SBMN input oriented model and network DEA models, but inefficient in SBMN output oriented and non-oriented models. This indicates that the inefficiency comes from output slacks. The node efficiency further indicates that the slacks related inefficiency is from the community node. The slack of emission shows that this unit can be improved by reducing its emission (930g). DMU 5 is efficient in both orientations in the network DEA models and the aggregate models. In this case, the network models provide as much insight about the demand scenario as the aggregate models do. On the other hand, the SBMN models further explore the source of inefficiency associated with the slacks. DMU 28 suggests a similar conclusion as DMU 5, while its inefficiency in SBM models results from the output shortage of revenue (3013$) and emission excess (4770g). In addition, in the network DEA, a DMU is technically efficient as long as one of the nodes is technically efficient, but in SBM model, a DMU is efficient only if all three nodes are efficient.

Table 5-5 Performance Exhibition of DMU 2, 5 and 28

	DMU	2		5			28			
		Eff.	Ref. Set	Eff.	Ref. Set	Slacks Emission	Eff.	Ref. Set	Slacks Revenue	Slacks Emission
NO	Network	1		0.9905			0.9151			
	P-Node	1	2	1	5		0.8713	5(0.8), 15(0.2)	3013	
	U-Node	1	2	1	5		1	28		
	C-Node	1	2	0.9720	2(0.7) 20(0.3)	930	0.8844	2(0.6) 20(0.4)		4770
O	Network	1		0.9905			0.9151			
	P-Node	1	2	1	5		0.8713	5(0.8), 15(0.2)	3013	
	U-Node	1	2	1	5		1	28		
	C-Node	1	2	0.9720	2(0.7) 20(0.3)	930	0.8844	2(0.6) 20(0.4)		4770
I	Network	1		1			1			
	P-Node	1	2	1	5		1	28		
	U-Node	1	2	1	5		1	28		
	C-Node	1	2	1	5		1	28		
Network Output	Network	1		1			1			
	P-Node	1	2	1	5		1	28		
	U-Node	1	2	1	5		1	28		
Network Input	Network	1		1			1			
	P-Node	1	2	1	5		1	28		
	U-Node	1	2	1	5		1	28		
Aggregate (O)		1	2	1	5		1	28		
Aggregate (I)		1	2	1	5		1	28		

Comparing the three SBMN models (Figure 5-9) under both VRS and CRS, the non-oriented model provides a relative low efficiency, and DMUs are more close to efficiency in the input oriented model. This further suggests that less inefficiency exists in the input excesses. In other words, inefficiency is more likely resulted from output shortages.
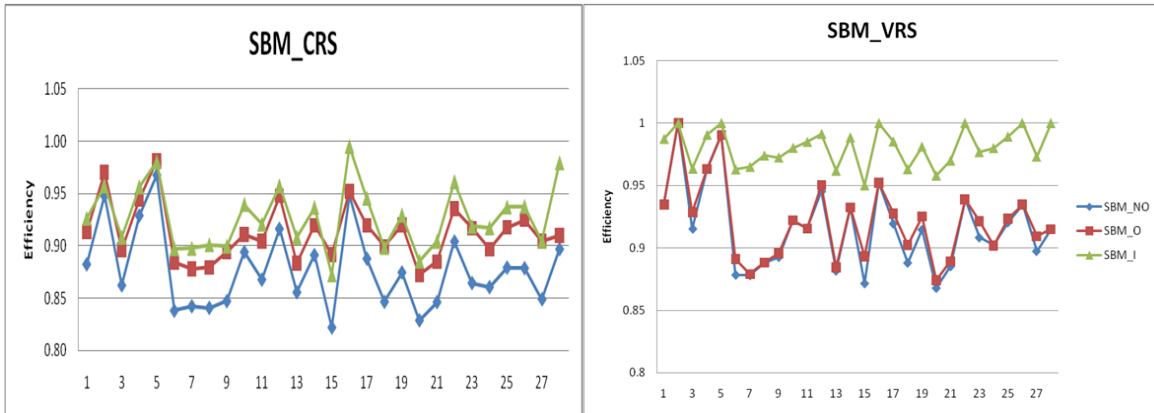
Figure 5-9 Efficiency Comparison

The SBMN formulation implies that the (in)efficiency of the three nodes is averaged in the network model. The SBMN efficiency score is determined jointly by a weighted average of the three nodes. In contrast, in network DEA model, the network efficiency of a DMU is determined by one of the three nodes, and the provider node dominates the network. Nevertheless, Table 5-6 suggests that the SBMN network efficiency scores have a higher correlation with the user node efficiency, and this indicates the dominance of the user node in the SBMN. This is consistent with the results found in the network DEA model. It shows that the slacks are mainly from the travel time (input to user node) and person miles (output from user node), and the inefficiency associated with provider node is mainly technical inefficiency. In SBMN, the network efficiency scores have the least correlation with the provider node.

Table 5-6 Correlation of Network Efficiency and Node Efficiency

	NO	O
Network	1	1
P-Node	0.49	0.56
U-Node	0.85	0.82
C-Node	0.65	0.63

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5.5   Concluding Remarks on the Example

In the original network DEA, the network efficiency is dominated by the provider node. This is resulted from the network structure. The provider node is the center of the network. It provides intermediate inputs to the community node and user node. This structure determines that the performance in provider node inevitably impact the performance of the other two nodes. However, the SBMN efficiency is constructed as a weighted average of the node efficiency. This average cuts down the dependency on the network structure. According to the fundamentals of the two approaches, the original (radial based) network DEA assume that one can be efficient by having the best ratio at any particular dimension. If a DMU is really good at using one of the inputs to produce one of the outputs, it can be identified as efficient in the radial model. In another words, it would move to the frontier along the shortest distance to become efficient. This may indicate that one is doing something unique to outperform other competitors. However, in the slacks based model, we care about all the inputs and outputs. This also explains the findings in the example that a DMU is technically efficient as long as one of the nodes is technically efficient in the network DEA, whereas a DMU is efficient only if all three nodes are efficient in SBMN model.

To decision maker, the original network DEA approach and the SBM network DEA approach provide different information. According to the information, decision maker may focus on different components or directions to improve the system performance. For example, in the example, the original network DEA may lead decision maker focusing more on the provider perspective, while the SBM network model may lead decision maker focusing on the user's node.

The network structure should reveal the real structure of transportation system. However, this depends on how much one knows about the system structure. If the framework is already somewhat inaccurately reflects the real system, then the value of the evaluation may be compromised. Additionally, because the evaluation of a DMU in DEA is relative to all the other DMUs, it is highly data dependent. The example did not numerate all the possible demand scenarios, and it has a limited number of demand scenarios. These DMUs may or may not represent the whole reality. Therefore, it is critical to understand that the methodology proposed in this example is more valuable than the absolute results. To addresses these deficits, further analysis is required.

6.0 Research Conclusions and Future Directions

6.1 Bridging Optimization, Simulation and Network DEA

This research bridges the DSRS optimization model, simulation model and the DEA model. Optimization and simulation are popular methods used in system engineering design. Optimization model is the foundation of the DSRS research. The optimization model is the actual decision making tool which enables decision maker to decide whether to accept or reject a trip reservation request. It is the core of the DSRS design. However, the optimization model itself cannot convey information, such as what the traffic flow conditions are under DSRS, whether the design of the system meets the stakeholders' requirements, and how system structure influences performance etc. Therefore, a further evaluation is established to determine whether requirements and performance measures are being met.

Simulation is one of the most popular tools used by transportation professionals. It is used to test and analyze the DSRS. The simulation model provides various transportation measures and helps the decision maker appreciate the system from a transportation perspective. However, additional performance measurement and system design issues need to be addressed beyond the simulation paradigm. First, it is not the absolute representation of performance that matters, but the idea of relative performance that is important. One might be more interested in how much performance can be improved when compared to best practices. Moreover, the simulation does not directly tell us how the key performance measures interact with each other, which is critical to understand the system structure. The current paper addresses these issues with a comprehensive performance measurement framework. On one hand, this approach provides a single index as representative of the overall system efficiency. On the other hand, the approach identifies the sources of inefficiency. This framework enables decision maker to gain an in-depth appreciation of the system design and the performance measurement issues.

In conclusion, the optimization model represents the designed system; the simulation and the network DEA models are the supporting frameworks that provide an evaluation of this system design. The two evaluation approaches are actually complementary. For the DSRS, the simulation approach supports the network DEA model by providing data, and the network DEA performance measurement complements the simulation model by taking into account the fundamental system structure.

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6.2   System Design Implications

The current research is an illustrative demonstration which shows how the network DEA works in assessing the DSRS or transportation system in general. The network DEA helps the decision maker understand the system that is being evaluated. It opens the classic DEA transformation "black box". This enables decision maker to locate the source of the inefficiency more accurately. It helps detect the potential directions to improve the system design, to include requirements into the design at the early stage. For instance, if the DEA model shows that the inefficiency is mainly from the user node, the decision maker may need to put more effort on the user's perspective, such as improving the people throughput via pricing policy adjustment. This kind of information is useful to adapt the reservation system to the decision maker's special need.

In addition, the research provides valuable indications about the design process. At the beginning of the DSRS development (Zhao and Triantis, 2008), the design of the system is oriented by the goal of mitigating congestion. It did not attempt to break down the goal into a finer level with respect to different perspectives in the initial design process. And the initial model formulation in that paper did not explicitly include the different perspectives, or at least, the model was not elaborated in that way, although implicitly the objective reflects the provider's and the user's perspectives. Therefore, reflecting on the performance evaluation in this paper, a system breakdown structure or work breakdown structure would help the design process by mapping requirements from one level of system specification to another.

6.3   Future Research Directions

Taking into account the fact that very limited network DEA application available in transportation performance measurement, following directions are recommended:

(1) The research can be expanded by conducting additional analysis with more data sets that come from different demand distributions to further study whether and how the demand generation relates to performance in DEA.

(2) To compensate for the lack of real world validation of the reservation system, future research may adopt the similar network to evaluate other transportation policies, such as congestion pricing, where people may obtain practical data of the system. This could future investigate whether the network DEA is an appropriate tool for transportation performance measurement.

(3) The network developed in this research is one of the many ways to represent the transportation system. The results obtained from this network might be biased to the perception about the network structure. Future research may depict the system with different structures. Such an analysis may help to answer questions as to what extent the DEA results relying on the network structure.

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CHAPTER 6 Research Conclusions and Future Directions

6.1 Bridging Optimization, Simulation and Network DEA

In this research we have explored the application of a reservation concept within a traffic congestion management framework. The DSRS provides transportation engineers and policy makers an alternative mechanism to mitigate traffic congestion in a metropolitan city. This research describes the conceptual representation of the reservation concept in the context of the traffic congestion management literature in a more systematic and comprehensive way. Furthermore, the research methodology used in this research can be used for the design and evaluation of other TDM strategies. It uses a three-step framework, i.e., the analytical, simulation modeling and performance evaluation steps. It integrates multiple modeling approaches (optimization, simulation, data envelopment analysis) for the purpose of system design and evaluation.

The three essays together address the questions raised at the beginning of this research. Essay 1 (Chapter 3) primarily answers the question of how to model a reservation system for a downtown area. The essay elaborates on how the optimization and artificial neural networks technologies are used to design the DSRS. Essay 2 (Chapter 4) provides a solution to the question of how to evaluate the impact of a reservation system on a transportation network. The essay suggests that microscopic traffic simulation is a valuable evaluation approach for the DSRS. Essay 3 (Chapter 5) furthermore supplements the simulation evaluation with an advanced system performance measurement approach - Network DEA. It potentially provides a new way to deal with the problem of evaluating the overall system performance of the DSRS. In addition, the questions about the benefits and costs associated with the system and the implementation issues are discussed in the three essays.

The first essay (Chapter 3) provides an analytical model that allows the transportation authority to make decisions as to which requests should be accepted by the system. An illustrative example based on the data from I-66 demonstrates the way that a reservation system can potentially work within a congestion management context for a downtown area. The proposed approach helps decision makers to consider congestion from a resource capacity

limitation point of view, where the capacity of a road network is clearly defined. Furthermore, the design and implementation of this system borrows concepts from congestion pricing, especially cordon-based congestion pricing because of the commonality between the two approaches. It is the intention of this research to build on the considerable research and practical experience in the literature with respect to congestion pricing. However, the proposed TDM strategy is not intended to substitute congestion pricing, or any other existing TDM strategies. Instead, together with other TDM strategies, it expands the solution domain for congestion management, especially for metropolitan areas.

In the second essay (Chapter 4), the microscopic simulation approach provides a mechanism to illustrate the advantages of the DSRS from a transportation planning point of view. Multiple demand scenarios are simulated. The modeling and analysis facilitate the promotion of the system and communicates the potential impacts of the system to stakeholders. The simulation modeling is a useful precursor for the later implementation of the DSRS. In addition, it can facilitate the DSRS design process. Findings and insights derived from simulation results can be used for further modification and improvement of the DSRS.

The third essay (Chapter 5) develops a transportation performance measurement framework with an application of a network-DEA efficiency measurement methodology. The framework captures the perspectives of transportation system providers, the users and the community, as well as the interrelationship among these stakeholders. The performance measurement compares and contrasts various instances (scenarios) that occur in the transportation network under the execution of the DSRS. The scenarios constitute the production possibility set for our analysis. The third essay presents a demonstration of a potential practical application of network DEA in transportation system and TDM strategy evaluation. It combines the network DEA technique with traffic simulation in performance measurement. It utilizes the outputs from the microscopic traffic simulation models as inputs data to the DEA models. Thus, the network-DEA model complements the micro level simulation performance measurement by accounting for a macro level performance measurement considerations. Furthermore, the network DEA approach detects potential improvement directions and helps identify system design requirements at the early stage before the reservation system is implemented.

The three essays can be used to facilitate the design process associated with the reservation system. The design process should be repetitive, meaning that each essay can be

viewed as a step of the design process and needs to be revisited based upon the feedback of the results and analysis (Figure 6-1) of the other two essays. The current research has accomplished the initial design process cycle. However, future research can extend the current research by revisiting each step and revising the design of the DSRS according to insights obtained from the analyses of all three steps. Furthermore, in each chapter (Chapter 3, 4, 5), we have provided detailed directions for the future research regarding that particular step.
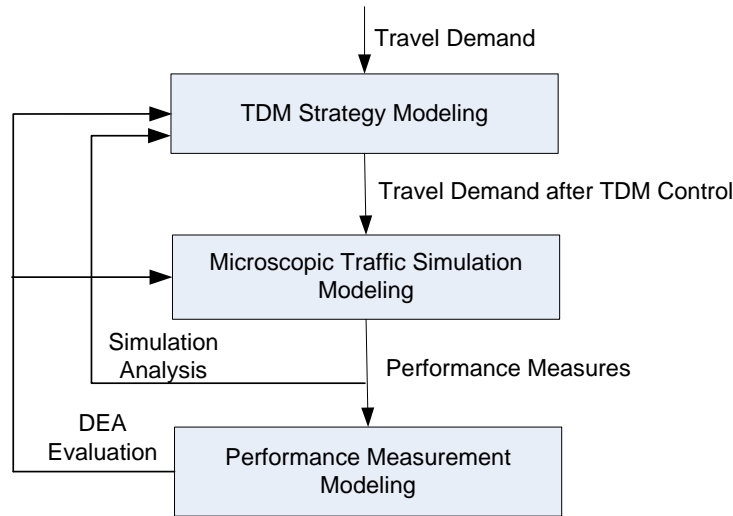
Figure 6-1 The System Design Process

6.2   Reservation System Design Implications

The current research demonstrates how the network DEA approach can assess the DSRS by helping the decision maker understand the system that is being evaluated. It opens the classic DEA black box representation and enables the decision maker to locate the sources inefficiency more accurately. It helps isolate potential design and include requirements into the design at an early stage. For instance, if the DEA model shows that the inefficiency stems mainly from the user node, the decision maker may need to put more effort on the user's perspective, such as improving the people throughput via a pricing policy adjustment.

In addition, the research provides valuable insights about the design process. At the beginning of the DSRS development (Zhao and Triantis, 2008), the design of the reservation system was focused on the goal of mitigating traffic congestion. It did not attempt to explicitly address different perspectives as evidenced by the formulation of the first essay although

implicitly the objective function reflects the provider's and the users' perspectives. Therefore, reflecting on the future design of the reservation system after the results obtained from both essays two and three, a system breakdown structure would help the future design process by mapping requirements from one level of the reservation system to another. For example, requirements need to be defined for the actual physical reservation system along with user and community requirements. Furthermore, the use of current systems engineering life-cycle design process as a way to realize the future DSRS design remains an open future developmental task.

6.3 Future Research Directions

Taking into account the fact that the use of the reservation concept as a means of mitigating traffic congestion is very limited as is the use of the network DEA application as a mechanism to assess transportation performance, some of following directions are recommended:

(1) The research can be expanded by conducting additional analysis with more data sets that come from different demand distributions to further study whether and how the demand generation affects the performance of the transportation network.

(2) To compensate for the lack of real world validation of the reservation system, future research may adopt a similar network DEA structure to evaluate other TDM policies, such as congestion pricing, where people may obtain practical data. This could shed some insight as to whether the network DEA is an appropriate approach for transportation performance measurement.

(3) The network DEA model developed in this research is one of the many ways to represent the transportation system. The results obtained from this network might be biased by the representation of network structure. Future research could evaluate alternative network DEA structures. Such an analysis may help to answer questions as to what extent the DEA results are a function of the network structure.

(4) The key to the successful use of the DSRS is to view it in connection with other TDM strategies. One of the most promising future initiatives is to see how the DSRS can be coupled with an intelligent parking reservation system. This could be one of many combined strategies that one could consider.

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Appendix A Data Generation for Essay 1

The demand data were generated in Microsoft Office Excel 2007.

Step 1. Extracte cumulative traffic volume from historical data
Table B-1: Cumulative Inbound Traffic Flow (Percentage)

Time Slot	Traffic Flow
7	0.08
8	0.22
9	0.38
10	0.5
11	0.57
12	0.62
13	0.66
14	0.72
15	0.79
16	0.85
17	0.91
18	0.96
19	1

Cumulative traffic volume during each time interval (percentage) from I-66 inbound at milepost 51.2

Step 2. Generate inbound traffic (Entry).
Table B-2: Inbound Trips

Request ID	Rand No.	Entry
R1	0.63218	12
R2	0.073	7
R3	0.47893	9
R4	0.57426	11
R5	0.85525	16
R6	0.20201	7
R7	0.15752	7
R8	0.55025	10
R9	0.45822	9
R10	0.87293	16
R11	0.46195	9
R12	0.904	16
R13	0.27441	8
…..	…..	…..

If the random number (Rand1) <0.08, the corresponding trip entry time is 6 (denoting 6:00-6:59); if 0.22 >the random number (Rand1) >=0.08, the entry time is 7 (denoting 7:00-7:59) etc.

Step 3. Generating outbound traffic (Departure)

Table B-3: Outbound Trips

Request ID	Rand No.	Rand No.	Staying Length (SL)	Departure[*]
R1	0.6593	0.4727	7.9317	20
R2	0.6159	0.7749	8.6042	15
R3	0.3744	0.1099	6.7733	16
R4	0.7397	0.0649	6.4852	18
R5	0.8798	0.7201	1.2915	18
R6	0.0149	0.5601	2.0756	10
R7	0.1349	0.6965	2.2572	10
R8	0.8707	0.0412	6.2634	17
R9	0.1349	0.0539	1.1962	11
R10	0.1479	0.6949	1.2549	18
R11	0.2669	0.1026	6.7333	16
R12	0.1714	0.7776	1.3821	18
R13	0.5811	0.8741	9.1460	18
….	….	….	….	….

Departure*=Staying Length (SL) + Enter

To generate the corresponding departure time for each trip, first the staying length is generated. And the departure time equals the entry time plus the staying length. To do that, we assume that the staying length of vehicles entering during different time interval follows different distributions. For example, if the entry time is 6, and the random number (Rand 2) is <= 0.4, the corresponding staying length (SL) for this trip is NORMINV(Rand3. 1, 0.1), otherwise, the staying length (SL) is NORMINV(Rand 3, 8, 0.8). This assumes that 40% of the vehicles spend about this amount of time in the downtown, and the time length is normally distributed with ($\mu=1$, $\sigma=0.1$) (SL distribution I). For the rest of 60% vehicle trips, the staying length is normally distributed with ($\mu=8$, $\sigma=0.8$) (SL distribution II).

We divide the entire time into five small time interval, and assume that in each time interval, the staying length follows the same distribution.

Table B-4: Staying Length Parameters

Time Interval	Percentage Separation line	SL distribution I	SL distribution II
6	0.4	NORMINV(Rand3. 1, 0.1)	NORMINV(Rand 3, 8, 0.8)
7-9	0.2	NORMINV(Rand3,2,0.5)	NORMINV(Rand3,8,1)
10-12	0.2	NORMINV(Rand3,1,0.5)	NORMINV(Rand3,8,1)
13-15	0.1	NORMINV(Rand3,1,0.1)	NORMINV(Rand3,2,1)
16-19	0.4	NORMINV(Rand3,1,0.5),	NORMINV(Rand3,1,0.5),

Note[1]: NORMINV (rand, μ, σ) could be negative sometimes, if so, discard the corresponding data point (each row is a data point).
Note[2]: Since the time slot is one-hour, the entry time and departure time are all rounded up to integers.

Step 4. Compare the generated outbound traffic flow with the historical data (I-66 Outbound milepost 51.2), if the generated data are close to the historical data, accept the current simulation results. Otherwise go back to step 3 and change the parameters in Table B-4.

Table B-5: Generated and Historical Data

Time Slot	Generated Outbound Flow	Historical Data
19	19.04%	8.43%
18	15.14%	14.16%
17	18.70%	12.80%
16	15.46%	8.43%
15	10.46%	7.08%
14	5.54%	7.98%
13	1.78%	7.08%
12	2.34%	6.17%
11	3.62%	4.67%
10	3.18%	3.77%
9	1.44%	3.77%
8	1.74%	5.72%
7	1.56%	6.17%

Step 5 Generate the rest of the data columns

Table B-6: Request Arrival Time and Veh. Class

Request ID	Request arrival time	Veh Class
R1	0.028224	SOV
R2	0.031648	HOV
R3	0.076845	SOV
R4	0.103272	SOV
R5	0.104651	SOV
R6	0.110395	SOV
R7	0.118643	SOV
R8	0.123487	SOV
R9	0.137578	SOV
R10	0.157688	SOV
R11	0.160216	SOV
R12	0.180381	SOV
R13	0.18987	TRUCK
….	….	….

Table B-7: Traffic Composition

Traffic Composition	
SOV	69%
HOV	23%
TRUCK	3%
BUS	5%

Exponentially distributed request head time

If Rand<=69%, Veh Class=SOV,
 if 69%<Rand<=92%, Veh Class=HOV
if 92%<Rand<=95%, Veh Class = TRUCK
if Rand > 95%, Veh Class = BUS

Table B 8. Occupancy and PCU

Request ID	Occupancy	PCU	Veh. Class (VC)
R1	1	1	SOV
R2	6	2	HOV
R3	1	2	SOV
R4	1	2	SOV
R5	1	2	SOV
R6	1	2	SOV
R7	1	1	SOV
R8	1	2	SOV
R9	1	1	SOV
R10	1	2	SOV
R11	1	2	SOV
R12	1	2	SOV
R13	1	4.5	TRUCK
….	….	….	…..

If VC=SOV, Occupancy = 1, PCU= Randbetween(1,2);

If VC = HOV, Occupancy = Randbetween (2,7), PCU=Randbetween(1,2.5)

If VC=TRUCK, Occupancy =1, PCU= 3.5

If VC=BUS, Occupancy = Randbetween (8,30),

In Step 1 and 2, Entry time and Departure time have been already generated, according to which, a binary matrix is generated indicating the time slot occupation. Each row of the matrix is corresponding to a vector $\mathbf{a}_j^i$ (see page 16).

Table B-9: Time Slot Occupancy Matrix

Request ID	7	8	9	10	11	12	13	14	15	16	17	18	19
R1	0	0	0	0	0	1	1	1	1	1	1	1	1
R2	1	1	1	1	1	1	1	1	1	0	0	0	0
R3	0	0	1	1	1	1	1	1	1	1	0	0	0
R4	0	0	0	0	1	1	1	1	1	1	1	1	0
R5	0	0	0	0	0	0	0	0	0	1	1	1	0
R6	1	1	1	1	0	0	0	0	0	0	0	0	0
R7	1	1	1	1	0	0	0	0	0	0	0	0	0
R8	0	0	0	1	1	1	1	1	1	1	1	0	0
R9	0	0	1	1	1	0	0	0	0	0	0	0	0
R10	0	0	0	0	0	0	0	0	0	1	1	1	0
R11	0	0	1	1	1	1	1	1	1	1	0	0	0
R12	0	0	0	0	0	0	0	0	0	1	1	1	0
R13	0	1	1	1	1	1	1	1	1	1	1	1	0
…..													

Table B-10: Entry and Departure

Request ID	Entry	Departure
R1	12	20
R2	6	15
R3	9	16
R4	11	18
R5	16	18
R6	7	10
R7	7	10
R8	10	17
R9	9	11
R10	16	18
R11	9	16
R12	16	18
R13	8	18
…..	…..	….

Table B-11: Unit Price

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
	7:00-	8:00-	9:00-	10:00-	11:00-	12:00-	13:00-	14:00-	15:00-	16:00-	17:00-	18:00-
SOV	2	2	2	1	1	1	1	1	1	1.5	1.5	1.5
HOV	1	1	1	0.5	0.5	0.5	0.5	0.5	0.5	1	1	1
TRUCK	2	2	2	1	1	1	1	1	1	1.5	1.5	1.5
BUS	1	1	1	0.5	0.5	0.5	0.5	0.5	0.5	1	1	1

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Table B-12: Reservation Price

Request ID	Price
R1	10.5
R2	12.5
R3	7.5
R4	8.5
R5	3
R6	5
R7	5
R8	8
R9	2
R10	3
R11	7.5
R12	3
R13	12.5
….	….

Table 9 * Table 11

For each request

$a_j^i * Pi = Price$
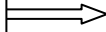
At this point, we have generated all the data, which are arranged in one table (Table B-13)

Table B-13. Travel Demand

Request ID	Request arrival time	Entry	Departure	Veh Class	Occupancy	PCU	Price
R1	0.028224	12	20	SOV	1	1	10.5
R2	0.031643	6	15	HOV	6	2	12.5
R3	0.076845	9	16	SOV	1	2	7.5
R4	0.103272	11	18	SOV	1	2	8.5
R5	0.104651	16	18	SOV	1	2	3
R6	0.110395	7	10	SOV	1	2	5
R7	0.118643	7	10	SOV	1	1	5
R8	0.123487	10	17	SOV	1	2	8
R9	0.137578	9	11	SOV	1	1	2
R10	0.157688	16	18	SOV	1	2	3
R11	0.160216	9	16	SOV	1	2	7.5
R12	0.180381	16	18	SOV	1	2	3
R13	0.18987	8	18	TRUCK	1	4.5	12.5
….	…...	…...	….	…...	….	….	….

Appendix B AMPL/CPLEX Programming Code for Essay 1

Data file (.dat)
```
set REQUESTS :=
R1
R2
R3
R4
R5
R6
....
R5000


set TIMESLOTS := m1 m2 m3 m4 m5 m6 m7 m8 m9 m10 m11 m12;


param:

      psg    PCU    pri    :=
R1    1      1      8
R2    1      1      10
R3    3      2      6
R4    1      2      8
R5    4      2      8
R6    1      2      8
R7    1      2      6
R8    1      1      6
R9    1      1      8
R10   3      1      8
R11   1      1      8
R12   1      1      10
R13   1      2      8
R14   4      1      6
R15   1      2      10
R16   1      2      8

.....
R5000 7      2      6;

param occ_slot:
    m1   m2   m3   m4   m5   m6   m7   m8   m9   m10   m11   m12 :=
R1   0    0    0    0    0    0    0    0    0    0     1     0
R2   0    1    1    1    1    1    1    1    1    1     0     0
R3   0    0    0    0    0    0    0    0    0    1     1     1
R4   0    0    0    0    0    0    0    0    0    0     1     0
R5   0    0    0    0    0    0    0    0    0    0     1     0
R6   0    1    1    1    1    1    1    1    1    1     0     0
R7   0    1    1    1    1    1    1    1    0    0     0     0
R8   0    0    0    0    0    1    1    1    1    1     1     1
R9   0    0    0    0    1    1    1    1    1    1     1     0
R10  0    0    0    0    0    0    0    0    0    0     1     1
R11  0    0    0    1    1    1    1    1    1    1     1     1
R12  0    0    0    0    0    0    0    0    0    1     1     0
R13  0    0    0    0    1    1    1    1    1    1     1     1
```

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```
R14   0   1   1   1   1   1   1   0   0   0   0   0
R15   0   0   0   1   1   1   1   1   1   1   1   1
R16   0   1   1   0   0   0   0   0   0   0   0   0
.....
R5000 0   0   1   1   0   0   0   0   0   0   0   0;

param cap :=
m1 1500
m2 1500
m3 1000
m4 1000
m5 1000
m6 1000
m7 1000
m8 1000
m9 1000
m10 1000
m11 1000
m12 1000
m13 1000
m14 1000;
param  lamda:= 3;
```

Model File (.mod)

```
###sets###

set REQUESTS;
set TIMESLOTS;

###Parameters###

param occ {j in REQUESTS};
param pcu {j in REQUESTS};
param pri {j in REQUESTS};
param occ_slot {j in REQUESTS, m in TIMESLOTS};
param cap {m in TIMESLOTS};
param lamda;

###variable###

var assignment {j in REQUESTS} binary;

###objective###

maximize throughput: sum{j in REQUESTS} ((lamda*(occ[j] / pcu[j]) +
lamda*pri[j]) * assignment[j]);

###constraints###

subject to capacity {m in TIMESLOTS}: sum{j in REQUESTS}
assignment[j]*pcu[j]*occ_slot[j,m] <= cap[m];
```

AMPL Scripts

```
model res.mod;
data res.dat;
option solver "/usr/ilog/ampl/cplexamp";
solve;
printf {j in REQUESTS} "%5s %d\n", j, assignment[j]>output.txt;
```

Appendix C VISSIM Trip Chain File for Essay 2

1.1
1;100;6;3;1004;101;6705;6708;6;101;20
2;100;2;3;1004;101;31247;31250;3;101;20
3;100;12;4;1003;101;2163;2167;12;101;20
4;100;13;4;1003;101;492;496;5;101;20
5;100;21;6;1001;101;2840;2846;21;101;20
6;100;11;6;1002;101;96;103;10;101;20
7;100;4;8;1003;101;6949;6957;4;101;20
8;100;11;8;1002;101;1637;1645;10;101;20
9;100;9;8;1002;101;3213;3221;8;101;20
10;300;6;10;1004;101;15703;15713;6;101;20
11;300;18;10;1001;101;1728;1739;19;101;20
12;100;9;12;1001;101;43270;43282;8;101;20
13;101;18;14;1003;101;11154;11168;19;101;20
14;100;9;16;1002;101;1572;1588;8;101;20
…….
…….
…….
5938;101;18;10782;1002;101;12747;23529;19;101;20
5939;100;15;10784;1002;101;2199;12982;16;101;20
5940;100;11;10785;1001;101;1623;12407;10;101;20
5941;101;6;10785;1004;101;10306;21091;6;101;20
5942;100;2;10787;1002;101;3249;14036;3;101;20
5943;100;2;10789;1004;101;1056;11845;3;101;20
5944;101;2;10790;1004;101;336;11125;3;101;20
5945;100;11;10791;1001;101;190;10981;10;101;20
5946;101;18;10792;1003;101;3251;14042;19;101;20
5947;101;9;10793;1003;101;557;11350;8;101;20
5948;100;12;10794;1002;101;1666;12460;12;101;20
5949;100;12;10799;1003;101;2781;13580;12;101;20

Appendix D VISSIM COM Access Using Visual Basic for Essay 2

	A	B	C	D	E	F
1	Scenarios	Random Seeds	File path	Input file	simulation period	
2	r1	70	D:\vissim boise1\1-Evaluation\eva-7000-s1\r1\base.inp	base.inp	12600	
3	r2	30	D:\vissim boise1\1-Evaluation\eva-7000-s1\r2\base.inp	base.inp	12600	
4	r3	43	D:\vissim boise1\1-Evaluation\eva-7000-s1\r3\base.inp	base.inp	12600	
5	r4	15	D:\vissim boise1\1-Evaluation\eva-7000-s1\r4\base.inp	base.inp	12600	
6	r5	4	D:\vissim boise1\1-Evaluation\eva-7000-s1\r5\base.inp	base.inp	12600	
7	r6	89	D:\vissim boise1\1-Evaluation\eva-7000-s1\r6\base.inp	base.inp	12600	
8	r7	65	D:\vissim boise1\1-Evaluation\eva-7000-s1\r7\base.inp	base.inp	12600	
9	r8	69	D:\vissim boise1\1-Evaluation\eva-7000-s1\r8\base.inp	base.inp	12600	
10	r9	77	D:\vissim boise1\1-Evaluation\eva-7000-s1\r9\base.inp	base.inp	12600	
11	r10	47	D:\vissim boise1\1-Evaluation\eva-7000-s1\r10\base.inp	base.inp	12600	
12						
13						

```
Sub autorun()
'
Dim Vissim As Vissim
Dim Simulation As Simulation

Dim SimulationFile As String
Dim RandomSeed As Integer
Dim RunIndex As Integer
'Dim period As Integer

Set Vissim = CreateObject("VISSIM.Vissim")
Set Simulation = Vissim.Simulation

Sheets("VISSIM").Select
'************************************************
For Row = 2 To 11
Cells(Row, 3).Select
SimulationFile = Selection.Value

Application.DisplayAlerts = False

Vissim.LoadNet SimulationFile
Vissim.LoadLayout "vissim.ini"

Simulation.period = Cells(Row, 5)
Simulation.Resolution = 10
RunIndex = 0

RandomSeed = Cells(Row, 2)
Simulation.RunIndex = RunIndex
Simulation.Comment = "Random Seed =" & RandomSeed
Simulation.RandomSeed = RandomSeed
Simulation.RunContinuous
Simulation.Stop
RunIndex = RunIndex + 1
Next Row
'*********************************************************
End Sub
```

Appendix E VISSIM simulation Output Files for Essay 2

Node evaluation

File: d:\vissim boise1\1-evaluation\eva-7000-s1-2\r1\base.inp
Comment: Random Seed =70
Date: Friday, June 13, 2008 2:35:19 PM

Node 22: State/10th
Node 23: State/9th
Node 24: Jefferson/11th
Node 25: Jefferson/10th
Node 26: Jefferson/9th
Node 27: Bannock/10th
Node 28: Bannock/9th
Node 29: State/8th
Node 30: State/6th
Node 32: Jefferson/8th
Node 33: Jefferson/6th
Node 44: Idaho/11th
Node 45: Idaho/10th
Node 46: Idaho/9th
Node 47: Main/11th
Node 48: Main/10th
Node 49: Main/9th
Node 50: Grove/11th
Node 51: Grove/10th
Node 52: Bannock/8th
Node 53: Bannock/Capitol
Node 54: Bannock/6th
Node 55: Idaho/8th
Node 56: Idaho/Capitol
Node 57: Idaho/6th
Node 59: Main/8th
Node 60: Main/Capitol
Node 61: Main/6th
Node 101: 9th/Grove
Node 103: Bannock/11th
Node 307: Jefferson/Capitol

Node: Node Number
EmissCO: Emissions CO [g]
EmissNOx: Emissions NOx [g]
EmissVOC: Emissions VOC [g]
FuelCons: Fuel Consumption [gal]
Veh(All): Number of Vehicles, All Vehicle Types
FromLink: Number of the link entering node
ToLink: Number of the link leaving node
Movement: Movement (Bearing from-to)

Node; EmissCO; EmissNOx; EmissVOC; FuelCons; Veh(All); FromLink; ToLink; Movement;
 22; 442.96; 86.18; 102.66; 6.34;   674;   9;   25;   SW-SE; 0.0;
 22; 169.06; 32.89; 39.18; 2.42;   226;   9;   18;   SW-NW; 0.0;
 22; 239.64; 46.62; 55.54; 3.43;   310;   9;   9;   SW-NE; 0.0;

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```
22;  73.41;   14.28;   17.01;    1.05;    178;     18;     9;   SE-NE; 0.0;
22;  56.61;   11.01;   13.12;    0.81;    111;     18;    21;   SE-SW; 0.0;
22;  87.00;   16.93;   20.16;    1.24;    197;     18;    18;   SE-NW; 0.0;
22;   0.00;    0.00;    0.00;    0.00;      0;     21;    18;   NE-NW; 0.0;
22;   0.00;    0.00;    0.00;    0.00;      0;     21;    25;   NE-SE; 0.0;
22;   0.00;    0.00;    0.00;    0.00;      0;     21;    21;   NE-SW; 0.0;
22;   0.00;    0.00;    0.00;    0.00;      0;     25;    21;   NW-SW; 0.0;
22;   0.00;    0.00;    0.00;    0.00;      0;     25;     9;   NW-NE; 0.0;
22;   0.00;    0.00;    0.00;    0.00;      0;     25;    25;   NW-SE; 0.0;
22; 1068.67;  207.92;  247.68;   15.29;   1696;      0;     0;   All; 0.0;
23;   0.00;    0.00;    0.00;    0.00;      0;      8; 10266;  NE-NW; 0.0;
23;   0.00;    0.00;    0.00;    0.00;      0;      8;    18;   NE-NW; 0.0;
23;   0.00;    0.00;    0.00;    0.00;      0;      8;   331;   NE-SW; 0.0;
23;   0.00;    0.00;    0.00;    0.00;      0;      8;    25;   NE-SE; 0.0;
23; 215.89;   42.00;   50.03;    3.09;    433;     18;   331;   SE-SW; 0.0;
23;   0.00;    0.00;    0.00;    0.00;      0;     18; 10266;  SE-NW; 0.0;
23; 215.37;   41.90;   49.91;    3.08;    439;     18;    18;   SE-NW; 0.0;
23; 232.29;   45.20;   53.84;    3.32;    614;     25;   331;   NW-SW; 0.0;
23; 211.86;   41.22;   49.10;    3.03;    508;     25;    25;   NW-SE; 0.0;
23; 875.41;  170.32;  202.88;   12.52;   1994;      0;     0;   All; 0.0;
24;  24.61;    4.79;    5.70;    0.35;     65;     23;   359;   SE-NE; 0.0;
24;  70.18;   13.65;   16.27;    1.00;    148;     23;    23;   SE-NW; 0.0;
24;   0.00;    0.00;    0.00;    0.00;      0;    359;    23;   SW-NW; 0.0;
24;   0.00;    0.00;    0.00;    0.00;      0;    359;   359;   SW-NE; 0.0;
24;  94.80;   18.44;   21.97;    1.36;    213;      0;     0;   All; 0.0;
25;  54.97;   10.70;   12.74;    0.79;     84;      9;    23;   SW-NW; 0.0;
25; 355.85;   69.24;   82.47;    5.09;    517;      9;     9;   SW-NE; 0.0;
25;   5.42;    1.05;    1.26;    0.08;     12;     21;    23;   NE-NW; 0.0;
25; 127.12;   24.73;   29.46;    1.82;    234;     21;    21;   NE-SW; 0.0;
25; 378.43;   73.63;   87.70;    5.41;    738;     23;     9;   SE-NE; 0.0;
25; 290.42;   56.51;   67.31;    4.15;    560;     23;    21;   SE-SW; 0.0;
25;  65.39;   12.72;   15.16;    0.94;    117;     23;    23;   SE-NW; 0.0;
25; 1277.60;  248.58;  296.10;   18.28;   2262;      0;     0;   All; 0.0;
26; 244.72;   47.61;   56.72;    3.50;    550;     23;   331;   SE-SW; 0.0;
26; 420.82;   81.88;   97.53;    6.02;    924;     23;    23;   SE-NW; 0.0;
26; 253.37;   49.30;   58.72;    3.62;    534;    331;    23;   NE-NW; 0.0;
26; 550.58;  107.12;  127.60;    7.88;    929;    331;   331;   NE-SW; 0.0;
26; 1469.49;  285.91;  340.57;   21.02;   2937;      0;     0;   All; 0.0;
27; 142.16;   27.66;   32.95;    2.03;    417;  10026;     1;   SW-SE; 0.0;
27;  12.48;    2.43;    2.89;    0.18;     33;      1;    21;   NW-SW; 0.0;
27;   9.07;    1.77;    2.10;    0.13;     21;      1;     9;   NW-NE; 0.0;
27;  37.69;    7.33;    8.74;    0.54;     86;      1;     1;   NW-SE; 0.0;
27;  15.29;    2.97;    3.54;    0.22;     29;      9;    24;   SW-NW; 0.0;
27; 156.20;   30.39;   36.20;    2.23;    372;      9;     9;   SW-NE; 0.0;
27;  19.50;    3.79;    4.52;    0.28;     44;     21;    24;   NE-NW; 0.0;
27; 173.49;   33.75;   40.21;    2.48;    276;     21;     1;   NE-SE; 0.0;
27; 234.85;   45.69;   54.43;    3.36;    409;     21;    21;   NE-SW; 0.0;
27; 113.91;   22.16;   26.40;    1.63;    207;     24;     9;   SE-NE; 0.0;
27; 208.91;   40.65;   48.42;    2.99;    351;     24;    21;   SE-SW; 0.0;
27;  23.96;    4.66;    5.55;    0.34;     40;     24;    24;   SE-NW; 0.0;
27; 1147.53;  223.27;  265.95;   16.42;   2285;      0;     0;   All; 0.0;
28;  97.18;   18.91;   22.52;    1.39;    196;      1;   331;   NW-SW; 0.0;
28; 344.63;   67.05;   79.87;    4.93;    584;      1;     1;   NW-SE; 0.0;
28; 130.55;   25.40;   30.26;    1.87;    204;     24;   331;   SE-SW; 0.0;
28; 211.82;   41.21;   49.09;    3.03;    337;     24;    24;   SE-NW; 0.0;
28;  96.95;   18.86;   22.47;    1.39;    261;    331;    24;   NE-NW; 0.0;
```

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```
28; 291.27;   56.67;   67.50;   4.17;    645;   331;    1;   NE-SE; 0.0;
28; 245.75;   47.81;   56.95;   3.52;    578;   331;  331;   NE-SW; 0.0;
28; 1418.16; 275.92;  328.67;  20.29;   2805;     0;    0;   All; 0.0;
29;   0.00;    0.00;    0.00;   0.00;      0;     3;   22;   SE-NE; 0.0;
29; 256.90;   49.98;   59.54;   3.68;    300;     3;    3;   SE-NW; 0.0;
29;  96.64;   18.80;   22.40;   1.38;    233;    25;   22;   NW-NE; 0.0;
29; 178.95;   34.82;   41.47;   2.56;    405;    25;   20;   NW-SE; 0.0;
29;  92.81;   18.06;   21.51;   1.33;    299;    60;   20;   SW-SE; 0.0;
29; 270.13;   52.56;   62.60;   3.86;    571;    60;    3;   SW-NW; 0.0;
29; 164.25;   31.96;   38.07;   2.35;    397;    60;   22;   SW-NE; 0.0;
29; 1059.68; 206.18;  245.59;  15.16;   2205;     0;    0;   All; 0.0;
30;   0.00;    0.00;    0.00;   0.00;      0;     3;    4;   SE-SW; 0.0;
30;   0.00;    0.00;    0.00;   0.00;      0;     3;    3;   SE-NW; 0.0;
30;   0.00;    0.00;    0.00;   0.00;      0;     4;    3;   NE-NW; 0.0;
30;   0.00;    0.00;    0.00;   0.00;      0;     4;   20;   NE-SE; 0.0;
30;   0.00;    0.00;    0.00;   0.00;      0;     4;    4;   NE-SW; 0.0;
30; 318.74;   62.02;   73.87;   4.56;    379;    20;    4;   NW-SW; 0.0;
30; 290.00;   56.42;   67.21;   4.15;    327;    20;   20;   NW-SE; 0.0;
30; 608.74;  118.44;  141.08;   8.71;    706;     0;    0;   All; 0.0;
32; 265.94;   51.74;   61.63;   3.80;    827;    23;   60;   SE-NE; 0.0;
32; 429.80;   83.62;   99.61;   6.15;   1048;    23;   23;   SE-NW; 0.0;
32; 206.58;   40.19;   47.88;   2.96;    451;    60;   23;   SW-NW; 0.0;
32; 281.20;   54.71;   65.17;   4.02;    487;    60;   60;   SW-NE; 0.0;
32; 1183.52; 230.27;  274.29;  16.93;   2813;     0;    0;   All; 0.0;
33;   0.00;    0.00;    0.00;   0.00;      0;     2;    4;   SE-SW; 0.0;
33;   0.00;    0.00;    0.00;   0.00;      0;     2;    2;   SE-NW; 0.0;
33; 216.98;   42.22;   50.29;   3.10;    499;     4;    2;   NE-NW; 0.0;
33; 407.97;   79.38;   94.55;   5.84;    734;     4;    4;   NE-SW; 0.0;
33; 624.96;  121.59;  144.84;   8.94;   1233;     0;    0;   All; 0.0;
44;   0.00;    0.00;    0.00;   0.00;      0;   138;  357;   SE-NE; 0.0;
44; 193.46;   37.64;   44.84;   2.77;    446;   138;  138;   SE-NW; 0.0;
44;   9.11;    1.77;    2.11;   0.13;     28;   357;  138;   SW-NW; 0.0;
44;   0.00;    0.00;    0.00;   0.00;      0;   357;  357;   SW-NE; 0.0;
44; 202.57;   39.41;   46.95;   2.90;    474;     0;    0;   All; 0.0;
45;  14.93;    2.91;    3.46;   0.21;     36;     9;  138;   SW-NW; 0.0;
45; 195.07;   37.95;   45.21;   2.79;    423;     9;    9;   SW-NE; 0.0;
45;  74.66;   14.53;   17.30;   1.07;    187;    21;  138;   NE-NW; 0.0;
45; 297.84;   57.95;   69.03;   4.26;    606;    21;   21;   NE-SW; 0.0;
45; 192.21;   37.40;   44.55;   2.75;    436;   138;    9;   SE-NE; 0.0;
45; 266.47;   51.84;   61.76;   3.81;    503;   138;   21;   SE-SW; 0.0;
45; 117.24;   22.81;   27.17;   1.68;    223;   138;  138;   SE-NW; 0.0;
45; 1158.42; 225.39;  268.48;  16.57;   2414;     0;    0;   All; 0.0;
46;  97.31;   18.93;   22.55;   1.39;    434; 10048;  331;   SE-SW; 0.0;
46; 171.03;   33.28;   39.64;   2.45;    709;   139;  138;   SE-NW; 0.0;
46; 183.15;   35.64;   42.45;   2.62;    483;   331;  138;   NE-NW; 0.0;
46; 234.29;   45.58;   54.30;   3.35;    495;   331;  331;   NE-SW; 0.0;
46; 685.79;  133.43;  158.94;   9.81;   2121;     0;    0;   All; 0.0;
47; 191.79;   37.31;   44.45;   2.74;    522;   355;  374;   SW-SE; 0.0;
47;  12.45;    2.42;    2.89;   0.18;     28;   355;   96;   SW-NE; 0.0;
47;   0.00;    0.00;    0.00;   0.00;      0;   374;   97;   NW-SW; 0.0;
47;   0.00;    0.00;    0.00;   0.00;      0;   374;   96;   NW-NE; 0.0;
47;   0.00;    0.00;    0.00;   0.00;      0;   374;  374;   NW-SE; 0.0;
47; 204.24;   39.74;   47.33;   2.92;    550;     0;    0;   All; 0.0;
48;  65.57;   12.76;   15.20;   0.94;    185;     9;  374;   SW-SE; 0.0;
48;  45.87;    8.92;   10.63;   0.66;    103;     9;    9;   SW-NE; 0.0;
48; 243.94;   47.46;   56.53;   3.49;    440;    21;  374;   NE-SE; 0.0;
```

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48;  357.22;   69.50;   82.79;    5.11;    622;    21;    21;    NE-SW; 0.0;
48;   23.19;    4.51;    5.37;    0.33;     46;   374;    21;    NW-SW; 0.0;
48;  194.99;   37.94;   45.19;    2.79;    355;   374;     9;    NW-NE; 0.0;
48;  248.61;   48.37;   57.62;    3.56;    508;   374;   374;    NW-SE; 0.0;
48; 1179.38;  229.46;  273.33;   16.87;   2259;     0;     0;    All; 0.0;
49;  200.52;   39.01;   46.47;    2.87;    536;   331;    92;    NE-SE; 0.0;
49;  159.87;   31.10;   37.05;    2.29;    395;   331;   331;    NE-SW; 0.0;
49;   49.07;    9.55;   11.37;    0.70;    101;   374;   331;    NW-SW; 0.0;
49;  568.80;  110.67;  131.82;    8.14;   1033;   374;    92;    NW-SE; 0.0;
49;  978.25;  190.33;  226.72;   13.99;   2065;     0;     0;    All; 0.0;
50;    0.00;    0.00;    0.00;    0.00;      0;    13;   354;    NW-SW; 0.0;
50;    0.00;    0.00;    0.00;    0.00;      0;    13;   353;    NW-NE; 0.0;
50;    0.00;    0.00;    0.00;    0.00;      0;    13;    13;    NW-SE; 0.0;
50;  178.52;   34.73;   41.37;    2.55;    432;   340;   353;    SE-NE; 0.0;
50;   67.91;   13.21;   15.74;    0.97;    120;   341;   354;    SE-SW; 0.0;
50;   34.02;    6.62;    7.89;    0.49;     62;   341;   341;    SE-NW; 0.0;
50;    0.00;    0.00;    0.00;    0.00;      0;   353;    13;    SW-SE; 0.0;
50;    0.00;    0.00;    0.00;    0.00;      0;   353;   341;    SW-NW; 0.0;
50;    0.00;    0.00;    0.00;    0.00;      0;   353;   353;    SW-NE; 0.0;
50;    0.00;    0.00;    0.00;    0.00;      0;   356;   341;    NE-NW; 0.0;
50;   48.25;    9.39;   11.18;    0.69;     84;   356;    13;    NE-SE; 0.0;
50;    0.00;    0.00;    0.00;    0.00;      0;   356;   354;    NE-SW; 0.0;
50;  328.70;   63.95;   76.18;    4.70;    698;     0;     0;    All; 0.0;
51;    0.00;    0.00;    0.00;    0.00;      0;     9;    13;    SW-SE; 0.0;
51;    0.00;    0.00;    0.00;    0.00;      0;     9;   341;    SW-NW; 0.0;
51;    0.00;    0.00;    0.00;    0.00;      0;     9;     9;    SW-NE; 0.0;
51;    0.00;    0.00;    0.00;    0.00;      0;    13;    21;    NW-SW; 0.0;
51;   86.50;   16.83;   20.05;    1.24;    166;    13;     9;    NW-NE; 0.0;
51;    0.00;    0.00;    0.00;    0.00;      0;    13;    13;    NW-SE; 0.0;
51;  238.03;   46.31;   55.17;    3.41;    506;    21;   341;    NE-NW; 0.0;
51;   57.02;   11.09;   13.21;    0.82;    100;    21;    13;    NE-SE; 0.0;
51;   36.37;    7.08;    8.43;    0.52;     62;    21;    21;    NE-SW; 0.0;
51;    0.00;    0.00;    0.00;    0.00;      0;    95;     9;    SE-NE; 0.0;
51;    0.00;    0.00;    0.00;    0.00;      0;    95;    21;    SE-SW; 0.0;
51;    0.00;    0.00;    0.00;    0.00;      0;    95;   341;    SE-NW; 0.0;
51;  417.91;   81.31;   96.86;    5.98;    834;     0;     0;    All; 0.0;
52;  105.68;   20.56;   24.49;    1.51;    259;     1;     7;    NW-SW; 0.0;
52;  230.75;   44.90;   53.48;    3.30;    545;     1;    60;    NW-NE; 0.0;
52;  185.12;   36.02;   42.90;    2.65;    425;     1;     1;    NW-SE; 0.0;
52;  174.09;   33.87;   40.35;    2.49;    439;    24;    60;    SE-NE; 0.0;
52;   96.45;   18.77;   22.35;    1.38;    230;    24;     7;    SE-SW; 0.0;
52;  252.22;   49.07;   58.45;    3.61;    593;    24;    24;    SE-NW; 0.0;
52; 1044.30;  203.18;  242.03;   14.94;   2491;     0;     0;    All; 0.0;
53;  101.93;   19.83;   23.62;    1.46;    173;     1;   238;    NW-NE; 0.0;
53;  108.66;   21.14;   25.18;    1.55;    206;     1;     1;    NW-SE; 0.0;
53;   12.22;    2.38;    2.83;    0.17;     29;    24;   240;    SE-NE; 0.0;
53;  295.63;   57.52;   68.52;    4.23;    625;    24;    24;    SE-NW; 0.0;
53;  318.94;   62.05;   73.92;    4.56;    634;   238;    24;    SW-NW; 0.0;
53;  221.49;   43.09;   51.33;    3.17;    445;   238;   238;    SW-NE; 0.0;
53;   73.08;   14.22;   16.94;    1.05;    203;   239;     1;    SW-SE; 0.0;
53;  285.01;   55.45;   66.05;    4.08;    628;   239;   240;    SW-NE; 0.0;
53; 1416.95;  275.69;  328.39;   20.27;   2943;     0;     0;    All; 0.0;
54;  105.33;   20.49;   24.41;    1.51;    247;     1;     4;    NW-SW; 0.0;
54;   87.68;   17.06;   20.32;    1.25;    163;     1;     1;    NW-SE; 0.0;
54;  180.00;   35.02;   41.72;    2.58;    490;     4;    24;    NE-NW; 0.0;
54;    9.89;    1.92;    2.29;    0.14;     28;     4;     1;    NE-SE; 0.0;
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54;  113.79;   22.14;   26.37;    1.63;    292;      4;     4;   NE-SW; 0.0;
54;    0.00;    0.00;    0.00;    0.00;      0;     24;     4;   SE-SW; 0.0;
54;    0.00;    0.00;    0.00;    0.00;      0;     24;    24;   SE-NW; 0.0;
54;  496.69;   96.64;  115.11;    7.11;   1220;      0;     0;    All; 0.0;
55;   54.04;   10.51;   12.52;    0.77;    193;  10101;     7;   SE-SW; 0.0;
55;  145.88;   28.38;   33.81;    2.09;    352;      7;   139;   NE-NW; 0.0;
55;   78.97;   15.36;   18.30;    1.13;    138;      7;     7;   NE-SW; 0.0;
55;  250.33;   48.70;   58.02;    3.58;    828;    139;   139;   SE-NW; 0.0;
55;  529.21;  102.97;  122.65;    7.57;   1511;      0;     0;    All; 0.0;
56;  153.04;   29.78;   35.47;    2.19;    361;    210; 10153;   SE-NE; 0.0;
56;  247.41;   48.14;   57.34;    3.54;    452;    210;   139;   SE-NW; 0.0;
56;  247.26;   48.11;   57.31;    3.54;    616;    255;   139;   SW-NW; 0.0;
56;  775.30;  150.85;  179.68;   11.09;   1549;    255; 10151;   SW-NE; 0.0;
56; 1423.02;  276.87;  329.80;   20.36;   2978;      0;     0;    All; 0.0;
57;  173.33;   33.72;   40.17;    2.48;    488;      4;   210;   NE-NW; 0.0;
57;   48.44;    9.43;   11.23;    0.69;    105;      4;   174;   NE-SW; 0.0;
57;    0.00;    0.00;    0.00;    0.00;      0;    210;   174;   SE-SW; 0.0;
57;    0.00;    0.00;    0.00;    0.00;      0;    210;   210;   SE-NW; 0.0;
57;  221.77;   43.15;   51.40;    3.17;    593;      0;     0;    All; 0.0;
59;  141.27;   27.49;   32.74;    2.02;    331;      7;    92;   NE-SE; 0.0;
59;  825.69;  160.65;  191.36;   11.81;   1568;     92;    92;   NW-SE; 0.0;
59;  966.95;  188.13;  224.10;   13.83;   1899;      0;     0;    All; 0.0;
60;  849.94;  165.37;  196.98;   12.16;   1527;     92;   255;   NW-NE; 0.0;
60;  174.65;   33.98;   40.48;    2.50;    341;     92;    93;   NW-SE; 0.0;
60;    0.00;    0.00;    0.00;    0.00;      0;    271;    93;   SW-SE; 0.0;
60;    0.00;    0.00;    0.00;    0.00;      0;    271;   255;   SW-NE; 0.0;
60; 1024.58;  199.35;  237.46;   14.66;   1868;      0;     0;    All; 0.0;
61;   40.23;    7.83;    9.32;    0.58;    112;     93;   184;   NW-SW; 0.0;
61;   88.88;   17.29;   20.60;    1.27;    229;     93;    93;   NW-SE; 0.0;
61;   26.08;    5.07;    6.04;    0.37;     71;    175;    93;   NE-SE; 0.0;
61;   14.09;    2.74;    3.27;    0.20;     34;    175;   184;   NE-SW; 0.0;
61;  169.28;   32.94;   39.23;    2.42;    446;      0;     0;    All; 0.0;
101;  127.50;   24.81;   29.55;    1.82;    497;    122;   122;   NE-SW; 0.0;
101;  127.50;   24.81;   29.55;    1.82;    497;      0;     0;    All; 0.0;
103;    0.00;    0.00;    0.00;    0.00;      0;      1;   358;   NW-NE; 0.0;
103;    0.00;    0.00;    0.00;    0.00;      0;      1;     1;   NW-SE; 0.0;
103;    0.80;    0.16;    0.19;    0.01;      2;     24;   358;   SE-NE; 0.0;
103;   53.04;   10.32;   12.29;    0.76;    111;     24;    24;   SE-NW; 0.0;
103;    0.00;    0.00;    0.00;    0.00;      0;    358;     1;   SW-SE; 0.0;
103;    0.00;    0.00;    0.00;    0.00;      0;    358;    24;   SW-NW; 0.0;
103;    0.00;    0.00;    0.00;    0.00;      0;    358;   358;   SW-NE; 0.0;
103;   53.84;   10.48;   12.48;    0.77;    113;      0;     0;    All; 0.0;
307;  296.45;   57.68;   68.70;    4.24;    598;      2;    23;   SE-NW; 0.0;
307;  210.55;   40.97;   48.80;    3.01;    618;    238;    23;    S-NW; 0.0;
307;  484.56;   94.28;  112.30;    6.93;    657;    240;    23;   SW-NW; 0.0;
307;  991.56;  192.92;  229.80;   14.19;   1873;      0;     0;    All; 0.0;
 0;24449.44; 4756.97; 5666.39;  349.78;  50996;      0;     0;    All; 0.0;
```

Network Performance

File: d:\vissim boise1\1-evaluation\eva-7000-s1-2\r1\base.inp
Comment: Random Seed =70
Date: Friday, June 13, 2008 2:35:19 PM

Simulation time from 1800.0 to 12600.0.

Parameter	;	Value;
Average delay time per vehicle [s], All Vehicle Types	;	561.856;
Average speed [mph], All Vehicle Types	;	12.941;
Average stopped delay per vehicle [s], All Vehicle Types	;	256.766;
Average number of stops per vehicles, All Vehicle Types	;	29.280;
Total travel time [h], All Vehicle Types	;	324.551;
Total Path Distance [mi], All Vehicle Types	;	4199.954;
Total delay time [h], All Vehicle Types	;	166.840;
Number of vehicles that have left the network, All Vehicle Types	;	1033;
Number of vehicles in the network, All Vehicle Types	;	36;

Link Evaluation

File: d:\vissim boise1\1-evaluation\eva-7000-s1-2\r1\base.inp
Comment: Random Seed =70
Date: Friday, June 13, 2008 2:35:19 PM

Vehicle Class: 0 = All Vehicle Types
Vehicle Class: 1 = All Vehicles
Vehicle Class: 2 = CAR
Vehicle Class: 3 = HOVCar
Vehicle Class: 10 = SOVCar
Vehicle Class: 20 = HGV
Vehicle Class: 30 = Bus
Vehicle Class: 40 = Tram
Vehicle Class: 50 = Pedestrian
Vehicle Class: 60 = Bike

Link: Link Number
Volume: Volume [veh/h] (Vehicle Class 0)
v: Average speed [mph] (Vehicle Class 0)
Density: Vehicle density [veh/mi] (Vehicle Class 0)
SegLen: Segment length [ft]

Link;	Volume(0);	v(0);	Density(0);	SegLen;
1;	28.39;	23.19;	1.22;	320.0;
1;	46.66;	13.28;	3.52;	320.0;
1;	146.67;	19.68;	7.45;	320.0;
1;	293.87;	11.44;	25.68;	320.0;
1;	338.38;	17.73;	19.09;	320.0;
1;	109.36;	10.85;	10.08;	320.0;
1;	127.12;	18.52;	6.86;	320.0;
1;	64.80;	13.41;	4.83;	320.0;
1;	60.47;	21.26;	2.84;	320.0;
1;	0.34;	29.78;	0.01;	147.5;
2;	26.37;	17.18;	1.53;	320.0;
2;	58.33;	11.81;	4.94;	320.0;
2;	126.22;	22.20;	5.69;	320.0;
2;	350.68;	25.00;	14.03;	300.8;
3;	44.53;	7.59;	5.87;	320.0;

```
 3;  127.65;   26.29;     4.86;  320.0;
 3;   95.11;   18.75;     5.07;  320.0;
 3;  100.03;   29.10;     3.44;  320.0;
 3;  139.38;   16.33;     8.54;  320.0;
 3;  274.42;   23.18;    11.84;   62.1;
 4;  110.22;    6.84;    16.12;  320.0;
 4;  385.71;   10.30;    37.44;  320.0;
 4;  266.06;   19.89;    13.37;  320.0;
 4;  176.83;   19.15;     9.23;  320.0;
 4;  130.47;    6.07;    21.50;   41.5;
 5;   79.57;    3.73;    21.31;   31.0;
 6;   73.85;    3.58;    20.61;   28.8;
 7;  145.26;   11.04;    13.16;  320.0;
 7;  105.63;   14.17;     7.46;  300.3;
 8;  122.69;   14.12;     8.69; 1085.8;
 9;   13.41;    8.64;     1.55;  320.0;
 9;   84.59;   15.50;     5.46;  320.0;
 9;  146.05;   12.89;    11.33;  320.0;
 9;  231.10;    9.15;    25.26;  320.0;
 9;  183.51;    8.42;    21.80;  320.0;
 9;  326.83;    5.91;    55.35;  320.0;
 9;  145.99;    8.63;    16.92;  320.0;
 9;    0.00;    0.00;     0.00;   44.6;
10;   85.07;    3.64;    23.34;   29.8;
11;  111.84;    2.83;    39.58;   32.7;
12;  100.66;   32.37;     3.11;  731.9;
13;   20.72;   14.06;     1.47; 1306.9;
14;   59.93;    4.68;    12.80;   43.2;
15;   74.47;    4.20;    17.71;   40.9;
16;  107.11;    3.72;    28.76;   33.5;
17;  111.11;    4.41;    25.19;   40.5;
18;  223.35;   13.03;    17.14;  320.0;
18;  137.70;   16.73;     8.23;  320.0;
18;  140.86;   29.02;     4.85;  275.4;
19;  119.60;   31.94;     3.74;  442.8;
20;  231.96;   27.22;     8.52;  320.0;
20;  234.94;   19.88;    11.82;  320.0;
20;  125.74;   12.74;     9.87;  320.0;
20;  104.00;   15.61;     6.66;  320.0;
20;    0.00;    0.00;     0.00;  185.2;
21;   12.14;    6.08;     2.00;  320.0;
21;   79.51;    9.57;     8.31;  320.0;
21;  207.73;    8.70;    23.88;  320.0;
21;  242.93;   11.82;    20.56;  320.0;
21;  308.83;   10.61;    29.12;  320.0;
21;  231.95;    9.93;    23.37;  320.0;
21;   35.81;    5.13;     6.97;  320.0;
21;    0.00;    0.00;     0.00;   49.6;
22;  106.20;   24.15;     4.40;  304.9;
23;  537.25;   13.13;    40.90;  320.0;
23;  447.55;   17.69;    25.29;  320.0;
23;  445.80;   16.46;    27.09;  320.0;
23;   97.68;    9.73;    10.04;  320.0;
23;   54.30;   15.25;     3.56;  320.0;
23;   21.99;   29.55;     0.74;  205.0;
24;   33.18;   12.05;     2.75;  320.0;
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24;    70.53;    26.14;     2.70;  320.0;
24;   162.94;    17.05;     9.56;  320.0;
24;   303.01;    16.93;    17.89;  320.0;
24;   329.24;    19.25;    17.11;  320.0;
24;   155.13;     8.46;    18.33;  320.0;
24;   184.41;     9.73;    18.95;  320.0;
24;    34.98;    22.21;     1.57;  320.0;
24;    37.05;    16.14;     2.30;  320.0;
24;     5.84;    29.67;     0.20;  149.4;
25;   169.00;    20.07;     8.42;  320.0;
25;   327.80;    23.88;    13.73;  320.0;
25;   226.80;    20.51;    11.06;  320.0;
25;   209.74;    12.73;    16.47;  120.5;
26;    13.91;    25.98;     0.54;  373.0;
27;    99.74;    29.81;     3.35;  438.3;
28;     2.99;     1.65;     1.81;   69.2;
29;     2.00;     1.36;     1.47;   69.2;
30;     1.00;     1.23;     0.82;   65.0;
31;     2.65;     1.30;     2.04;   57.7;
32;     1.00;     1.01;     0.99;   66.1;
33;     1.00;     1.75;     0.57;   66.1;
34;     1.67;     1.56;     1.07;   60.7;
35;     1.34;     0.90;     1.49;   60.7;
36;     0.00;     0.00;     0.00;   78.6;
37;     0.00;     0.00;     0.00;   78.6;
38;     1.00;     2.18;     0.46;   74.2;
39;     0.34;     1.00;     0.33;   74.2;
40;     0.67;     0.98;     0.68;   77.2;
41;     1.00;     2.15;     0.47;   77.2;
42;     0.67;     1.89;     0.35;   78.0;
43;     0.67;     0.94;     0.71;   78.0;
44;     1.00;     2.21;     0.45;   80.0;
45;     0.34;     0.82;     0.41;   80.0;
46;     3.00;     1.37;     2.20;   72.3;
47;     2.33;     1.39;     1.67;   72.3;
48;     1.32;     1.57;     0.84;   71.4;
49;     1.33;     1.24;     1.07;   71.4;
50;     0.98;     1.49;     0.66;   71.9;
51;     0.67;     0.97;     0.69;   71.9;
52;     3.67;     1.22;     2.99;   73.3;
53;     2.33;     1.10;     2.12;   73.3;
54;     3.33;     1.22;     2.72;   74.4;
55;     3.67;     1.26;     2.92;   74.4;
56;     4.34;     1.25;     3.47;   71.2;
57;     3.32;     1.27;     2.62;   71.2;
58;     2.33;     1.41;     1.65;   67.4;
59;     2.00;     1.03;     1.94;   67.4;
60;   278.25;     9.71;    28.65;  320.0;
60;   388.53;     9.13;    42.56;  308.8;
61;     1.00;     1.13;     0.89;   68.2;
62;     1.33;     0.99;     1.35;   68.2;
63;     5.00;     0.86;     5.82;   71.1;
64;     5.01;     0.92;     5.44;   71.1;
65;     1.00;     0.79;     1.27;   71.6;
66;     1.33;     0.77;     1.72;   71.6;
67;     3.33;     1.42;     2.35;   75.2;
```

```
68;    1.67;    1.76;    0.95;   67.6;
69;    0.67;    1.48;    0.45;   67.6;
70;    1.33;    1.07;    1.25;   65.3;
71;    1.33;    1.47;    0.90;   65.3;
72;    0.33;    0.83;    0.40;   71.6;
73;    0.33;    3.38;    0.10;   71.6;
74;    0.33;    0.70;    0.48;   68.9;
75;    0.33;    1.20;    0.28;   68.9;
76;    4.33;    1.06;    4.09;   69.4;
77;    4.00;    1.33;    3.01;   69.4;
78;    2.67;    1.11;    2.41;   70.3;
79;    1.99;    1.60;    1.24;   70.3;
80;    2.33;    0.89;    2.62;   65.0;
81;    4.33;    1.13;    3.83;   68.6;
82;    5.33;    1.33;    4.01;   68.6;
83;    3.33;    1.25;    2.66;   67.6;
84;    1.67;    1.62;    1.03;   77.6;
85;    2.67;    0.97;    2.76;   77.6;
86;    3.33;    1.29;    2.59;   72.2;
87;    3.33;    1.12;    2.98;   72.2;
88;    3.33;    1.39;    2.39;   71.1;
89;    2.67;    1.33;    2.01;   71.1;
90;    1.67;    1.10;    1.52;   69.1;
91;    1.34;    1.08;    1.24;   69.1;
92;  518.99;   12.97;   40.00;  320.0;
92;  598.02;   12.88;   46.43;  320.0;
92;  383.00;    6.37;   60.10;  103.6;
93;   77.77;   26.68;    2.91;  704.7;
94;   64.90;    4.66;   13.92;   44.4;
95;   39.41;   12.82;    3.07;  315.6;
96;    9.20;   25.00;    0.37;   21.4;
97;   23.12;   16.04;    1.44;   17.4;
98;    2.67;    1.72;    1.55;   70.4;
99;    1.66;    1.91;    0.87;   70.4;
100;   2.67;    1.12;    2.39;   62.1;
101;   3.00;    0.83;    3.62;   62.1;
102;   1.34;    1.09;    1.23;   60.2;
103;   3.67;    1.20;    3.06;   62.1;
104;   5.33;    1.36;    3.92;   63.2;
105;   2.00;    1.24;    1.61;   63.2;
106;   1.00;    1.02;    0.98;   87.0;
107;   1.00;    0.92;    1.08;   87.0;
108;   2.33;    1.98;    1.18;   80.1;
109;   2.00;    1.18;    1.69;   80.1;
110;   3.00;    1.21;    2.47;   71.1;
111;   2.86;    1.03;    2.77;   71.1;
112;   3.67;    1.18;    3.10;   81.9;
113;   3.67;    1.31;    2.81;   81.9;
114;   0.67;    1.24;    0.54;   68.8;
115;   0.00;    0.00;    0.00;   68.8;
116;   0.67;    3.13;    0.21;   74.3;
117;   1.00;    1.13;    0.88;   74.3;
118;   2.66;    1.37;    1.94;   72.3;
119;   2.67;    1.60;    1.66;   72.3;
120;   0.67;    0.80;    0.83;   75.7;
121;   0.66;    2.27;    0.29;   75.7;
```

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122;  164.66;   28.17;    5.84;  282.0;
123;   64.87;    3.93;   16.50;   33.5;
124;   50.46;   26.31;    1.92;  139.7;
125;   59.95;    4.06;   14.75;   41.5;
126;   73.30;    3.46;   21.21;   27.2;
127;   82.59;    4.32;   19.12;   42.6;
128;   81.00;    4.83;   16.76;   44.6;
129;   89.07;    6.20;   14.36;   64.5;
130;   59.43;    3.68;   16.14;   34.1;
133;    3.00;    1.10;    2.72;   75.2;
134;    1.31;    2.66;    0.49;  100.5;
135;    0.67;    1.99;    0.33;  100.5;
136;    0.00;    0.00;    0.00;  100.4;
137;    2.00;    1.45;    1.38;  100.4;
138;  362.73;   13.70;   26.48;  320.0;
138;  146.77;   24.11;    6.09;  320.0;
138;  154.31;   19.74;    7.82;  320.0;
138;  157.96;   29.75;    5.31;  320.0;
138;  158.03;   29.59;    5.34;  320.0;
138;    9.08;   29.65;    0.31;  320.0;
138;    0.00;    0.00;    0.00;   32.1;
139;  330.14;   14.35;   23.01;  320.0;
139;  358.66;   22.18;   16.17;  320.0;
139;  328.47;    8.04;   40.85;   53.6;
140;    7.34;    1.23;    5.98;   68.7;
141;    5.99;    1.21;    4.96;   68.7;
142;    6.34;    1.17;    5.44;   66.9;
143;    6.33;    1.22;    5.18;   66.9;
144;    1.00;    1.10;    0.91;   67.0;
145;    1.00;    1.22;    0.82;   67.0;
146;    0.67;    1.78;    0.37;   64.4;
147;    1.65;    1.37;    1.20;   64.4;
158;    0.33;    3.44;    0.10;   53.8;
159;    0.33;    1.80;    0.19;   53.8;
160;    0.00;    0.00;    0.00;   65.3;
161;    0.00;    0.00;    0.00;   65.3;
162;    1.74;    1.14;    1.52;   58.1;
163;    0.67;    1.05;    0.63;   58.1;
164;    0.33;    0.85;    0.39;   64.7;
165;    0.34;    1.97;    0.17;   64.7;
166;    0.00;    0.00;    0.00;   77.0;
167;    0.33;    1.84;    0.18;   77.0;
168;    0.67;    1.14;    0.59;   71.7;
169;    0.67;    2.22;    0.30;   71.7;
170;    0.67;    1.97;    0.34;   61.6;
171;    0.67;    0.82;    0.81;   61.6;
172;    1.00;    1.54;    0.65;   70.7;
173;    1.00;    1.10;    0.91;   70.7;
174;   35.04;   25.18;    1.39;   72.6;
175;   32.66;   15.57;    2.10;  191.8;
176;    1.97;    1.25;    1.58;   61.6;
177;    1.33;    1.44;    0.92;   61.6;
178;    3.00;    1.16;    2.58;   67.7;
179;    4.66;    1.61;    2.90;   67.7;
180;    3.00;    1.12;    2.67;   63.7;
181;    2.66;    1.12;    2.37;   63.7;
```

```
182;    0.67;    2.07;    0.32;  66.6;
183;    1.00;    0.95;    1.06;  66.6;
184;   42.99;   25.20;    1.71; 402.2;
185;    0.34;   24.15;    0.01; 172.0;
186;    2.00;    1.46;    1.37;  67.3;
187;    1.67;    1.29;    1.29;  67.3;
188;    3.00;    1.27;    2.36;  68.8;
189;    3.00;    1.03;    2.90;  68.8;
190;    1.31;    1.62;    0.81;  57.1;
191;    1.66;    0.98;    1.69;  57.1;
192;    4.00;    1.03;    3.88;  62.1;
193;    2.00;    1.36;    1.48;  68.6;
206;    3.34;    1.28;    2.60;  67.6;
207;    2.00;    1.27;    1.57;  68.6;
210;   42.05;    7.44;    5.65; 320.0;
210;  246.79;   21.63;   11.41; 320.0;
210;  254.49;    3.76;   67.67;  39.5;
229;  603.98;   17.92;   33.70;  77.8;
230;    2.00;    1.19;    1.68;  68.4;
231;    2.00;    1.71;    1.17;  68.4;
232;    2.00;    1.01;    1.98;  72.8;
233;    4.00;    1.37;    2.93;  72.8;
234;    1.67;    1.13;    1.47;  60.2;
235;    3.33;    1.54;    2.16;  76.4;
236;    2.66;    1.66;    1.61;  70.7;
237;    1.33;    1.49;    0.89;  70.7;
238;  304.50;   10.25;   29.70; 320.0;
238;  205.36;   21.35;    9.62; 241.2;
239;  262.13;    9.69;   27.04; 129.8;
240;  217.59;   10.34;   21.04; 299.2;
241;    0.00;    0.00;    0.00;  38.5;
242;    0.33;    3.12;    0.11;  54.5;
243;    0.33;    3.21;    0.10;  54.5;
244;    0.00;    0.00;    0.00;  38.5;
245;    0.00;    0.00;    0.00;  34.2;
246;    0.00;    0.00;    0.00;  34.2;
247;    1.33;    1.64;    0.81;  76.7;
248;    2.00;    1.71;    1.17;  76.7;
249;    0.67;    1.60;    0.42;  79.0;
250;    1.00;    1.44;    0.69;  79.0;
251;    0.00;    0.00;    0.00;  77.7;
252;    0.00;    0.00;    0.00;  77.7;
253;    0.33;    1.72;    0.19;  81.9;
254;    0.67;    1.40;    0.48;  83.2;
255;  644.19;   11.47;   56.14; 320.0;
255;    0.00;    0.00;    0.00;   0.8;
256;    2.00;    1.96;    1.02;  78.8;
257;    1.67;    1.26;    1.33;  78.8;
258;    5.00;    1.49;    3.37;  60.2;
259;    1.33;    1.10;    1.21;  78.3;
260;    2.00;    1.20;    1.66;  78.3;
261;    1.33;    1.73;    0.77;  76.1;
262;    5.79;    1.20;    4.82;  84.5;
263;    4.00;    1.30;    3.08;  84.5;
271;  129.62;   16.52;    7.85; 662.4;
317;    7.67;    2.81;    2.73;  92.4;
```

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318;    6.33;   3.00;    2.11;  92.9;
323;    5.66;   1.20;    4.71;  60.2;
331;  451.93;   8.75;   51.63; 320.0;
331;  471.71;  14.17;   33.28; 320.0;
331;  320.14;  14.18;   22.58; 320.0;
331;  277.43;  19.03;   14.58; 320.0;
331;  165.52;  15.53;   10.66; 251.0;
332;    2.32;   1.59;    1.46;  57.7;
335;    3.34;   1.22;    2.74;  76.4;
336;    1.33;   1.16;    1.15;  76.1;
340;  140.22;  12.03;   11.66;  72.6;
341;   72.26;  16.86;    4.29; 806.2;
346;    0.00;   0.00;    0.00; 161.1;
350;   32.35;  24.61;    1.31; 181.7;
353;   34.11;  10.91;    3.13; 323.9;
354;   17.34;  24.36;    0.71; 259.3;
355;  163.70;  15.52;   10.55; 277.1;
356;   23.92;   8.23;    2.91; 327.0;
357;    7.03;  22.73;    0.31; 320.0;
357;    0.00;   0.00;    0.00;  22.1;
358;    0.00;  10.39;    0.00; 320.0;
358;    0.68;  12.35;    0.05;  18.7;
359;    0.00;   0.00;    0.00; 320.0;
359;   21.07;  23.35;    0.90; 277.7;
373;    0.00;   0.00;    0.00; 268.6;
374;  176.40;  15.40;   11.46; 320.0;
374;  274.42;  13.21;   20.77; 320.0;
374;  361.88;  18.19;   19.89; 320.0;
374;  356.26;   3.86;   92.38;  48.2;
```

Appendix F Network DEA Input Oriented (CCR) VBA Code for Essay 3

network_node 1,node 2 &node3_input.xls [Compati...

M9

	A	B	C	D	E	F	G	H	I	J	K	L
1												
2	Demand S	Cost (xc	VMT(yvmt	average speed (	revenue (y	feul (x	travel time (	person miles (	emmission (ye)			
3	1	5000	4048	13.1128	22082	332.9	206.057356	13298.99228	33186.547			
4	2	5000	3743	13.2068	22575.4	300	178.048104	10877.60457	29901.103			
5	3	5000	3938	13.0268	22667.8	323.8	228.39608	12082.31815	32280.369			
6	4	5000	3916	13.0147	22897.3	322.6	204.525413	13013.08073	32163.949			
7	5	5000	3916	12.907	23679.8	324	220.165882	14022.14985	32321			
8	6	5000	4150	12.0342	22261	366.9	233.770073	14257.36552	36583.684			
9	7	5000	4192	12.8882	22210.9	349.5	225.876928	13226.16738	34843.444			
26	24	5000	4326	12.83	22080.5	358.6	212.453937	14182.64733	35750.163			
27	25	5000	4330	12.7611	22050.3	363.9	219.654069	15817.36463	36278.629			
28	26	5000	4306	12.8544	22007.9	365	203.457994	15080.69889	36392.855			
29	27	5000	4326	12.7609	21956.3	362.1	235.207115	15181.44285	36099.026			
30	28	5000	4367	12.6554	20401.7	365.9	215.410232	16660.32044	36484.089			
101												
102		Input	Intermed.	Intermed.	output	Input	Input	output	output			
103		xc	yvmt	yas	yr	xf	xtt	ypm	ye			
104	Demand S	Cost	VMT	average speed	revenue	feul	travel time	person miles	emmission			
105	28	5000	4366.5598	12.6554	20401.7	365.9	215.410232	16660.32044	36484.089			
106												
107				Efficiency		1	min		1			
108												
109		Node 1	Node 2	Node 3								
110	Demand S	Lam. P	Lam. U	Lam. C			constraints					
111	1	0	0	0			(I) cost	5000 >=		5000	0	
112	2	0	0	0		Node	(o) VMT	4366.5598 <=		4366.5598	0	
113	3	0	0	0		1	(o) Avg. spd.	12.6554 <=		12.6554	0	
114	4	0	0	0			(O) revenue	20401.7 <=		20401.7	0	
115	5	0	0	0			(I) Feul	365.939 >=		365.939	0	
116	6	0	0	0.997277612		Node	(I) travel t.	215.4102321 >=		215.4102321	0	
117	7	0	0	0		2	(I) Avg. spd.	12.6554 >=		12.6554	0	
118	8	0	0	0			(O) PM	16660.32044 <=		16660.32044	0	
119	9	0	0	0			(I) VMT	4366.5598 >=		4139.075768	227.484	
120	10	0	0	0		Node 3	(O) Emmissi	36484.089 =		36484.089	0	
121	11	0	0	0								
134	24	0	0	0								
135	25	0	0	0								
136	26	0	0	0								

Model_CCR Results_CCR Slacks_CCR Model_BCC Results_BCC Slacks_BCC

Ready

	A	B	C	D	E	F	G	H	I	J	K	L
1												
2	Demand S	Cost (xc)	VMT(yvmt)	average speed (yas)	revenue (yr)	feul (xf)	travel time (xtt)	person miles (ypm)	emmission (ye)			
3	1	5000	4048	13.1128	22082	332.862	206.0573565	13298.99228	33186.547			
4	2	5000	3743	13.2068	22575.4	300	178.0481043	10877.60457	29901.103			
29	27	5000	4326	12.7609	21956.3	362.078	235.2071154	15181.44285	36099.026			
30	28	5000	4367	12.6554	20401.7	365.939	215.4102321	16660.32044	36484.089			
31												
101												
102		Input	Intermed.	Intermed.	output	Input	Input	output	output			
103		xc	yvmt	yas	yr	xf	xtt	ypm	ye			
104	Demand S	Cost	VMT	average speed	revenue	feul	travel time	person miles	emmission			
105	28	VLOOKUP(A105,A3:J30, 2)	VLOOKUP(A105,A3:J30,3)	VLOOKUP(A105,A3:J30, 4)	VLOOKUP(A105,A3:J30, 5)	VLOOKUP(A105,A3:J30, 6)	VLOOKUP(A105,A3:J30, 7)	VLOOKUP(A105,A3:J30, 8)	VLOOKUP(A105,A3:J30, 9)			
106												
107				Efficiency		1	min	E107				
108												
109		Node 1	Node 2	Node 3								
110	Demand S	Lam. P	Lam. U	Lam. C			constraints			slacks		
111	1	0	0	0			(I) cost	E107*B105	>=	SUMPRODUCT(B111:B138, B3:B30)	H111-J111	
112	2					Node	(o) VMT	C105	<=	SUMPRODUCT(B111:B138, C3:C30)	J112-H112	
113	3					1	(o) Avg. spd.	D105	<=	SUMPRODUCT(B111:B138,D3:D30)	J113-H113	
114	4						(O) revenue	E105	<=	SUMPRODUCT(B111:B138, E3:E30)	J114-H114	
115	5						(I) Feul	E107*F105	>=	SUMPRODUCT(C111:C138, F3:F30)	H115-J115	
116	6					Node	(I) travel t.	E107*G105	>=	SUMPRODUCT(C111:C138, G3:G30)	H116-J116	
117	7					2	(I) Avg. spd.	D105	>=	SUMPRODUCT(C111:C138, D3:D30)	H117-J117	
118	8						(O) PM	H105	<=	SUMPRODUCT(C111:C138, H3:H30)	J118-H118	
119	9						(I) VMT	C105	>=	SUMPRODUCT(D111:D138, C3:C30)	H119-J119	
120	10					Node 3	(O) Emmission	I105	=	SUMPRODUCT(I3:I30, D111:D138)		
121	11											
122	12											
123	13											
124	14											
125	15											
126	16											
127	17											
128	18											
129	19											
130	20	0	0	0								
131	21		0	0								

Solver Parameters V8.0

- Objective
  $G$107 (Min)
- Variables
  - Normal
    $B$111:$D$138,$E$107
  - Recourse
- Constraints
  - Normal
    $H$111 >= $J$111
    $H$112:$H$114 <= $J$112:$J$114
    $H$115:$H$117 >= $J$115:$J$117
    $H$118 <= $J$118
    $H$119 >= $J$119
    $H$120 = $J$120
  - Chance
  - Bound
  - Conic
  - Integers
- Uncertainties

Solve
Model
Options
Standard LP/Quadratic
Add
Reset All
Change
Help
Delete
Close

Model_CCR | Results_CCR | Slacks_CCR | Model_BCC | Results_BCC | Slacks_BCC

```vba
Sub CCR_1()
'
' CCR_1 Macro
'
Application.ScreenUpdating = False

Dim n As Integer

Sheets("Results_CCR").Select
Sheets("Results_CCR").Range("B3").Select

Sheets("Slacks_CCR").Select
Range("B4").Select

For n = 1 To 28

Sheets("Model_CCR").Select
Sheets("Model_CCR").Range("A105").Value = n

'Range("E107").Select
'Selection.Value = 1

'Range("B111:D138").Select
'Selection.Value = 0

 SolverOk SetCell:="$G$107", MaxMinVal:=2, ValueOf:=0, ByChange:= _
     "$B$111:$D$138,$E$107", Engine:=1, EngineDesc:="Standard LP/Quadratic"
     SolverSolve (True)

Sheets("Model_CCR").Select
Range("E107").Copy
Sheets("Results_CCR").Select
ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
       False, Transpose:=False

ActiveCell.Offset(0, 1).Select
Sheets("Model_CCR").Range("B111:B138").Copy
Sheets("Results_CCR").Select
ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
       False, Transpose:=True

ActiveCell.Offset(31, 0).Select
Sheets("Model_CCR").Range("C111:C138").Copy
Sheets("Results_CCR").Select
ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
       False, Transpose:=True
```

```
ActiveCell.Offset(31, 0).Select
Sheets("Model_CCR").Range("D111:D138").Copy
Sheets("Results_CCR").Select
ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True

ActiveCell.Offset(-61, -1).Select

Sheets("Model_CCR").Range("K111:K121").Copy
Sheets("Slacks_CCR").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True
ActiveCell.Offset(1, 0).Select

Next n

Sheets("Results_CCR").Select
Sheets("Results_CCR").Range("B3:B30").Copy
Sheets("Results_CCR").Range("B34:B61").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False

Sheets("Results_CCR").Range("B65:B92").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False

End Sub
```

Appendix G Network DEA Input Oriented (BCC) VBA Code for Essay 3

The following is a screenshot of an Excel spreadsheet titled "network_node1,node2 &node3_input.xls [Compatib...".

Selected cell: L30

	A	B	C	D	E	F	G	H	I	J	K	L
1												
2	Demand S	Cost (xc	VMT(yvmt	average speed (	revenue (y	feul (xf	travel time (	person miles (	emmission (ye			
3	1	5000	4048	13.1128	22082	332.9	206.057356	13298.99228	33186.547			
4	2	5000	3743	13.2068	22575.4	300	178.048104	10877.60457	29901.103			
5	3	5000	3938	13.0268	22667.8	323.8	228.39608	12082.31815	32280.369			
6	4	5000	3916	13.0147	22897.3	322.6	204.525413	13013.08073	32163.949			
26	24	5000	4326	12.83	22080.5	358.6	212.453937	14182.64733	35750.163			
27	25	5000	4330	12.7611	22050.3	363.9	219.654069	15817.36463	36278.629			
28	26	5000	4306	12.8544	22007.9	365	203.457994	15080.69889	36392.855			
29	27	5000	4326	12.7609	21956.3	362.1	235.207115	15181.44285	36099.026			
30	28	5000	4367	12.6554	20401.7	365.9	215.410232	16660.32044	36484.089			
101												
102		Input	Intermed.	Intermed.	output	Input	Input	output	output	output		
103		xc	yvmt	yas	yr	xf	xtt	ypm	ye	ya		
104	Demand S	Cost	VMT	average speed	revenue	feul	travel time	person miles	emmission	attraction		
105	28	5000	4366.5598	12.6554	20401.7	365.9	215.410232	16660.32044	36484.089	0		
106												
107				Efficiency		1	min		1			
108												
109		Node 1	Node 2	Node 3								
110	Demand S	Lam. P	Lam. U	Lam. C			constraints					
111	1	0	0	0.124758366			(I) cost	5000 >=		5000	0	
112	2	0	0	0		Node	(o) VMT	4366.5598 <=		4366.5598	0	
113	3	0	0	0		1	(o) Avg. spd.	12.6554 <=		12.6554	0	
114	4	0	0	0			(O) revenue	20401.7 <=		20401.7	0	
115	5	0	0	0			(I) Feul	365.939 >=		365.939	0	
116	6	0	0	0		Node	(I) travel t.	215.4102321 >=		215.4102321	0	
117	7	0	0	0		2	(I) Avg. spd.	12.6554 >=		12.6554	0	
118	8	0	0	0			(O) PM	16660.32044 <=		16660.32044	0	
119	9	0	0	0			(I) VMT	4366.5598 >=		4207.310534	159.2493	
120	10	0	0	0		Node 3	(O) Emmissi	36484.089 =		36484.089	0	
121	11	0	0	0								
122	12	0	0	0		N1		1 =		1		
123	13	0	0	0		N2		1 =		1		
124	14	0	0	0		N3		1 =		1		
125	15	0	0	0								
126	16	0	0	0								
127	17	0	0	0.875241634								
128	18	0	0	0								
129	19	0	0	0								

Sheet tabs: Model_CCR / Results_CCR / Slacks_CCR / Model_BCC / Results_BCC / Slacks_BCC

```
Sub BCC_1()
'
' BCC_1 Macro
Application.ScreenUpdating = False

Dim n As Integer
Sheets("Results_BCC").Select
Sheets("Results_BCC").Range("B3").Select

Sheets("Slacks_BCC").Select
Range("B4").Select

For n = 1 To 28

Sheets("Model_BCC").Select
Sheets("Model_BCC").Range("A105").Value = n
```

```vba
'Range("E107").Select
'Selection.Value = 1
'Range("B111:D138").Select
'Selection.Value = 0

 SolverOk SetCell:="$G$107", MaxMinVal:=2, ValueOf:=0, ByChange:= _
     "$B$111:$D$138,$E$107", Engine:=1, EngineDesc:="Standard LP/Quadratic"
     SolverSolve (True)

Sheets("Model_BCC").Select
Range("E107").Copy
Sheets("Results_BCC").Select
ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False

ActiveCell.Offset(0, 1).Select
Sheets("Model_BCC").Range("B111:B138").Copy
Sheets("Results_BCC").Select
ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True

ActiveCell.Offset(31, 0).Select
Sheets("Model_BCC").Range("C111:C138").Copy
Sheets("Results_BCC").Select
ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True

ActiveCell.Offset(31, 0).Select
Sheets("Model_BCC").Range("D111:D138").Copy
Sheets("Results_BCC").Select
ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True

ActiveCell.Offset(-61, -1).Select

Sheets("Model_BCC").Range("K111:K121").Copy
Sheets("Slacks_BCC").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True
ActiveCell.Offset(1, 0).Select
Next n

Sheets("Results_BCC").Select
Sheets("Results_BCC").Range("B3:B30").Copy
Sheets("Results_BCC").Range("B34:B61").Select
```

```vba
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False

Sheets("Results_BCC").Range("B65:B92").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False

End Sub
```

Appendix H Network DEA Output Oriented (BCC) VBA Code for Essay 3


```
Sub BCC_1()
'
' BCC_1 Macro
'
Application.ScreenUpdating = False

Dim n As Integer

Sheets("Results_BCC").Select
Sheets("Results_BCC").Range("B3").Select

Sheets("Slacks_BCC").Select
Range("B4").Select

For n = 1 To 28

Sheets("Model_BCC").Select
```

```
Sheets("Model_BCC").Range("A105").Value = n

'Range("E107").Select
'Selection.Value = 1

'Range("B111:D138").Select
'Selection.Value = 0


 SolverOk SetCell:="$G$107", MaxMinVal:=1, ValueOf:=0, ByChange:= _
     "$B$111:$D$138,$E$107", Engine:=1, EngineDesc:="Standard LP/Quadratic"
     SolverSolve (True)


Sheets("Model_BCC").Select
Range("E107").Copy
Sheets("Results_BCC").Select
ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False


ActiveCell.Offset(0, 1).Select
Sheets("Model_BCC").Range("B111:B138").Copy
Sheets("Results_BCC").Select
ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True


ActiveCell.Offset(31, 0).Select
Sheets("Model_BCC").Range("C111:C138").Copy
Sheets("Results_BCC").Select
ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True


ActiveCell.Offset(31, 0).Select
Sheets("Model_BCC").Range("D111:D138").Copy
Sheets("Results_BCC").Select
ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True

ActiveCell.Offset(-61, -1).Select


Sheets("Model_BCC").Range("K111:K121").Copy
Sheets("Slacks_BCC").Select
```

```
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=True
ActiveCell.Offset(1, 0).Select


Next n

Sheets("Results_BCC").Select
Sheets("Results_BCC").Range("B3:B30").Copy
Sheets("Results_BCC").Range("B34:B61").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False

Sheets("Results_BCC").Range("B65:B92").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
    False, Transpose:=False

End Sub
```

Appendix I Network DEA Output Oriented (CCR) VBA Code for Essay 3


```vba
Sub CCR_1()
'
' CCR_1 Macro
'
Application.ScreenUpdating = False

Dim n As Integer

Sheets("Results_CCR").Select
Sheets("Results_CCR").Range("B3").Select

Sheets("Slacks_CCR").Select
Range("B4").Select

For n = 1 To 28

Sheets("Model_CCR").Select
Sheets("Model_CCR").Range("A105").Value = n
```

```
'Range("E107").Select
'Selection.Value = 1

'Range("B111:D138").Select
'Selection.Value = 0


 SolverOk SetCell:="$G$107", MaxMinVal:=1, ValueOf:=0, ByChange:= _
     "$B$111:$D$138,$E$107", Engine:=1, EngineDesc:="Standard LP/Quadratic"
     SolverSolve (True)


Sheets("Model_CCR").Select
Range("E107").Copy
Sheets("Results_CCR").Select
ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False


ActiveCell.Offset(0, 1).Select
Sheets("Model_CCR").Range("B111:B138").Copy
Sheets("Results_CCR").Select
ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True


ActiveCell.Offset(31, 0).Select
Sheets("Model_CCR").Range("C111:C138").Copy
Sheets("Results_CCR").Select
ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True


ActiveCell.Offset(31, 0).Select
Sheets("Model_CCR").Range("D111:D138").Copy
Sheets("Results_CCR").Select
ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True

ActiveCell.Offset(-61, -1).Select


Sheets("Model_CCR").Range("K111:K121").Copy
Sheets("Slacks_CCR").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
```

```
        False, Transpose:=True
ActiveCell.Offset(1, 0).Select


Next n

Sheets("Results_CCR").Select
Sheets("Results_CCR").Range("B3:B30").Copy
Sheets("Results_CCR").Range("B34:B61").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False

Sheets("Results_CCR").Range("B65:B92").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False

End Sub
```

Appendix J SBM Network DEA Output Oriented (VRS) VBA Code for Essay 3

The first screenshot shows an Excel spreadsheet "network_output_BCC with node eff.xls [Compatibility Mode] - Microsoft Excel" with the following data:

	A	B	C	D	E	F	G	H	I
2	Demand S	Cost (xc	VMT(yvmt	average speed (	revenue (	feul (x	travel time (xtt	person miles (	emmission (ye)
3	1	5000	4048	13.1128	22082	332.9	206.0573565	13298.99228	33186.547
4	2	5000	3743	13.2068	22575.4	300	178.0481043	10877.60457	29901.103
5	3	5000	3938	13.0268	22667.8	323.8	228.3960796	12082.31815	32280.369
6	4	5000	3916	13.0147	22897.3	322.6	204.5254129	13013.08073	32163.949
7	5	5000	3916	12.907	23679.8	324	220.1658821	14022.14985	32321
28	26	5000	4306	12.8544	22007.9	365	203.4579943	15080.69889	36392.855
29	27	5000	4326	12.7609	21956.3	362.1	235.2071154	15181.44285	36099.026
30	28	5000	4367	12.6554	20401.7	365.9	215.4102321	16660.32044	36484.089

	A	B	C	D	E	F	G	H	I
102		Input	Intermed.	Intermed.	output	Input	Input	output	output
103		xc	yvmt	yas	yr	xf	xtt	ypm	ye
104	Demand S	Cost	VMT	average speed	revenue	feul	travel time	person miles	emmission
105	28	5000	4366.5598	12.6554	20401.7	365.9	215.4102321	16660.32044	36484.089

| 107 | | | | Efficiency | 0.915072 | max | 1.092809799 | | |

		Node 1	Node 2	Node 3			constraints				Slacks
110 Demand S		Lam. P	Lam. U	Lam. C							
111	1	0	0	0		Node 1	(I) cost	5000 =		5000	0
112	2	0	0	0.633148929			(O) revenue	20401.7 =		20401.7	3013.141
113	3	0	0	0			(I) Feul	365.939 =		365.939	0
114	4	0	0	0		Node 2	(I) travel t.	215.4102321 =		215.4102321	0
115	5	0.8343	0	0			(O) PM	16660.32044 =		16660.32044	0
116	6	0	0	0			(O) Emmission	36484.089 =		36484.089	4769.88291
117	7	0	0	0		Node 3					
118	8	0	0	0			(inm) VMT	0 =		0	
119	9	0	0	0			(inm) Avg, spd.	0 =		0	
120	10	0	0	0				1 =		1	
121	11	0	0	0			VRS	1 =		1	
122	12	0	0	0				1 =		1	
126	16	0	0	0							
127	17	0	0	0			Nodes	Weights	# of inputs	# of outputs	Node Eff
128	18	0	0	0			n1	0.33	1	1	0.87131491
129	19	0	0	0			n2	0.33	2	1	1
130	20	0	0	0.366851071			n3	0.33	0	1	0.88437761
131	21	0	0	0							0.91507232
132	22	0	0	0							
133	23	0	0	0							

Sheet tabs: Model_NO Results_NO Slacks_NO **Model_O** Results_O Slacks_O Model_I Results_I Slacks_I She...

	A	B	C	D	E	F	G	J
107 max		G128*(1+(1/I128)*(K112/E105))+G129*(1+(1/I129)*(K115/H105))+G130*(1+(1/I130)*(K116/I105))						
110		constraints						Slacks
111 Node 1	(I) cost	B105			=	SUMPRODUCT(B111:B138, B3:B30)+K111		0
112	(O) revenue	E105			=	SUMPRODUCT(B111:B138, E3:E30)-K112		3013.141
113	(I) Feul	F105			=	SUMPRODUCT(C111:C138,F3:F30)+K113		0
114 Node 2	(I) travel t.	G105			=	SUMPRODUCT(C111:C138, G3:G30)+K114		0
115	(O) PM	H105			=	SUMPRODUCT(C111:C138, H3:H30)-K115		0
116	(O) Emmission	I105			=	SUMPRODUCT(I3:I30, D111:D138)+K116		4769.88291
117 Node 3								
118	(inm) VMT	SUMPRODUCT(B111:B138, C3:C30)			=	SUMPRODUCT(D111:D138, C3:C30)		
119	(inm) Avg, spd.	SUMPRODUCT(B111:B138,D3:D30)			=	SUMPRODUCT(C111:C138, D3:D30)		
120		SUM(B111:B138)			=		1	
121 VRS		SUM(C111:C138)			=		1	
122		SUM(D111:D138)			=		1	
127 Nodes	Weights	# of inputs		# of outputs				Node Eff
128 n1	0.33	1		1				1/(1+(1/I128)*(K112/E105))
129 n2	0.33	2		1				1/(1+(1/I129)*(K115/H105))
130 n3	0.33	0		1				1/(1+(1/I130)*(K116/I105))
131								1/(G128/K128+G129/K129+G130/K130)

Sheet tabs: Model_NO Results_NO Slacks_NO **Model_O** Results_O Slacks_O Model_I Results_I Slacks_I Sheet1

Sub Model_O()

```vba
"
Application.ScreenUpdating = False

Dim n As Integer

Sheets("Results_O").Select
Sheets("Results_O").Range("B3").Select

Sheets("Slacks_O").Select
Range("B4").Select

For n = 1 To 28

Sheets("Model_O").Select
Sheets("Model_O").Range("A105").Value = n

 SolverOk SetCell:="$G$107", MaxMinVal:=1, ValueOf:=0, ByChange:= _
    "$B$111:$D$138,$K$111:$K$116", Engine:=1, EngineDesc:="Standard LP/Quadratic"
    SolverSolve (True)


Sheets("Model_O").Select
Range("E107").Copy
Sheets("Results_O").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False

'Node 1 Intensity variables *******
ActiveCell.Offset(0, 1).Select
Sheets("Model_O").Range("B111:B138").Copy
Sheets("Results_O").Select
ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True

'node 1 efficiency
ActiveCell.Offset(0, 28).Select
Sheets("Model_O").Select
Range("K128").Copy
Sheets("Results_O").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False

'node 2 Intensity
ActiveCell.Offset(31, -28).Select
Sheets("Model_O").Range("C111:C138").Copy
Sheets("Results_O").Select
```

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```
ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True

'node 2 efficiency
ActiveCell.Offset(0, 28).Select
Sheets("Model_O").Select
Range("K129").Copy
Sheets("Results_O").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False

'node 3 intensity
ActiveCell.Offset(31, -28).Select
Sheets("Model_O").Range("D111:D138").Copy
Sheets("Results_O").Select
ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True


'node 3 efficiency
ActiveCell.Offset(0, 28).Select
Sheets("Model_O").Select
Range("K130").Copy
Sheets("Results_O").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False

ActiveCell.Offset(-61, -29).Select

'slacks
Sheets("Model_O").Range("K111:K116").Copy
Sheets("Slacks_O").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True
ActiveCell.Offset(1, 0).Select

Next n

Sheets("Results_O").Select
Sheets("Results_O").Range("B3:B30").Copy
Sheets("Results_O").Range("B34:B61").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False

Sheets("Results_O").Range("B65:B92").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
```

False, Transpose:=False

End Sub

Appendix K SBM Network DEA Input Oriented (VRS) VBA Code for Essay 3

	F	G	H	I	J	K	L	M	N
107	min	G128*(1-(1/H128)*(K111/B105))+G129*(1-(1/H129)*(K113/F105+K114/G105))+G130							
108									
109									
110		constraints				Slacks			
111	Node 1	(I) cost	B105	=	SUMPRODUCT(B111:B138, B3:B30)+K111	0			
112		(O) revenue	E105	=	SUMPRODUCT(B111:B138, E3:E30)-K112	105.3082			
113		(I) Feul	F105	=	SUMPRODUCT(C111:C138,F3:F30)+K113	14.76566			
114	Node 2	(I) travel t.	G105	=	SUMPRODUCT(C111:C138, G3:G30)+K114	10.04025			
115		(O) PM	H105	=	SUMPRODUCT(C111:C138, H3:H30)-K115	0			
116		(O) Emmissi	I105	=	SUMPRODUCT(I3:I30, D111:D138)+K116	1558.233			
117	Node 3								
118		(inm) VMT	SUMPRODUCT(B111:B138, C3:C30)	=	SUMPRODUCT(D111:D138, C3:C30)				
119		(inm) Avg, s	SUMPRODUCT(B111:B138,D3:D30)	=	SUMPRODUCT(C111:C138, D3:D30)				
120			SUM(B111:B138)	=	1				
121		VRS	SUM(C111:C138)	=	1				
122			SUM(D111:D138)	=	1				
123									
124									
125									
126									
127	Nodes	Weights	# of inputs		# of outputs	Node eff			
128	n1	0.33	1		1	(1-(1/H128)*(K111/B105))			
129	n2	0.33	2		1	(1-(1/H129)*(K113/F105+K114/G105))			
130	n3	0.33	0		1	1			
131						SUMPRODUCT(G128:G130,K128:K130)			
132									

```
Sub Model_I()
'

Application.ScreenUpdating = False

Dim n As Integer

Sheets("Results_I").Select
Sheets("Results_I").Range("B3").Select

Sheets("Slacks_I").Select
Range("B4").Select

For n = 1 To 28

Sheets("Model_I").Select
Sheets("Model_I").Range("A105").Value = n


 SolverOk SetCell:="$G$107", MaxMinVal:=2, ValueOf:=0, ByChange:= _
    "$B$111:$D$138,$K$111:$K$116", Engine:=1, EngineDesc:="Standard LP/Quadratic"
    SolverSolve (True)

'Efficiency Score
Sheets("Model_I").Select
Range("G107").Copy
Sheets("Results_I").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False
```

```vba
'Node 1 Intensity variables *******
ActiveCell.Offset(0, 1).Select
Sheets("Model_I").Range("B111:B138").Copy
Sheets("Results_I").Select
ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True

'node 1 efficiency
ActiveCell.Offset(0, 28).Select
Sheets("Model_I").Select
Range("K128").Copy
Sheets("Results_I").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False


'node 2 Intensity
ActiveCell.Offset(31, -28).Select
Sheets("Model_I").Range("C111:C138").Copy
Sheets("Results_I").Select
ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True

'node 2 efficiency
ActiveCell.Offset(0, 28).Select
Sheets("Model_I").Select
Range("K129").Copy
Sheets("Results_I").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False


'node 3 intensity
ActiveCell.Offset(31, -28).Select
Sheets("Model_I").Range("D111:D138").Copy
Sheets("Results_I").Select
ActiveCell.PasteSpecial Paste:=xlValue, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True

'node 3 efficiency
ActiveCell.Offset(0, 28).Select
Sheets("Model_I").Select
Range("K130").Copy
Sheets("Results_I").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
```

```vba
        False, Transpose:=False

ActiveCell.Offset(-61, -29).Select


'slacks
Sheets("Model_I").Range("K111:K116").Copy
Sheets("Slacks_I").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True
ActiveCell.Offset(1, 0).Select


Next n

Sheets("Results_I").Select
Sheets("Results_I").Range("B3:B30").Copy
Sheets("Results_I").Range("B34:B61").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False

Sheets("Results_I").Range("B65:B92").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False


End Sub
```

Appendix L SBM Network DEA Non-Oriented Model (VRS)

L.1. Solving SBM Non-oriented Model
The nonlinear formulation of non-oriented model can be transformed into linear formulations by introducing a positive scalar variable t.

$$\text{Min } \tau = \sum_{k=1}^{K} w^k [t - \frac{1}{m_k}(\sum_{i=1}^{m_k} t \frac{s_i^{k-}}{x_{i0}^k})]$$

Subject to:

$$1 = \sum_{k=1}^{K} w^k [t + \frac{1}{r_k}(\sum_{r=1}^{r_k} t \frac{s_r^{k+}}{y_{i0}^k})]$$

$$x_0^k = X^k \lambda^k + s^{k-} (k = 1,..., K)$$

$$y_0^k = Y^k \lambda^k + s^{k+} (k = 1,..., K)$$

$$\sum_{j=1}^{n} \lambda_j^k = 1 \ (\forall k)$$

$$\lambda^k \geq 0, s^{k-} \geq 0, s^{k+} \geq 0, (\forall k)$$

(3) Discretionary intermediate inputs/outputs constraints
$$Z^{(k,h)} \lambda^h = Z^{(k,h)} \lambda^k, (\forall (k,h)),$$

(4) Non-discretionary intermediate inputs/outputs constraints
$$Z_0^{(k,h)} = Z^{(k,h)} \lambda^h \ (\forall (k,h)),$$

$$Z_0^{(k,h)} = Z^{(k,h)} \lambda^k \ (\forall (k,h)).$$

Define S⁻=ts⁻, S⁺=ts⁺, and Λ=tλ, the Non-oriented program becomes:

$$\text{Min } \tau = \sum_{k=1}^{K} w^k [t - \frac{1}{m_k}(\sum_{i=1}^{m_k} \frac{S_i^{k-}}{x_{i0}^k})]$$

Subject to:

$$1 = \sum_{k=1}^{K} w^k [t + \frac{1}{r_k}(\sum_{r=1}^{r_k} \frac{S_r^{k+}}{y_{i0}^k})]$$

$$tx_0^k = X^k \Lambda^k + S^{k-} (k = 1,..., K)$$

$$ty_0^k = Y^k \Lambda^k + S^{k+} (k = 1,..., K)$$

$$\sum_{j=1}^{n} \Lambda_j^k = t \ (\forall k)$$

$$\Lambda^k \geq 0, S^{k-} \geq 0, S^{k+} \geq 0, t > 0 (\forall k)$$

(1) Discretionary intermediate inputs/outputs constraints
$$Z^{(k,h)} \Lambda^h = Z^{(k,h)} \Lambda^k, (\forall (k,h)),$$

(2) Non-discretionary intermediate inputs/outputs constraints

$$tZ_0^{(k,h)} = Z^{(k,h)} \Lambda^h \ (\forall(k,h)),$$

$$tZ_0^{(k,h)} = Z^{(k,h)} \Lambda^k \ (\forall(k,h)).$$

An optimal solution is $(\tau^*, t^*, \Lambda^*, S^{-*}, S^{+*})$ for the transformed program. Then the optimal solution for the non-oriented SBM model is defined by:

$$\rho^* = \tau^*, \ \lambda^* = \Lambda^*/t^*, \ s^{-*} = S^{-*}/t^*, \ s^{+*} = S^{+*}/t^*$$

L.2 SBM Non-oriented Network DEA Model VBA Code

L125

	F	G	H	I	J	K	L	M
28	365	203.4579943	15080.69889	36392.855				
29	362.1	235.2071154	15181.44285	36099.026				
30	365.9	215.4102321	16660.32044	36484.089				
101								
102	Input	Input	output	output				
103	xf	xtt	ypm	ye				
104	feul	travel time	person miles	emmission				
105	365.9	215.4102321	16660.32044	36484.089	0			
106								
107	min	(G128*(M111-(1/H128)*(L111/B105))+G129*(M111-(1/H129)*(L113/F105+L114/G105))+G130*M111)						
108								
109								
110		constraints				Slacks (s)	S	t
111	Node 1	(I) cost	M111*B105	=	SUMPRODUCT(B111:B138, B3:B30)+L111	L111/$M$111	0	0.915072
112		(O) revenue	M111*E105	=	SUMPRODUCT(B111:B138, E3:E30)-L112	L112/$M$111	2757.241931	
113		(I) Feul	M111*F105	=	SUMPRODUCT(C111:C138,F3:F30)+L113	L113/$M$111	0	
114	Node 2	(I) travel t.	M111*G105	=	SUMPRODUCT(C111:C138, G3:G30)+L114	L114/$M$111	0	
115		(O) PM	M111*H105	=	SUMPRODUCT(C111:C138, H3:H30)-L115	L115/$M$111	0	
116		(O) Emmission	M111*I105	=	SUMPRODUCT(I3:I30, D111:D138)+L116	L116/$M$111	4364.787829	
117	Node 3							
118		(inm) VMT	SUMPRODUCT(B111:B138, C3:C30)	=	SUMPRODUCT(D111:D138, C3:C30)			
119		(inm) Avg. spd.	SUMPRODUCT(B111:B138,D3:D30)	=	SUMPRODUCT(C111:C138, D3:D30)			
120			SUM(B111:B138)	=	M111			
121		VRS	SUM(C111:C138)	=	M111			
122			SUM(D111:D138)	=	M111			
123		J128*(M111+(1/I128)*(L112/E105))+J129*(M111+(1/I129)*(L115/H105))+J130*(M111+(1/I130)*(L116/I105))		=	1			
124								
125								
126								
127	Nodes	Weights	# of inputs	# of outputs			Node Eff	
128	n1	0.33	1	1	0.333333333		(1-(1/H128)*(K111/B105))/(1+(1/I128)*(K112/E105))	
129	n2	0.33	2	1	0.333333333		(1-(1/H129)*(K113/F105+K114/G105))/(1+(1/I129)*(K115/H105))	
130	n3	0.33	0	1	0.333333333		1/(1+K116/I105)	
131							SUMPRODUCT(J128:J130,L128:L130)	
132								
133								
134								
135								
136								
137								

Model_NO / Results_NO / Slacks_NO / Model_O / Results_O / Slacks_O / Model_I / Results_I / Slacks_I / Sheet1

```
Sub Model_NO()
'
'
Application.ScreenUpdating = False

Dim n As Integer

Sheets("Results_NO").Select
Sheets("Results_NO").Range("B3").Select

Sheets("Slacks_NO").Select
Range("B4").Select

For n = 1 To 28

Sheets("Model_NO").Select
Sheets("Model_NO").Range("A105").Value = n


 SolverOk SetCell:="$G$107", MaxMinVal:=2, ValueOf:=0, ByChange:= _
     "$B$111:$D$138,$L$111:$L$116, $M$111", Engine:=1, EngineDesc:="Standard
LP/Quadratic"
     SolverSolve (True)


Sheets("Model_NO").Select
Range("G107").Copy
Sheets("Results_NO").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
       False, Transpose:=False


'Node 1 Intensity variables *******
ActiveCell.Offset(0, 1).Select
Sheets("Model_NO").Range("B143:B170").Copy
Sheets("Results_NO").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
       False, Transpose:=True

'node 1 efficiency
ActiveCell.Offset(0, 28).Select
Sheets("Model_NO").Select
Range("L128").Copy
Sheets("Results_NO").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
       False, Transpose:=False
```

```vba
'node 2 Intensity
ActiveCell.Offset(31, -28).Select
Sheets("Model_NO").Range("C143:C170").Copy
Sheets("Results_NO").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True

'node 2 efficiency
ActiveCell.Offset(0, 28).Select
Sheets("Model_NO").Select
Range("L129").Copy
Sheets("Results_NO").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False


'node 3 intensity
ActiveCell.Offset(31, -28).Select
Sheets("Model_NO").Range("D143:D170").Copy
Sheets("Results_NO").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True

'node 3 efficiency
ActiveCell.Offset(0, 28).Select
Sheets("Model_NO").Select
Range("L130").Copy
Sheets("Results_NO").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False

ActiveCell.Offset(-61, -29).Select


'slacks
Sheets("Model_NO").Range("K111:K116").Copy
Sheets("Slacks_NO").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=True
ActiveCell.Offset(1, 0).Select


Next n
```

```
Sheets("Results_NO").Select
Sheets("Results_NO").Range("B3:B30").Copy
Sheets("Results_NO").Range("B34:B61").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False

Sheets("Results_NO").Range("B65:B92").Select
ActiveCell.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False
'

End Sub
```

Appendix M IIE Conference Paper

Transportation Network Performance Measurement-The Impact of The Downtown Space Reservation System: A Network-DEA Approach[16]

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Abstract

A transportation network is a multiple input/output system. Transportation service providers may be interested in the transportation system efficiency and effectiveness. Transportation users may be concerned with their mobility. The community may care more about environment and safety issues. To represent these multiple perspectives in a performance evaluation framework, network-DEA is used. The perspectives are inter-related through the intermediate inputs/outputs in the network-DEA approach. An illustrative example is provided using the data propagated from a microscopic traffic simulation model of the Downtown Space Reservation System. Thus, the network-DEA model complements the micro level simulation performance evaluation by accounting for a macro level measurement consideration.

Keywords
Data Envelopment Analysis (DEA), Network DEA, Transportation Network Performance.

1.   Introduction

Transportation systems play an essential role in our daily life. Not only are travelers impacted by these systems but people living in the community, in a broad sense, are also impacted through, for instance, safety and environmental issues. At the same time, transportation service providers are striving to meet their financial constraints. These wide-ranging interests may conflict with each other, making the traditional transportation economic evaluation method such as Benefit-Cost analysis inadequate to capture the complexity and the underlying structure of the transportation system. Therefore, an effective measurement tool is paramount for today's comprehensive evaluation of transportation systems. Especially, since many transportation agencies are beginning to look favorably at Travel Demand Management (TDM) strategies to facilitate congestion reduction, environment protection, energy conservation and economic considerations. Conventional transportation evaluation approaches tend to undervalue TDM strategies by ignoring and understating costs associated with automobile usage and the benefits of more efficient and diversified transportation systems. The need for a more comprehensive performance measurement approach has emerged for TDM evaluation.

In order to address this need, this research develops a transportation performance measurement framework with an application of a new efficiency measurement methodology, namely network-DEA. This proposed framework expands on Färe and Grosskopf's network DEA approach [1] and captures the perspectives of transportation system providers, the users and the community, as well as the interrelationships among these views, providing an overall performance (efficiency) measure for a transportation network. Our approach is to compare and contrast various instances (scenarios) that occur in the transportation network under the execution of a TDM strategy, namely the Downtown Space Reservation System (DSRS). The scenarios constitute the production possibility set for our

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analysis. The data that support the analytical framework is obtained from the execution of microscopic simulations where traffic flows of a downtown area where the DSRS is implemented are obtained.

This research contributes to the existing performance measurement literature in that it utilizes the outputs from the microscopic traffic simulation models. This constitutes an innovative application of the DEA modeling framework. Further, the network-DEA model complements the micro level simulation performance measurement by accounting for a macro level performance measurement considerations. Additionally, this research differentiates itself from the others in the efficiency literature in that it incorporates the undesirable outputs directly in the network DEA models with the hyperbolic efficiency measures proposed by Färe, Grosskopf, Lovell and Pasurka [2].

The paper is organized as follows. The introduction is provided in Section 1 whereas Section 2 presents a brief background of the DSRS and the microscopic traffic simulation. Section 3 describes the conceptual framework with the measures selected in the framework. Section 4 provides the mathematic formulations of the network model. Finally, preliminary results are presented in Section 5.

2. Background

The transportation network evaluated in this research is characterized by the implementation of the TDM strategy, namely the DSRS. It is developed for the purpose of congestion mitigation, especially for the center of a city or Central Business District (CBD). With the DSRS, travelers who want to drive in a designated downtown area have to book their time slots before making their trips. The transportation authority, who administers and supervises the DSRS, allocates time slots to travelers based on the availability of resources (i.e., road network capacity). Only those who get permission from the transportation authority can drive in the downtown area during the requested time period. The system intends to alleviate traffic congestion by reducing excessive vehicles on the road [3].

The core of the DSRS is an optimization module that is maximizing two components, i.e., people throughput (the total number of travelers that the transportation system serviced) and revenue, subject to the transportation network capacity constraint. Building upon the initial formulation development of the DSRS, a microscopic traffic simulation model was built to evaluate performance of this TDM strategy, to help obtain a better understanding of the system behavior, and to evaluate the impact of changes in the system. The simulation model provides a means to test the DSRS before it is implemented by providing a range of effectiveness measures. The simulation was run under different scenarios characterized with travel demand levels and reservation policy specifics. The TDM policy was varied by changing the relative importance of the people throughput and revenue in the reservation system [4].
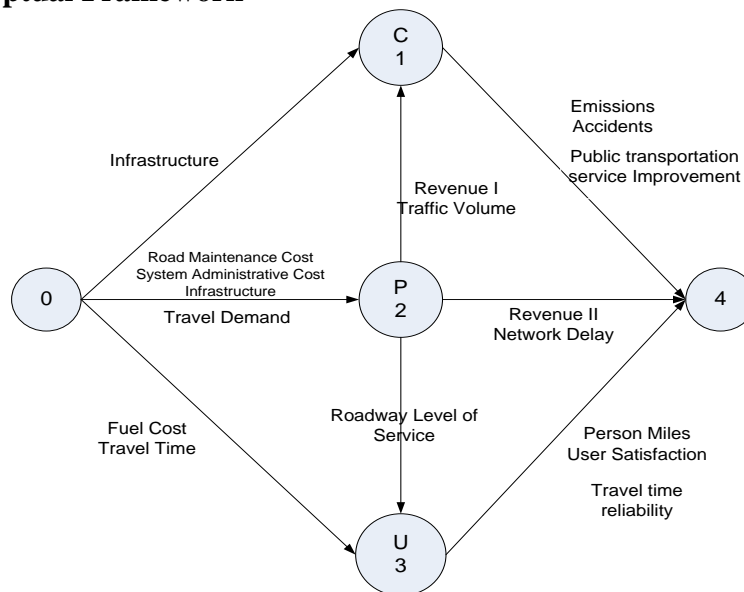
3. The Conceptual Framework

Figure 1: Three perspectives of the performance network structure

According to the literature, we assume that travelers are more concerned about their mobility. This is reflected with the travel time related measures. Transportation service providers are mostly interested in the system efficiency and effectiveness, which is reflected by revenue and the vehicle miles traveled etc. Last but not least, the community typically cares more about environment and safety issues that are associated with the traffic. Therefore, sustainability oriented measures are more appropriate to reflect their interests.

The unit of analysis is the transportation system under different scenarios. Each scenario may represent a unique operating environment which is characterized by travel demand and/or reservation policies. The performance network of Figure 1 represents the underlying structure of transportation system with respect to different perspectives and the interrelationships among the perspectives. The network consists of five nodes. Node 0 and Node 4 are dummy nodes. The major function of these nodes is to distribute inputs to and collect outputs from the intermediate nodes (Node 1, Node 2 and Node 3). Therefore, the framework reflects the interrelationship among the three viewpoints.

Node 1, Node 2 and Node 3 represent the different perspectives. Node 1 represents the community's viewpoint. The community is directly impacted by the transportation system in their territory. Node 2 represents the perspective of the transportation service provider. Node 3 is transportation user's perspective. The connection between nodes is directed, indicating the information and/or material transformation from inputs to outputs.

For instance, from providers' point of view, the inputs to the transportation system include different categories of cost, infrastructure and the unfulfilled travel demand; the outputs include revenue, traffic volume, Level of Service (LOS), and network delay. From the community's point of view, the inputs are the infrastructure, the revenue from transportation service and the traffic volume; the outputs are the emissions, accidents and public transportation improvements. From the users' perspective, the inputs are the fuel cost, travel time and reservation fee they spend on their trips; the outputs are the person miles traveled, user satisfaction and travel time reliability. Among them, there are two types of inputs/outputs – intermediate inputs/outputs and final outputs. The final outputs are the outputs that are finally fed into Node 4, such as emissions, accidents, network delay and person miles etc. The intermediate outputs, LOS, traffic volume and revenue, are the outputs from providers' point view, while they are also the inputs to Node1 and Node3.

4. The Network-DEA Model Formulation

In this research, the network DEA takes into account the perspectives of different stakeholders. The network DEA model is essentially a family of models by formulating a DEA model for each node. Each node has one set of intensity variables. Färe and Crosskopf [5] proved that if each of the nodes satisfies the free disposability of inputs and outputs and constant returns to scale, so does the network model. Because of the limited number of DMUs available from the microscopic simulations, the DEA network has been simplified in this example (Figure 2), keeping the vital and representative variables of the network of Figure 1.
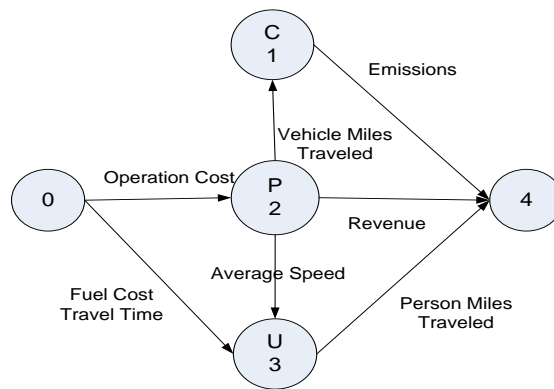

Figure 2: Simplified network

Since the community is assumed to bear the adverse effects of traffic congestion, i.e. emission and accidents, these outputs are expected to be minimized while the other desirable variables are to be maximized. Efficiency measurement with the incorporation of undesirable outputs in production models has been widely studied by different researchers. Färe, Grosskopf and Pasurka [6] first modeled the effects of environmental controls restricting the disposal of undesirable outputs with the classic radial efficiency measurement. Following this approach, Färe, Grosskopf, Lovell and Pasurka [2] modified the efficiency measures to allow for asymmetric treatment of desirable and undesirable outputs. The approach belongs to the category of hyperbolic efficiency measurement. For illustration purpose, here we use the same variable notation of their paper, where θ is the efficiency score; q_k is the undesirable output; Q is the undesirable output vector; z is the intensity variable; $\bar{Z}$ is the intensity variable vector. The hyperbolic efficiency measure requires solving a nonlinear programming problem. The authors converted the nonlinear problem to a linear programming problem by taking a linear approximation to the nonlinear constraint $\frac{q_k}{\theta} \leq Q\bar{Z}$. The linear approximation is $2q_k - \theta q_k \leq Q\bar{Z}$. However, Zofio and Prieto [7] suggested computing the hyperbolic measure by converting the nonlinear constraint to $\theta q_k^{-1} \geq (\sum_{k=1}^{K} q_{tk} z_k)^{-1}$ for computational purposes.

However, as our analysis has shown that this constraint is actually still nonlinear with respect to the intensity variables z_k. The computational benefit from replacing nonlinear constraint $\frac{q_k}{\theta} \leq Q\bar{Z}$ with the constraint $\theta q_k^{-1} \geq (\sum_{k=1}^{K} q_{tk} z_k)^{-1}$ is actually very limited. Therefore, in this paper, we use the linear transformation proposed by Färe et al. [2] for simplicity.

Assuming there are K Decision Making Units (DMUs). The DEA formulation will evaluate the efficiency of k_0th DMU by computing the efficiency measures θ_{k0}, and N sets of intensity variables $\lambda_n^{k_0}$. N equals the number of nodes (not including the dummy nodes). The network DEA model is written in terms of an output increasing performance measure as:

$$\text{Max } \theta$$

Subject to:
Node 1 (community's perspective):

$$y_{vmt} \geq \sum_{k=1}^{K} \lambda_c^k y_{vmt}^k \tag{1}$$

$$\frac{y_e}{\theta} \leq \sum_{k=1}^{K} \lambda_c^k y_e^k \tag{2}$$

Node 2 (providers' perspective):

$$x_c \geq \sum_{k=1}^{K} \lambda_p^k x_c^k \tag{3}$$

$$y_{as} \leq \sum_{k=1}^{K} \lambda_p^k y_{as}^k \tag{4}$$

$$y_{vmt} \leq \sum_{k=1}^{K} \lambda_p^k y_{vmt}^k \tag{5}$$

$$\theta \cdot y_r \leq \sum_{k=1}^{K} \lambda_p^k y_r^k \tag{6}$$

Node 3 (users' perspective):

$$x_f \geq \sum_{k=1}^{K} \lambda_u^k x_f^k \tag{7}$$

$$x_{tt} \geq \sum_{k=1}^{K} \lambda_u^k x_{tt}^k \tag{8}$$

$$y_{as} \geq \sum_{k=1}^{K} \lambda_u^k y_{as}^k \tag{9}$$

$$\theta . y_{pm} \leq \sum_{k=1}^{K} \lambda_u^k \, y_{pm}^k \tag{10}$$

y_{vmt}: Vehicle miles traveled, intermediate outputs from node 2 and intermediate input to node1;

y_e: Emission, output from node 1;

x_c: System operation cost (maintenance cost and administrative cost) incurred by the system provider;

y_{as}: Average speed, intermediate output from node 2 and input to node 3;

y_r: The total revenue obtained from the reservation system, an output of node 2;

x_f: Fuel consumption, input consumed by transportation users;

x_{tt}: Average travel time used by transportation users;

y_{pm}: Person miles traveled, final output from users' perspective.

$\lambda_p^k, \lambda_u^k, \lambda_c^k$ are non-negative.

Expressions (1) – (2) are associated with the technology of Node 1, (3) to (6) are associated with Node 2, and (7) to (10) are associated with Node 3. The objective is to find out a set of intensity variables $\lambda_n^{k_0}$ for each node. This allows us to identify an efficient hypothetical DMU that serves as a reference point for each DMU. The constraints guarantee that the hypothetical DMU consumes no more of each input and each intermediate product as does DMU k_0, and the hypothetical DMU produces at least as much of each product (i.e. final outputs and intermediate outputs) as does DMU k_0 at node n. Additionally, we assume that only the final outputs are scaled by factor θ and the intermediate outputs are not controllable. Similar to the standard DEA model, this (1) to (10) assume constant return to scale. For variable return to scale, three additional constraints are necessary:

$$\sum_{k=1}^{K} \lambda_u^k = 1 \tag{11}$$

$$\sum_{k=1}^{K} \lambda_c^k = 1 \tag{12}$$

$$\sum_{k=1}^{K} \lambda_p^k = 1 \tag{13}$$

5.   Results

Data used in this example are mostly obtained from a micro-simulation model which simulated the traffic conditions after the implementation of the DSRS. Different scenarios were simulated. The scenarios were varied in terms of the total demand level, the reservation policies and the uncertainty imbedded in the traffic flow itself. Altogether, there are 28 scenarios, thus 28 DMUs. Operational cost is assumed constant for all 28 DMUs. Table 1 shows the statistical summary for the data set.

Table 1: Summary statistics of the inputs and outputs data

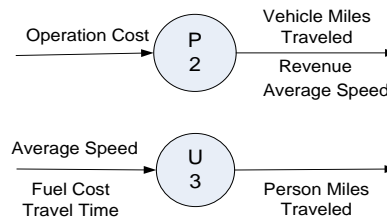|	Fuel Consumption	Avg. Travel Time	Revenue	Avg. Speed	Emission	Vehicle Miles Traveled	Person Miles Traveled
Mean	349.12	216.11	22251.7	12.83	34807.9	4179.25	14325.75
Minimum	299.91	176.96	20401.7	11.38	29901.1	3743.16	11385.04
Maximum	370.65	268.83	23679.8	13.21	36954.13	4366.56	16862.95
Standard Deviation	16.46	18.63	526.56	0.35	1639.837	151.25	1562.631
STD %	4.71%	8.62%	2.37%	2.72%	4.71%	3.62%	10.91%

Figure 3: Node 2 and Node 3

We first solved standard DEA models for each node individually (Figure 3), and then solved the network model. However, for the present analysis, we did not run the standard DEA for node 1 because of the undesirable output. According to the efficiency scores obtained from both the standard and network DEA model (Table 2), following observations were obtained: (1) if one of the two nodes is efficient (technical efficiency), then the network is efficient (technical efficiency); (2) the network efficiency score equals the efficiency score of one of the two nodes; (3) the network efficiency is dominated by the node with the lowest efficiency score; (4) the standard deviation in Table 1 suggests that the variation of the input and output data across the 28 DMUs is not significant. Therefore, it is not surprising that the efficiency scores may not differ by that much.

As the network model shows, each node has one set of intensity variables and each node has its own peers. For node 2, DMU2, 5, 10, 14, 18, 20, and 25 are considered as peers for the inefficient DMUs. Among them, DMU5, 18 are the most frequent peers. For node 3, DMU16 and DMU28 are the peers for all the other DMUs. The inefficiency associated with the nonzero slacks is referred as mix inefficiency [8]. In this example, only DMU28 is mix efficient according to this definition.

Table 2: Nodes efficiency and network efficiency (CCR)

DMU	Node 2	Node 3	Network	DMU	Node 2	Node 3	Network
1	1.0208	1.1642	1.0208	15	1.0368	1.0891	1.0368
2	**1.0000**	1.2598	**1.0000**	**16**	1.0152	**1.0000**	**1.0000**
3	1.0190	1.2831	1.0190	17	1.0026	1.0533	1.0026
4	1.0127	1.1652	1.0127	**18**	**1.0000**	1.1496	**1.0000**
5	**1.0000**	1.1063	**1.0000**	19	1.0218	1.0579	1.0218
6	1.0271	1.1112	1.0271	**20**	**1.0000**	1.2624	**1.0000**
7	1.0218	1.2448	1.0218	21	1.0068	1.1863	1.0068
8	1.0279	1.2283	1.0279	22	1.0105	1.0131	1.0105
9	1.0281	1.1668	1.0281	23	1.0042	1.0707	1.0042
10	**1.0000**	1.1814	**1.0000**	**24**	**1.0000**	1.1542	**1.0000**
11	1.0356	1.1468	1.0356	**25**	**1.0000**	1.0551	**1.0000**
12	1.0216	1.0227	1.0216	26	1.0142	1.0434	1.0142
13	1.0022	1.2573	1.0022	27	1.0077	1.0967	1.0077
14	**1.0000**	1.1237	**1.0000**	**28**	**1.0000**	**1.0000**	**1.0000**

Based on the preliminary results obtained in this example, further research is expected in following directions: (1) What further insights about the DSRS can be inferred from the efficiency scores, the peers and the slacks?; (2) How much is the structure of the network responsible for the (in)efficiency? Or another way of posing the same question is, how do interactions among the nodes impact performance?; (3) How much does the input/output data quality (in this case very little data variability) impact the results obtained? Addressing this issue would require conducting similar analyses using additional data sets.

Acknowledgements

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Appendix N Reviewers' Comments and Feedback on the 2nd Essay

Response to Reviewers

Evaluation of Travel Demand Strategies: A Microscopic Traffic Simulation Approach

We appreciate the comments of the reviewers. In order to address their comments we provide a major re-write and re-organization of the document so as to respond effectively to their comments. Because of the revision, some of the table and figure numbers in the current paper may not be the same as they were in the original document. In this response, the table and figure numbers of the revised paper will be displayed in parenthesis.

Reviewer 1

1. **Reviewer's Comment:** Introduction is too long, for my taste too much consideration why simulation is needed here – in my opinion, this is obvious.

    Response: The introduction section has been rewritten and the description of why simulation is needed has been condensed.

2. **Reviewer's Comment:** In the third paragraph of the introduction you remark "…support from all the stakeholders is needed."; please remark also here, that in addition not only research is needed how well such a DSRS will work, but additionally research is needed to find out what is needed to gain support from all the stakeholders – please add such a comment.

    Response: The comment has been added in the document (page 2).

3. **Reviewer's Comment:** Second paragraph of section 2: the efforts needed to run a micro-sim will getting smaller in the near future, due to better data and due to the fact that people are getting better with this tool. So, please mention this, otherwise the impression solidifies that micro-sim studies are usually very hard.

    Response: The comment is added in the document (page 4).

4. **Reviewer's Comment:**   Please give the number of trips actually performed; especially table 8 needs this information, and it explains some of the results (you only have mentioned it in the end, but it needs to be here). Additionally, clarify in the description of your simulation experiments what happens with the trips that are being rejected by the DSRS (again, you tell it only in the end).

    Response: The number of trips actually performed for each scenario has been added in Table 8 (currently Table 9). The rejected trips are assumed to be accommodated by other travel modes and departure times. The assumption has been addressed in the current version of the paper (page 4).

5. **Reviewer's Comment:** This one cannot be changed: I think the modelling of the traffic that is related in finding a parking lot is very poor. I would expect that a DSRS has a big advantage in this regard; it reduces this search-for-a-parking-lot traffic a lot. Since I cannot expect from you to do such a study

from scratch, you should mention somewhere that you have disregarded this explicitly, for whatever reason.

Response: The Downtown Space Reservation System (DSRS) itself is not about reserving parking. The main idea of DSRS is to ask the driver to reserve before driving into a downtown area. The DSRS is proposed as a cordon-based strategy. Similar to the cordon-based congestion pricing (e.g., London congestion pricing), there is a boundary that defines the reserving/charging area. Only the people entering the area will need to reserve in advance and pay the reservation fee. The exact parking location of vehicles is not considered by the DSRS. The parking lots defined in the simulation model are primarily for conducting the dynamic traffic assignment. However, it is worth noting that the behavior related to finding a parking lot does impact traffic congestion considerably in practice, as noted by the reviewer. However, such impacts are not considered in our current analysis. Within the same project (NSF Project #0527252), the impact of searching for a parking space is being studied separately (Roper and Triantis, 2009). The reviewer's comment also has been addressed on page 9 of the current version of the paper. What could be an interesting extension of this research is the study of the combined effect of the DSRS and an intelligent reservation parking system.

6. **Reviewer's Comment:** Please add a short description, how the DSRS works. It works on single parking lots, or on bigger car parks? And why is there a limitation to the number of parking lots in the DSRS, while in the scenario without DSRS car park space is unlimited?

Response: A description about the DSRS (Section 3, page 4) has been added in the current document. As explained in the previous comment, the DSRS is about reserving a right to enter the downtown area during certain time period. In the DSRS, the decision maker limits the number of trips entering the downtown area in order to provide less congestion conditions to the drivers that have made the reservation and whose request has been accepted. The maximum number of allowed vehicles is considered as a capacity constraint in the optimization formulation (page 7). For the scenario without DSRS the decision maker does not actively limit any of the trips entering the downtown area. Please refer to the previous comment as far as the consideration of parking garages in the downtown area.

7. **Reviewer's Comment:** May be, you can shorten the rather lengthy discussion about dynamic traffic assignment with VISSIM.

Response: The discussion about dynamic assignment has been condensed (page 14).

8. **Reviewer's Comment:** In Table 9, it is not clear to me, what is the difference between the ten scenarios? Please explain!

Response: In Table 9 (currently Table 10), we have changed the "demand scenarios" to "demand instances". The travel demand varies across these instances because of the stochastic variations associated with the number of arriving vehicles, entry/exit times, and occupancies. The average arrival rate is held constant at 7000 vehicles/3-hours.

9. **Reviewer's Comment:** In Table 12: which of the results are really statistically meaningful? It seems to me, that the difference in #people for 8:1 and for 1:0 is hardly significant? Please test!

Response: The purpose of Table 12 (currently Table 13) was to illustrate the sensitivity analysis. However, in order to address the statistical significance concern raised by the reviewer, we ran two additional pair-wise t tests. We chose w=0.5, w=0.89, w=1. The results are shown in Table 14 (page 22).

10. **Reviewer's Comment:** What is the difference between # of people and # of accepted trips? I thought that the DSRS could only change the #of accepted trips? So: please explain what is the meaning of the # of people?

   Response: # of accepted trips is the total number of accepted vehicles by the DSRS. Each vehicle may carry more than one person. # of people is the total people that have been accepted by the DSRS. We have changed the header of that column to "# of accepted vehicles" (Table 13). This hopefully makes the discussion clearer.

11. **Reviewer's Comment:** Conclusions: make your conclusions more careful; they are correct only within the limitations of your study, and as said above, I'm especially unhappy with the search-for-a-parking-lot traffic, and the difference with the capacity limitations of the DSRS and the unlimited normal and FCFS scenarios. Please mention this explicitly, I think this means that under a more general modelling approach the benefits of a DSRS should increase.

   Response: Changes to the conclusion section in the document have been made to make it clear that our conclusion is only based on the experiment conducted in this paper. Concerning the search-for-a-parking-lot traffic issue, it has been addressed in a previous comment (comment #5). For the differences associated with the three different scenarios, i.e., capacity limitations of the DSRS and the unlimited normal and FCFS scenarios, first of all, we want to clarify the notion of capacity, which is defined as the capacity of the transportation road network in the area, meaning how many vehicles the road network can accommodate. It is not the capacity of the parking lots. Furthermore, it is noted that the network capacity has to be satisfied in the DSRS, meaning that once the accepted number of vehicles equals the total network capacity, no request will be accepted for the period. For the FCFS reservation, the capacity constraint still has to be satisfied. Only in the case without the reservation system, the network capacity is not explicitly considered. VISSIM will accept all the trips entering the network during the simulation until it is constrained by the simulation itself.

Minor:

12. **Reviewer's Comment:** In equation (1), why is there the factor ½ ?

   Response: this equation is derived from the fundamental relations between speed, volume and density. The derivation steps are included in another paper which is under review at the moment (Zhao, Y., Triantis, K., Teodorović, D., and P. Edara, 2008). We include the derivation subsequently. However, due to space limitations we have not included this subsequent discussion in the current version of the paper.
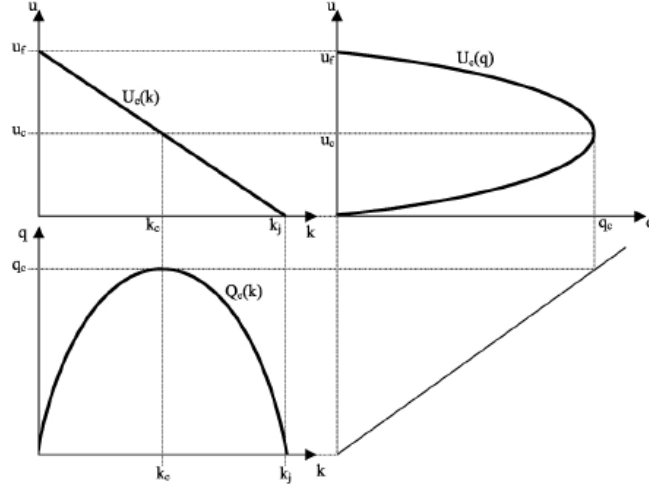
Figure 7: Fundamental Relationships

Greenshield assumed a number of fundamental relationships among speed (u), density (k) and flow (q) (Figure 7). The fundamental relationships are used here to derive a maximum number of vehicles on a link. The flow (q) by definition is number of automobiles (n) passing a point over time (t). We denote speed and density respectively by u and k.

$$q = \frac{n}{t} \qquad (1)$$

Travel time along observed link l equals:

$$t = \frac{l}{u} \qquad (2)$$

After substituting (2) into (1) we get:

$$q = \frac{n}{\frac{l}{u}} = \frac{n}{l}u = ku \qquad (3)$$

Speed-density relationship in Greenshields model is denoted as: $u = u_f (1 - \frac{k}{k_j}) \qquad (4)$

Combining relations (3) and (4, we get: $q = kv = kv_f (1 - \frac{k}{k_j}) \qquad (5)$

According to the definition of density, $k = \frac{n}{l} \qquad (6)$

Relation (5) can be written as: $q = q(n) = kv_f (1 - \frac{k}{k_j}) = \frac{n}{l} v_f (1 - \frac{\frac{n}{l}}{k_j}) = \frac{v_f}{l} n - \frac{v_f}{l^2 k_j} n^2 \qquad (7)$

In relation (7), traffic flow rate is a function of total number of vehicles in the link at that time. For any link, a maximum throughput is desired from a system view of point. To achieve this objective, maximum flow rate needs to be reached. The first order derivative of q(n) is:

$$\frac{dq}{dn} = \frac{v_f}{l} - 2n \frac{v_f}{l^2 k_j} \qquad (8)$$

The second order derivative: $\frac{d^2 q}{dn^2} = -2 \frac{v_f}{l^2 k_j} <= 0 \qquad (9)$

Relation (9) indicates the concavity of function q(n). Therefore we can obtain optimal solution at:

$$\frac{dq}{dn} = \frac{v_f}{l} - 2n \frac{v_f}{l^2 k_j} = 0 \qquad (10)$$

Solving equation (10) for n, we can get: $n^* = \frac{lk_j}{2} \qquad (11)$

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This is the maximum flow rate the link can reach. Under the maximum flow rate, the link achieves its maximum throughput. The combination of this number for a set of links (A) is called as a network capacity.

13. **Reviewer's Comment:** p. 18 , first line: (…) average speed "skyrockets" from (…) – skyrockets is not the scientifically appropriate word here, use something less journalistic like increases or so.

   Response: The sentence has been modified according to the comment (page 17).

Reviewer 2

1.   General comments:
Managing travel demand and devise management strategies which best match the demand and the network supply is of great importance. The paper presents an evaluation of the performance of a proposed travel demand management strategy, abbreviated DSRS, using microsimulation software VISSIM. It tested the strategy under a number of different travel demand scenarios and compared with other similar strategies. General conclusions were drawn on the sensitivity of the strategy to traffic congestion and suggestions were made as to the appropriate traffic conditions for the strategy and the choice of objectives it might help to achieve. In this sense the paper is addressing a relevant topic. In general the paper is written clearly.

The paper described in detail the micro-simulation tests in terms of the input data preparation, test scenarios, network description, demand inputs, and model outputs used. However, the paper omitted the core information on the proposed DSRS (stands for Dynamic Space Reservation System) on: how the system optimises the reservation process, how the system and the different reservation policies are modelled in VISSIM. Without such basic technical description of the system, the readers could not: (a) judge how truthfully was the system represented in the micro-simulation model; and (b) appreciate the results from the simulation.

For example, the paper described, in Section 4.3, the estimation of network capacity which it says was an essential input parameter to the DSRS and the model. But without any description on what its function is in the DSRS system and how this parameter is used in the microsimulation model.

As it seems that the authors have submitted a separate paper to a separate journal describing the full system and how it works. The information in that paper would, presumably, have included the above mentioned background information. However, that paper has not been published and therefore is not available in the public domain. Understandably, the authors do not wish to duplicate the material in this paper. But they are such vital information for the readers of this paper to understand and appreciate. It is pointless to just look at the simulation results, without knowing what they are supposed to represent!

There are simply too many assumed knowledge of the readers about DSRS. Perhaps a better dissemination strategy for the authors would be to submit this current paper as a follow-up to their other paper to the same journal (as a Part I and II series), and aim to have both published in the same edition/volume, so to give the readers a full picture. If the paper is to stand on its own, it does need to have a brief description of the essentials of the DSRS system, a diagrammatic illustration of its decision-making logics/processes, and how they are represented in VISSIM.

Response to the general comments: In order to address the omitted information on the DSRS, we have reorganized and rewritten the paper. A separate section has been added to provide some basic knowledge

of the DSRS (Section 3.0). Four additional figures have been added in the current document. Figure 1 and Figure 2 illustrate the decision making processes of the DSRS, and show how the system works in practice. Figure 5 and Figure 6 show how the DSRS is implemented in the VISSIM simulation, and how the simulation results are processed.

Specific comments:

2.   **Reviewer's Comment:** Abstract: It is generally not advisable to include reference in abstract, especially one not yet published. Instead, describe briefly what the DSRS is.

   Response: The abstract has been revised.

3.   **Reviewer's Comment:** P. 2, end of paragraph 2: reference to a paper does not need to include the page number.
   Response: The introduction section has been revised. This issue has been fixed.

4.   **Review's Comment:** P. 5 Table 1: In general, one needs to explain in the main text what the data presented in a table are. For example, under the title "Time of making request", the data (such as "08/11") look more like date than time. What does "Entry time" mean? Is it the time a request was made? Likewise, what is "departure time" – the time the person wishes to travel?

   Response: These issues have been addressed in the revised paper (page 6).

5.   **Reviewer's Comment:** P. 6 Step 2: In describing an individual vehicles' characteristics on "trip start/end time and start/end locations", please explain what their relationships are with the DSRS and the micro-simulation model.
   What are their roles in the DSRS system and how are they represented in the microsimulation model? For example, is the "trip start time" the driver's desired start time or the DRSR system allocated start time? Would the vehicle "enter" the network in the microsimulation model at this particular time? Is the "trip end time" the latest time a driver wishes to travel or the actual end-time of a trip? If the trip start/end times are both desired times, the simulation analysis should look at how much they differ to the DSRS resulted times. If they are the actuals, what are their roles in demonstrating the performance of the system?

   Response: The trip start/end time indicates the time of a vehicle enters and the time a vehicle departs the network respectively.   As stated in the previous response, we have added a new section describing the DSRS in more detail.   In this section, the optimization module, which is the foundation of the DSRS, is presented.   The trip start and end times are needed as inputs to the optimization module.   In the simulation, the desired entry and exit times and locations are entered as inputs.

   Although, vehicles will enter the network at their desired entry times, it may not be possible to depart at the desired exit time due to network congestion. For the demand scenarios shown in section 5.3, all the vehicles are able to enter the network in both cases – with and without DSRS. However, regarding the departure times trips, 97% vehicles are able to leave the network during the simulation period when the DSRS is used, and 89% vehicles are able to leave the network without the DSRS. This is because congestion mainly occurs in the inner network, not at the boundary links of the network. In addition, observing other measures (Table 9) such as average delay, total path distance the DSRS also improves the overall network performance significantly.

6. **Reviewer's Comment:** P. 6 Step 3: What are the independent variables used to represent the different reservation policies? What and how they would alter the behaviour of the micro-simulation model?

   Response: The independent variables used to represent the different reservation policies are the relative weights assigned to the people throughput and the reservation revenue of the objective function of the optimization approach. The section about the experiment has been rewritten and reorganized to incorporate the comment that a brief description of the DSRS is needed in the paper. Therefore, the independent and dependent variables used in the experiment are indicated in the description of the experimental procedure, and they are not separately listed any more. The relative weights assigned to the people throughput and revenue impacts the decision as to which requests will be accepted. And fundamentally, the accepted requests will determine what types of vehicles will show up in the VISSIM network.

7. **Reviewer's Comment:** P. 13 example of trip chain file: suggests to remove AN1, AN2 and MST2 as they are not relevant to the current study.

   Response: The document has been revised according to the reviewer's comment.

8. **Reviewer's Comment:** P. 13 last para: what are the "utility functions and logit functions" used?

   Response: Given that the reviewers requested that we make our presentation more concise, one of the discussions deleted from the paper had to do with the use of the utility and logit functions. Since we do not mention these functions in the current version of the paper, we do not include the following discussion which is provided as an answer to the reviewer's comment.

   The utility and logit functions used in the traffic assignment are defined by the VISSIM software as follows (PTV, 2007):
   The utility function of a parking lot is defined as:

$$U_{k,s} = \alpha_{k,s} \cdot C_{parking}$$
$$+ \beta_{k,s} \cdot attraction$$
$$+ \gamma_{k,s} \cdot D_{dest}$$
$$+ \delta_{k,s} \cdot D_{veh}$$
$$+ \varepsilon_{k,s} \cdot fs$$

where
$Cpark$ = parking cost
$Ddest$ = direct distance between parking lot and the destination zone´s center of gravity
$Dveh$ = general cost of best route from current vehicle position
fs = availability of free parking spaces
k = index of the vehicle type
s = index of the decision situation (departure, routing decision...)

Kirchhoff distribution formula computes the probability of route j to be chosen:

$$p(R_j) = \frac{U_j^k}{\sum_i U_i^k}$$

where
Uj = utility of route j

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$p(Rj)$ = probability of route j to be chosen
k = sensitivity of the model

Actually the Kirchhoff distribution formula can be expressed as a Logit function, if the utility function is transformed to be logarithmic:

$$p(R_j) = \frac{U_j^k}{\sum_i U_i^k} = \frac{e^{k \cdot \log U_j}}{\sum_i e^{k \cdot \log U_i}} = \frac{e^{-k \cdot \log C_j}}{\sum_i e^{-k \log C_i}}$$

where Cj is the general cost of route j.

Reviewer 3

I have mixed feeling about this paper. On one hand, the topic is of potential interest and application of a traffic micro-simulation model for different TDM forms is an important avenue. On the other hand, throughout the paper, I have been struggling with numerous technical aspects that I have not been able to understand since they are described in a brief "black-box" fashion. It leaves me with kind of a "rabbit-in-a-bag" feeling that makes it difficult to unambiguously recommend or reject the paper for publication. More specific comments and questions are listed below:

1. **Reviewer's Comment:** Some more description of the Downtown Space Reservation System (DSRC) in real-world terms is needed. How exactly can this system be implemented? What is the underlying technology and communication media? Phone, Internet? How are the control and enforcement going to be implemented? How early should a request be submitted and how long will it take to respond? What if the permission had been received for a vehicle entry up to a certain hour and then it proved that the person needs to stay in the Downtown area for a longer period of time? Is this system realistic at all?

   Response: A section on the implementation issues of the DSRS has been added in the revised paper (page22). We hope that this section addresses the reviewer's concerns.

2. **Reviewer's Comment:** How does this system compare to pricing forms in a broader sense (like congestion area pricing or dynamic pricing)? Is not the necessity to request permits is additional hassle for the users where variable pricing would be simpler and as effective a form? How about equity that is an important consideration for substantiation of a pricing form in practice?

   Response: There are some similarities and differences between DSRS and congestion pricing. Both are travel demand management strategies that address the congestion problem by adjusting the demand for a given supply. The DSRS differs from congestion pricing in the sense that it can provide more reliable traffic conditions because the travel demand is known in advance. In a congestion pricing situation, the travel demand is not known (or uncertain) until vehicles actually show up on the roadway. On the other hand, in a DSRS the decision maker (e.g., a state transportation agency) has more control over the transportation system (since the uncertainty in demand is removed) and hence can aim to maximize the system performance to the fullest extent. The DSRS is more equitable than congestion pricing in the sense that drivers who reserve well in advance (and help reduce demand uncertainty) don't have to pay the same amount as the drivers reserving at a later time point. In this way, the system is fair towards low income drivers as well by providing an option to reserve early. The evaluation of the congestion pricing as a travel demand strategy is being evaluated as part of the same research project (Liu, Triantis and Sarangi, 2009)

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3. **Reviewer's Comment:** More detailed mathematical description of the optimization algorithm is needed. How is each request processed and why does it have an advantage versus First Come First Serve (FCFS) strategy? It also seems that the maximum Revenue criterion will be heavily dependent on the adopted pricing form. For example, if large vehicles are subject to higher price, the algorithm should reject them more frequently, etc. The same with the price differentiation by entry hours, exit hours, and duration. Where are the details of the pricing forms and differentiation?

Response: A brief description about the DSRS (Section 3) has been added in the revised paper (including the mathematical formulation of the optimization model). We have also included a diagram to illustrate how the DSRS works (Figure 1 and Figure 2). To answer these questions more clearly, we would like to state the following subsequently:

Each request is submitted to the decision making centre through internet, phone, local offices just like any other reservation system such as airlines, hotels, etc. Under both the DSRS and FCFS reservation, network capacity has to be honored. According to the analysis in Section 5.4, the DSRS outperforms the FCFS in terms of the total number people and revenue obtained from reservation. This means that with the same capacity, the DSRS can serve more people and collect more revenue than the FCFS reservation.

For the question that the revenue criterion will be heavily dependent on the adopted pricing form, we are maximizing two objectives at the same time, and the revenue maximization and people throughput maximization somehow impact each other. A larger vehicle subject to a higher price may or may not have a higher possibility of being rejected. This is because a large vehicle pays a higher price and from a revenue point of view, it is actually more possible for it to be accepted. However, from a capacity constraint point of view, it could be rejected because it consumes more space than a smaller vehicle. Therefore, whether a request is accepted or not is not solely determined by how much the requestor pays, but also by how much is required in terms of capacity. The pricing mechanism used in the experiment is shown in Table 2 (page 6). The price is arbitrary, and only used for illustration purposes in this study.

4. **Reviewer's Comment:** The number of rejected trips represents an interesting statistic. Each rejected trip has an associated disutility that might change the evaluation of strategies. What if the rejected trip is for medical reasons or represents an important appointment? Since this cannot be verified, there should be a way for a traveller to buy a trip at a higher price if it was rejected.

Response: This is certainly an important and relevant issue raised by the reviewer. The intent of this paper is to present the basic idea of DSRS, a mathematical model of such a system, and illustrative examples using simulation to describe the effectiveness of this system at reducing congestion in downtown areas. The intent, however, was not to comprehensively address all the issues that will arise from a DSRS deployment. This is simply not possible to do at a proof-of- concept stage. We have included a section on implementation and social issues in the revised paper (page22) that describes this and other relevant issues that are critical for the DSRS implementation.

5. **Reviewer's Comment:** (Page 5, Table 1) Entry and Exit times are requested with an unrealistic level of accuracy that cannot be known by the travellers in advance. Also, it is not clear how the PCU coefficient is assigned. Based on the vehicle type and size?

Response: In the DSRS, the entry and exit time are aggregated into five-minute intervals in the simulation experiment. The display of the entry and exit time has been changed in Table 1 (Page 6) to show the data that were actually used in the example.

In addition, PCU is assigned to different vehicle classes according to the general guidelines from VTPI (www.vtpi.org), which indicates that large trucks and buses tend to be equivalent to 1.5-4 PCUs depending on roadway conditions, and a large SUV are equivalent to 1.4 PCUs and a van 1.3 to PCUs when travelling through an intersection. Therefore, in this simulation example, we assume that SOV and HOV is equivalent to 1 or 1.4 PCUs, Bus is equivalent to 3 PCUs, and Truck is equivalent to 4 PCUs

6. **Reviewer's Comment:** (Page 7) Since DSRC operates with both entry and exit times (i.e. accounts for the duration of stay in Downtown) I do not quite understand the discussion on the simulation time horizon and decision to model the AM period only. Most of the trip chains to-and-from Downtown will fall out of this narrow window at least partially. I'm getting lost at this point.

   Response: In the illustrative examples described in the paper, the DSRS is assumed to be operating only during the AM peak period, when heavy traffic enters a downtown region. The DSRS needs the exit time of a trip in order to, 1) compute the available network capacity at future time points, and 2) to compute the reservation fees for the trip. As pointed out by the reviewer, it is true that some of the trip chains will fall out of this AM peak period window. In such cases, only the portion of the trip chain that occurs during the reservation period (in this case AM peak period) determines the available allocation capacity and the reservation fees.

7. **Reviewer's Comment:** (Page 9, Table 2 (Table 5) and page 12, Table 3) I find the definition of demand scenarios too narrow. It is based on a single parameter of arrival rate, while the trip generation rates by entry points are assumed fixed.

   Response: The demand scenarios were chosen so as to represent a range of traffic conditions – from light traffic to heavy traffic conditions. In the revised paper, we also varied the trip generation rates by entry points as suggested by the reviewer. We conducted additional simulations for demand scenarios S1 and S5 with different trip attraction rates (attraction percent in Table 3). The original simulation assumes that all the trips produced by all entry points are evenly distributed over all four zones (attraction percent in Table 3). The new study assumes that the trips are distributed according to the total miles of roads in a zone. For example, if the total road miles in a zone is 20% of the total road miles of the entire network, 20% of the total generated trips will be distributed to that zone. The results of the new study are shown in Table 2 below. As before, the DSRS clearly outperformed the base case for both scenarios. Due to space limitations of the paper, we have not included this table in the revised paper. However, we do mention (Page 9) that a sensitivity analysis of the trip attraction rates yielded similar results.

Table 1 (Table 3 in the paper): Trip Generation

Entry Points	ZONE1	ZONE2	ZONE3	ZONE4	Production	Production Percent (Production/Total Trips)
1	25	25	25	25	100	1.54%
2	191	191	191	191	764	11.78%
4	46	46	46	46	184	2.84%
6	167	167	167	167	668	10.30%
8	23	23	23	23	92	1.42%
9	200	200	200	200	800	12.34%
11	242	242	242	242	968	14.93%
12	121	121	121	121	484	7.46%
13	65	65	65	65	260	4.01%
14	75	75	75	75	300	4.63%
15	116	116	116	116	464	7.16%
18	225	225	225	225	900	13.88%
22	57	57	57	57	228	3.52%
20	25	25	25	25	100	1.54%
21	43	43	43	43	172	2.65%
Attraction	1621	1621	1621	1621	6484	
Attraction Percent	25%	25%	25%	25%		
Attraction Percent*	20%	27%	29%	24%		

Table 2: VISSIM results with New Attraction Percent*

		Average delay time per vehicle [s]	Average speed [mph]	Total travel time [h]	Total Path Distance [mi]	Total delay time [h]
S1 (λ=7000)	with dsrs	534	13.05	311	4059	157
	no dsrs	694	12.3035	394	4844	210
	%	-23.13%	6.07%	-21.03%	-16.22%	-25.18%
S5 (λ=7800)	with dsrs	538	12.806	307	3926	157
	no dsrs	1335	7.0513	1101	4382	935
	%	-59.73%	81.61%	-72.14%	-10.41%	-83.17%

8. **Reviewer's Comment:** (Page 12) In Table 4, there is a deterministic one-to-one correspondence between entry and exit points. In Figure 2, it seems a many-to-many probabilistic correspondence. Which one was actually implemented?

   Response: Figure 2 (currently Figure 4) shows all the possible combinations, and Table 4 was actually implemented.

9. **Reviewer's Comment:** (Page 14) The definition of network capacity is not linked to the optimization algorithm. How is it used? Also, it seems that the summation in formulas (1) and (3) is done over all links in the network without distinction of bottleneck facilities.

Response: The optimization formulation has been added in the revised paper. Relation (5) on page 7 shows how the optimization module is linked to the network capacity constraint. The right-hand side is the network capacity.

The detailed definition of network capacity has been addressed in another paper which is under review at the moment. We would like to use what we have in that paper to address the question about network capacity in this paper as well.

In highway management, capacity has been measured in passenger car units (pcus)/hour for a highway segment. The actual capacity can be measured at a certain point of the highway by counting the number of vehicles passing through that location during the hour. For a network with one origin, one destination, and one user class, the capacity is determined by the minimum of cut-set capacities (Bell and Iida, 1997). However, for more general networks with multiple origins, destinations, there is no method for determining an area-wide road network capacity (Bell and Iida, 1997). Therefore, an open question is how to define the area-wide road network capacity. In this research, we propose a method of dealing with capacity determination based on the fundamental traffic flow theory based on volume, density and speed. The approach is described in the response to Reviewer 1 comment #12.

Several other directions could provide alternative methods regarding the determination of capacity. One direction is to derive capacity from the intersection capacity as transportation professionals argue that traffic speed and flow on urban streets are determined primarily by intersection capacity. Another way of dealing with the determination of capacity is to take into account the routing problem, which is essentially the traffic assignment model. The potential approaches may not be confined to these.

Due to space limitations of the revised paper, we did not include this detailed explanation in the paper. However, if the reviewer suggests we include it, we will try to condense some other text to incorporate this information.

10. **Reviewer's Comment:** (page 15) It has to be better explained what is the difference between Table 5 (produced with the same random seed) and Table 6 (different random seeds). If the same seed is applied, what is the source of variation across runs in Table 5?

    Response: We have revised this paragraph to better explain the two tables. First, the dynamic assignment algorithm (DA) is run until it converges for a single random seed (R1). The obtained routes are then entered into the simulation model and the model is run for random numbers R2 to R10. These results are shown in Table 5 (now Table 6 in the revised paper). The source of variation comes from the stochastic arrivals as in a typical simulation model. Next, the DA algorithm is independently run for each random seed (R1 to R10) and allowed to converge. These results are shown in Table 7.

11. **Reviewer's Comment:** (Page 17) It should be explained why we obtain more vehicle trips the mileage drops for some scenarios. Does it mean that the trips have not been completed? Or the chosen trips are relatively shorter?

    Response: The trend noted by the reviewer happens for scenario S6 in Table 9. There were 4812 vehicles trips entering the network in the case of the DSRS and there were 6284 vehicles entering the network without the DSRS. However, the total path distance (3936) without the DSRS is lower than the distance (4114) with the DSRS. This happened mainly because of vehicles not being able to

complete their trips due to excessive congestion in the network (the average delay per vehicle was 3 times higher for the without DSRS case).

References

Liu, S. Triantis, K. and Sarangi, S., A framework for evaluating the dynamic impacts of a congestion charging policy for a socioeconomic transportation system, under review Transportation Research Part A, 2009

PTV, VISSIM 4.30 User Manual, 2007

Roper, M. and Triantis, K., Modeling the Effects of Parking Revenue Management and Intelligent Reservations on Urban Congestion Levels, *Proceedings of the 2009 Industrial Engineering Research Conference,* p. 468-473

VTPI, www.vtpi.org, 2009

Zhao, Y., Triantis, K., Teodorović, D., and P. Edara, A Travel Demand Management Strategy: The Downtown Space Reservation System, under review European. Journal of Operational Research, 2008

Bell, M. G. H. and Lida, Y., 1997. Transportation Network Analysis. John Wiley & Sons, New York.

Appendix O Reviewers' Comments on the 1st Essay

Reviewer #1:

PLEASE INDICATE YOUR ANSWER BY ENTERING AN X IN THE APPROPRIATE FIELD.
PLEASE USE THIS SCALE:
 False = 1
 Rather false = 2
 Questionable = 3
 Rather true = 4
 True = 5

 General Judgment

The author is familiar with the existing state of knowledge.
1____ 2____ 3____4____   5__x__

The topic is relevant to the scope of EJOR.
1____ 2____ 3____4____   5__x__

This is a new and original contribution.
1____ 2____ 3____4____   5__x__

The paper makes a valuable contribution to the practice of OR.
1____ 2____ 3____4____   5__x__

The title is appropriate.
1____ 2____ 3____4____   5__x__

The abstract and keywords are adequate.
1____ 2____ 3____4____   5__x__

The paper is logically and technically correct.
1____ 2____ 3____4____   5__x__

The interpretations and conclusions are sound and justified by the results.
1____ 2____ 3____4____   5__x__

The paper is well presented and organized.
1____ 2____ 3____4____   5__x__

The writing style/English is clear and understandable.
1____ 2____ 3____4____   5__x__

The paper is of the right length.
1____ 2____ 3____4____   5___x_
If not, please explain:

The references are adequate.
1____ 2____ 3____4____   5__x__

Rating of this paper in comparison to similar papers published in
top-rated scientific journals:

____ Below publ. level
____ Bottom 20%
____ Below average
____ Average
____ Above average
___x_ Top 20%

Excellent literature review and context of the problem.

It would be helpful to know how many cities have need of such a DSRS
and the size of the cities.

Page 8, line 10:
Historical demand and reservation information are assumed attainable.

Page 8, line 11: Please note that standard traffic counts, VOR
counts, parking capacity, even Census data, give an initial estimate
of reservation demand and capacity (line 51). (as eventually noted on page 18).

Page 11, line 47: It seems impractical to track and enforce auto
occupancy in order to maximize people in the cordon area.

Page 16+: Neural network methodology explained in an approachable
qualitative manner with example.

Page 18, line 39: Data . are.

 Page 18: A brief note on data acquired at the traffic observation stations would be helpful. A citation to
indicate feasibility of data collection and enforcement would be helpful.

Page 20: The congestion mitigation effects sound intriguing. Look forward to a simulation in the second
paper.

Pages 20, 21: Discussion of implementation issues is appreciated and down played. They are significant.

Page 22: ". the mobility of people is improved by restraining the excessive amount of automobiles entering the area." This statement would be hotly debated by commuters and visitors and depends on location, perspective, and alternative modes available. The statement should be less assertive pending additional studies. The conclusions regarding the methodology are more appropriate for this paper.

Overall - well written, innovative approach, easy to read, worthy paper for publication. Look forward to the next follow-on paper.

Reviewer #2:

PLEASE INDICATE YOUR ANSWER BY ENTERING AN X IN THE APPROPRIATE FIELD.

PLEASE USE THIS SCALE:
False = 1
Rather false = 2
Questionable = 3
Rather true = 4
True = 5

General Judgment

The author is familiar with the existing state of knowledge.
1____ 2____ 3____ 4_x__   5____

The topic is relevant to the scope of EJOR.
1____ 2____ 3____ 4____   5__x_

This is a new and original contribution.
1____ 2__x_ 3____ 4____   5____

The paper makes a valuable contribution to the practice of OR.
1____ 2_x_ 3____ 4____   5____

The title is appropriate.
1____ 2____ 3_x__ 4____   5____

The abstract and keywords are adequate.
1____ 2____ 3____ 4_x__   5____

The paper is logically and technically correct.
1____ 2_x__ 3____ 4____   5____

The interpretations and conclusions are sound and justified by the results.
1____ 2____ 3__x_4____   5____

The paper is well presented and organized.
1____ 2____ 3_x__4____   5____

The writing style/English is clear and understandable.
1____ 2____ 3____4__x_   5____

The paper is of the right length.
1____ 2____ 3__x_4____   5____
If not, please explain:

The references are adequate.
1____ 2____ 3____4_x__   5____

Rating of this paper in comparison to similar papers published in top-rated scientific journals:

____ Below publ. level
___ Bottom 20%
__x_ Below average
____ Average
____ Above average
____ Top 20%

The main purpose of the research paper is to provide the transportation authority an analytical model when considering building an area transportation control system. The authors applying the reservation mechanism (from the models for highway system) into urban system is a superior idea.This paper also demonstrates that the neural network module can resemble the optimal solution within an acceptable error range.

The reservation system in this paper deals with the decision of whether to accept or reject an application for an area entrance permit. As the authors mentioned, several framework and models have been developed in prior research; for example, Edara and Teodoravic (2008) proposed a highway space inventory control system with a real-time neural-network based on decision making subsystem. Thus, this new application (not a new idea, new method, or new framework) makes a less contribution to the field of transportation reservation system research Some major Comments to the authors:

(1)   The major flaw in this paper is the construction of objective function.
Transportation system always serves as infrastructure to provide the activities of daily living and business for residence. In order to provide a better service, government needs to utilize the traffic management to reduce the inefficiency of transportation system. Maximizing the revenue from road pricing is not an objective for traffic authority. The main purpose in this reservation system for public goods should be to provide a fair and efficient mechanism for society. Therefore, social welfare maximum or system cost

minimum should be a more appropriate objective (see, e.g. Yang and Huang (1998), Verhoef (2002), Edara and Teodoravic (2008)). From the society point of view, the road fee is a transfer from road users to government which will not increase or decrease the social welfare. The revenue issue could be considered as a constraint for self-financing.

(2)   The authors emphasized the proposed DSRS strategy is to work togetherwith other TDM strategies (for example, congestion pricing). However, in this paper, the authors did not mention how their proposed DSRS work with other strategies. The authors should demonstrate the value-add for their supportive TDM strategy. The results of this paper do not echo its purpose. In other word, this paper failed to show how the reservation system can potentially work within a congestion context for a downtown area to perform a better traffic management scheme.

(3)   Some critical discussions of the computational process are ignored. For example, the accepted rate of off-line optimal results and the corresponding distribution of vehicle class; the comparison of the results of neural network outputs, optimal output, and current real data. Understandably, to reject some vehicles for using transportation system (reduce the number of vehicles on road) will lessen the congestion. The key issue is to provide a fair and effective reject system (reservation system). The current study failed to prove the proposed system could deal with the issue of fairness.

(4)   How this system deals with the fake information (vehicle type, entertime, or departure time) providers? Does this system need to monitor all the vehicles inside this urban area (or just at the cordon)? The privacy issue and the cost of enforcement should be addressed.

(5)   The authors split the decision mechanisms into two parts: off-line optimal decision module and on-line artificial intelligent module. The on-line artificial intelligent module is trained and tested by the output of the off-line optimal decision module. Is the output of the integer optimal programming unique? If not, what the non-uniqueness effects the proper (not only concerning the correction of test result) of neural network process? In addition, authors should consider the impact of path dependence (rigorous ofresult) for using an artificial process.

(6)   Some important issues related to a reservation system (include the cancellation, late/early show up, traffic incident impacts) are briefly described as the future research issues. I suggest authors incorporate these issues into their intelligent system.

 References:
H Yang, HJ Huang, 1998, Principle of marginal-cost pricing: how does it work in a general road network? Transportation Research Part A, 32A, pp. 45-54

Verhoef, E.T., 2002. Second-best congestion pricing in general static transportation networks with elastic demands. Regional Science and Urban Economics 32, pp. 281-310.

Reviewer #3:

PLEASE INDICATE YOUR ANSWER BY ENTERING AN X IN THE APPROPRIATE FIELD.

 PLEASE USE THIS SCALE:
 False = 1
 Rather false = 2

Questionable = 3
Rather true = 4
True = 5

General Judgment

The author is familiar with the existing state of knowledge.
1____ 2____ 3____4__X_   5____

The topic is relevant to the scope of EJOR.
1____ 2____ 3____4____   5__X__

This is a new and original contribution.
1____ 2____ 3____4__X_   5____

The paper makes a valuable contribution to the practice of OR.
1____ 2____ 3__X__4____   5____

The title is appropriate.
1____ 2____ 3____4____   5___X_

The abstract and keywords are adequate.
1____ 2____ 3____4____   5__X__

The paper is logically and technically correct.
1____ 2____ 3____4__X__   5____

The interpretations and conclusions are sound and justified by the results.
1____ 2____ 3____4__X__   5____

 The paper is well presented and organized.
1____ 2____ 3____4____   5__X__

The writing style/English is clear and understandable.
1____ 2____ 3____4____   5__X__

The paper is of the right length.
1____ 2____ 3____4____   5_X___
If not, please explain:

The references are adequate.

1____ 2____ 3____ 4__X__   5____

Rating of this paper in comparison to similar papers published in top-rated scientific journals:

____ Below publ. level
____ Bottom 20%
____ Below average
____ Average
___X_ Above average
____ Top 20%

This is a very interesting paper, presenting a novel approach to travel demand management in cities. It is clearly written, and maintains an appropriate balance between analysis and practical application.

Since the method is novel, the paper makes a number of simplifying assumptions which are in the main clearly identified. I have concerns over a few of these:

1.   The difference between inflow and outflow is compared with "capacity"(p9). In practice, as noted briefly on p14, two capacities are involved:that of the network for moving vehicles, and that of the parking stock while they are stationary. It would be helpful to discuss how the latter should be considered.

2.   On p11, the goal of TDM is proposed to be "placing more people in fewer vehicles". This is in practice a rather limited definition. Most policy focuses on optimising social welfare, which can result in some journeys not being made. Several papers in the field of road pricing optimise against this more complex objective. It would be helpful to acknowledge this complication.

3.   On p13 it is suggested that there is no method for determining area-wide road network capacity. There are in practice methods for doing so (and references can be offered if desired), but it is true that capacity depends on the distribution of origins and destinations. It is important to note that the assumption in the second paragraph on p14 is wrong; in a network which is at capacity, certain links will be significantly below capacity.

4.   A key issue for the analysis of benefits, as hinted on p21, will be to consider the alternatives which those whose applications are rejected will adopt. This can critically affect the overall evaluation.

None of these considerations makes the paper unacceptable, but it would be helpful to reflect them in the final version

I recommend that, subject to doing so, the paper be accepted for publication.

In publishing, the authors should note two minor errors:
*   The author of the seminal traffic flow theory is Greenshields, not Greenshield.
*   In the sentence after (Daganzo, 1997) on p13, the final word "flow" should be deleted.

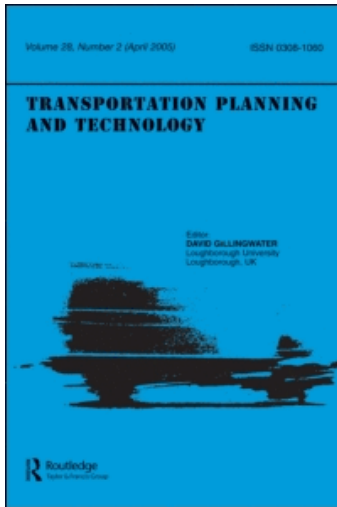# Appendix P Auction Based Congestion Pricing Paper

Transportation Planning and Technology

Auction-Based Congestion Pricing

Dušan Teodorovi [a]; Konstantinos Triantis [b]; Praveen Edara [c]; Yueqin Zhao [b]; Snežana Mladenovi [a]
[a] Faculty of Transport and Traffic Engineering, University of Belgrade, Belgrade, Serbia, USA [b] Virginia
Polytechnic Institute and State University, VA, USA [c] Virginia Transportation Research Council,
Charlottesville, VA, USA

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ARTICLE

Auction-Based Congestion Pricing

DUŠAN TEODOROVIĆ*, KONSTANTINOS
TRIANTIS**, PRAVEEN EDARA†, YUEQIN ZHAO**
& SNEŽANA MLADENOVIĆ*

**Faculty of Transport and Traffic Engineering, University of Belgrade, Belgrade,
Serbia, USA; **Virginia Polytechnic Institute and State University, VA, USA &
†Virginia Transportation Research Council, Charlottesville, VA, USA*

ABSTRACT Planners, engineers and economists have introduced various demand
management methods in an attempt to reduce the fast growing traffic congestion.
The basic idea behind various demand management strategies is to force drivers
to travel and use transportation facilities more during off-peak hours and less
during peak hours, as well as to increase the usage of underutilized routes. In this
paper, a new demand management concept – Auction-based Congestion Pricing –
is proposed and modeled.

KEY WORDS: Demand management; strategies; congestion pricing; auction

Introduction

The number of trips by private cars has significantly increased in recent
decades in many cities around the world. Urban road networks in many
countries are severely congested, resulting in increased travel times,
increased number of stops, unexpected delays, greater travel costs,
inconvenience to drivers and passengers, increased air pollution and
noise levels, and increased number of traffic accidents. Expanding
traffic network capacities by building more roads is extremely costly as
well as environmentally damaging. More efficient usage of the existing

supply, by spreading the peak demand onto off-peak hours, is vital in order to sustain the growing travel demand.

Planners, engineers and economists have introduced various *transportation demand management* (TDM) methods in an attempt to reduce the fast growing traffic congestion (park-and-ride, high occupancy vehicle lanes (HOV), HOT lanes, ridesharing and transit use, congestion pricing, parking pricing, telecommuting, alternative work hours, increased fuel tax/mile fee). TDM is a common term for various activities that advocate a decrease in the demand for existing transportation systems. Demand management actions also force transportation network users to travel and use transportation facilities more during off-peak hours. Some of the demand management strategies could advance the transportation choices accessible to users. Some other demand management strategies generate changes in departure time, route choice, destination or mode choice. Successfully planned and implemented demand management strategies can result in significant toll revenues, decrease in total number of vehicle trips, decrease in total number of vehicle trips during peak periods, increase in the number of vehicle trips during off-peak periods, increase in ridesharing, rise in public transit rider ship, and in some cases increased cycling, walking, and tele work. It should be noted that some of the demand management strategies have been already successfully implemented.

The concept of congestion pricing (value pricing) is to charge road users with different fees during different traffic conditions. Various fees or tolls that vary with a location in the network, time of day and/or level of traffic congestion have been proposed. In other words, drivers should pay for using specific road, corridor, bridge, or for entering particular area during some time periods. The basic idea behind the concept of congestion pricing is to force drivers to travel and use transportation facilities more during off-peak hours and less during peak hours, as well as to increase the usage of underutilized routes. Various congestion pricing models have been developed during the last four decades. Some of them have been already implemented. The widely known implementations are in Singapore Phang and Toh (2004), Hong Kong, London and Stockholm. William Vickrey, winner of the Nobel Prize for Economics, is considered among researchers as the 'father' of congestion pricing concepts Vickrey (1955, 1963, 1969, 1994). Following the pioneering work of Vickrey (1955, 1963, 1969, 1994), many researchers studied various aspects of the congestion pricing problems Verhoef *et al.* (1995), Sullivan and El Harake (1998), Yang and Huang (1998, 1999), Verhoef (2002), Zhang and Yang (2004), Kockelman and Kalmanje (2005), Teodorović and Edara (2005) and Teodorović and Edara (2007).

In this paper, a new demand management concept – what we call *Auction-based Congestion Pricing* – is proposed and modeled. The

paper is organized as follows: Section 'Auctions' explains the basic principles of auctions while Section 'Auction-Based Congestion Pricing: Downtown Time Slot Auction' presents the model of the problem considered, and Sections 'Solving the Downtown Area Time Slot Auction Problem' and 'Internet Downtown Time Slot Auction Issues' the proposed solution approaches and modeling issues, respectively. This paper includes a numerical example in Section 'A Numerical Example' while conclusions are offered in Section 'Conclusions'.

Auctions

The auction represents a *market-based* procedure Portera *et al.* (2003), de Vries and Vohra (2003) and Fang *et al.* (2004) in which an item or a collection of items is sold on the basis of *bids* (prices offered by the auction participants for the item being auctioned). The auction participants are also called *bidders*, or *agents*. Post stamps, old coins, paintings, old automobiles are typical items that are frequently auctioned. Recently, many services have started also to be auctioned. For example, the US Federal Communications Commission (FCC) created a great application of Game Theory in 1996. The auction participants played 112 rounds with open bids while competing for rights to operate wireless personal communications services. Nevertheless, depending on the items being auctioned, auctions may be performed online or offline. Most frequently auctions are conducted with respect to one item (service). In this case, there are multiple auction participants (buyers) trying to buy the auctioned item. In the case of the so-called *reverse auction* there are multiple sellers (manufacturers, operators) trying to sell the product (service) to one buyer. The *English auction* is a sequential auction in which bidders try to beat the current bid. Any new bid must increase the current bid by a previously defined increase. The *English auction* finishes when no bidder is ready to beat the last offered bid. The winner of the English auction is the bidder who offered the *last bid*. They then pay the amount they bid.

On the other hand, the *Dutch auction* starts with the initial price much higher than any bidder is willing to pay. The price is decreased little by little until one of the bidders expresses their willingness to pay. The auction is then finished and the winner pays the amount they indicated. The price never goes below the minimum price set up by the auctioneer. This auction type is a widespread market mechanism for selling flowers in Holland.

There are a few other forms of auctions. *First price auction* is an auction where the winner is the auction participant who *submits* the highest bid. They then pay the amount they bid. In a *Vickrey auction*,

all auction participants submit bids simultaneously. The highest bidder is the winner. In the end, the winner pays the *second-highest bid* offered. Finally, in *combinatorial auctions,* bidders compete to buy many different but related items. Every auction participant makes one or more bids for any of the possible item combinations. If not all requested resources are assigned to the bidder, the partial acquisition of the resources has *much less value* for the bidder.

The *winner determination problem* in the case of combinatorial auctions could be defined in the following way: Identify the winning set of bids that maximizes revenue of the auctioneer. It has been shown that this winner determination problem is a NP-hard problem. In reality, auction participants make bids only for a limited number of item combinations. An auctioneer frequently prescribes the *maximum number of bids* per auction participant in order to reduce the problem dimensions. Combinatorial auction mechanisms have been proposed as a convenient tool for allocation of resources in public services (electromagnetic spectra, time slots for landing at airports, etc).

Auction-Based Congestion Pricing: Downtown Time Slot Auction

The basic ideas of the Auction-based Congestion Pricing concept is that all drivers who want to enter downtown (Figure 1) have to *participate in an auction*. The operator (traffic authority) is the auctioneer who makes the decision whether to accept or reject particular bids sent by the drivers.

Let us introduce the following notation:

i - agent index
j - bid index
I - total number of agents (bidders)
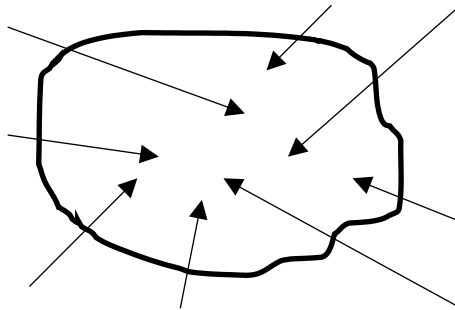$J(i)$ - the total number of bids made by the agent a_i

Figure 1. Drivers' requests

Let us divide the considered time interval (for example, one week) into smaller time intervals (the width of small time interval could be, for example, 15 minutes). We denote by T the total number of small time intervals. We use small time intervals to measure the duration of the visit to downtown. For example, a vehicle stays in the downtown area for three time intervals, five time intervals, eight time intervals, etc. The driver (Agent a_i) makes one or more bids for one or more downtown visits during the observed time period (one week) (see Figure 2).

We call the set of requested time intervals the *collection of visits*. Let us denote by $c_{i,j}$ the j-th collection of visits created by the agent a_i. The agent a_i offers to the auctioneer (operator of the system) m_{ij} monetary units for the right to stay in downtown during time intervals defined in the collection of visits $c_{i,j}$.

Let us note the small time interval as t. We define parameters $d_{ij}(t)$ in the following way:

$$d_{ij}(t) = \begin{cases} 1, \text{if collection } c_{ij} \text{ created by the agent } a_i \text{ contains small time} \\ \quad \text{interval } t \\ 0, \text{otherwise} \end{cases}$$

(1)

Let us introduce variables x_{ij} defined in the following way:

$$x_{ij}(t) = \begin{cases} 1, \text{if the auctioneer accepts collection } c_{ij} \text{ requested by the agent } a_i \\ 0, \text{otherwise} \end{cases}$$

(2)

The Winner Selection Problem (*WSP*) in the case of downtown time slot auctions could be defined in the following way: Discover the best set of collection of visits that should be accepted by auctioneer. The *WSP* is expressed mathematically in the following way:Maximize

$$R = \sum_{i=1}^{I} \sum_{j=1}^{J(i)} m_{ij} x_{ij}$$
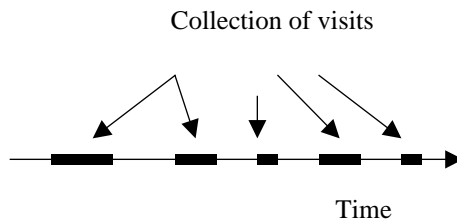
(3)

Collection of visits

Time

Figure 2. Collection of visits to the downtown area

subject to:

$$\sum_{i=1}^{I} \sum_{j=1}^{J(i)} d_{ij}(t)x_{ij} \leq D_{\max}, t = 1, 2, ..., T \tag{4}$$

$$\sum_{j=1}^{J(i)} x_{ij} \leq 1, i = 1, 2, ..., I \tag{5}$$

The objective function represents the total revenue R of the auctioneer that should be maximized. We denote by D_{max} the maximum allowed number of cars that could be present in downtown *at any time point in time*. (We propose in Section 'Maximum Allowable Number of Vehicles in the Downtown Area' an approach to determine the D_{max} values). The total number of cars that are present in a downtown area during small time interval t equals $\Sigma_{i=1}^{I} \Sigma_{j=1}^{J(i)} d_{ij}(t)x_{ij}$. This number must be less than or equal to the maximum allowed number of cars in the downtown area denoted by D_{max} (equation (4)). Constraint (3) indicates that maximum one bid of any agent that could be accepted. The WSP is a difficult combinatorial optimization problem.

The model described by the relations Vickrey (1963, 1969, 1994) is related to the *One-Shot Auction*. *Multiple Round Auctions* are the auctions in which bidders can bid for combinations of items and modify their bids in response to bids from the other agents. Multiple Round Auction is by its nature an *Iterative Combinatorial Auction*. An Iterative Combinatorial Auction would enable drivers to avoid peak hours, switch to other time slots, and pay smaller amount for right to enter downtown, or change the mode of transportation, based on the information they received from the previous round. In the case of a One-Shot Auction, drivers would not have a chance to change their decisions despite the fact that some of the available time slots could be
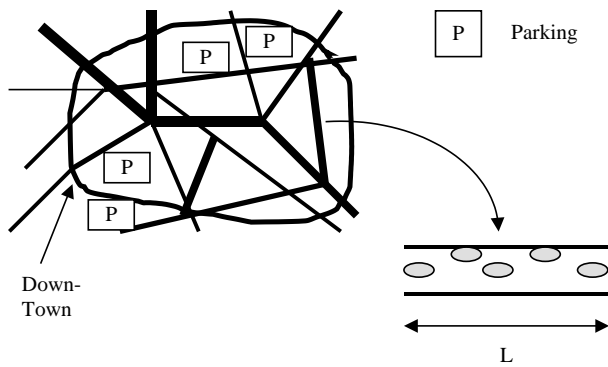

Figure 3. Downtown and observed link whose length equals L

'acceptable' for some of the drivers. Costs, implementation issues and potential benefits of the One-Shot Auction versus Multiple Round Auction will be highlighted in more detail in Section 'Conclusions'.

Maximum Allowable Number of Vehicles in the Downtown Area

In order to determine the maximum allowed number of vehicles in the downtown area D_{max}, (Figure 3) we introduce the following notation and assumptions.

We count every parked vehicle and every vehicle on every link in the downtown area during time period T. Let us note a specific link in the downtown area whose length is L. We denote by N the total number of vehicles counted on this link during time period T.*Flow q* [veh/h] on the observed link equals:

$$q = \frac{N}{T} \tag{6}$$

Traffic *density k* on the link equals:

$$k = \frac{N}{L} \tag{7}$$

The traffic density is expressed in [veh/km]. So-called *jam density* describes traffic conditions when cars on a freeway are bumper to bumper. At this density traffic stops.

We also denote by u_f the *free flow speed* (speed influenced exclusively by the performance of our vehicle and by posted speed limits). We assume a linear speed-density relationship (Figure 4):

$$u = u_f(1 - \frac{k}{k_j}) \tag{8}$$

Free flow speed u_f and jam density k_j are indicated in the Figure 4. Linear speed-density relationship is an approximation of reality. This
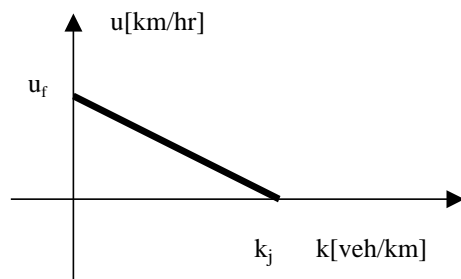

Figure 4. Speed – traffic density relationship

relationship is known as the Greenshields model. Many field measurements have shown that the speed-density relationship is non-linear especially in the areas of low and high-speed traffic density. On the other hand, the linear relationship is simple, and helps us to better understand complex issues in traffic flow.

Relation (8) could be written as:

$$u_f - u = \frac{u_f}{k_j} k \tag{9}$$

We consider link whose length equals L (Figure 3). Since:

$$u_f - u = u_f - \frac{L}{t} \tag{10}$$

Combining relations (9) and (10) we get:

$$\frac{u_f}{k_j} k = u_f - \frac{L}{t} \tag{11}$$

The travel time along considered link equals:

$$t = \frac{k_j L}{u_f(k_j - k)} \tag{12}$$

We denote by t_f the free-flow travel time. We also denote by D the delay experienced by the vehicle while traveling along a typical link. We define the delay D in the following way:

$$D = t - t_f \tag{13}$$

Combining relations (12) and (13) we get:

$$D = \frac{k_j L}{u_f(k_j - k)} - \frac{L}{u_f} \tag{14}$$

$$D = \frac{L}{u_f}\left(\frac{k}{k_j - k}\right) \tag{15}$$

We denote by D_i the delay at the i-th link. We assume that there is a cordon around downtown. The calculation of the maximum number of cars that could be on the streets in the downtown area is based on the following:

The delay at any link in the network should not be greater than D^*, i.e.

$$D_i \leq D^* \quad i = 1, 2, ..., |A| \tag{16}$$

where D^* is the maximum delay that we are ready to accept.

In this way, the maximum number of cars that could be on the streets in the downtown area depends on the maximum delay that we are ready to accept. Combining relations (15) and (16) we obtain:

$$\frac{L_i}{u_f}\left(\frac{k_i}{k_j - k_i}\right) \le D^* \quad i = 1, 2, ..., |A| \tag{17}$$

Traffic density on the *i*-th link should satisfy the following inequality:

$$k_i \le \frac{D^* \frac{u_f}{L_i} k_j}{1 + D^* \frac{u_f}{L_i}} \quad i = 1, 2, ..., |A| \tag{18}$$

Traffic density on the *i*-th link equals:

$$k_i = \frac{TV_i}{L_i} \tag{19}$$

where TV_i represents total number of vehicles on the *i*-th link. Combining relations (18) and (19) we obtain:

$$\frac{TV_i}{L_i} \le \frac{D^* \frac{u_f}{L_i} k_j}{1 + D^* \frac{u_f}{L_i}} \quad i = 1, 2, ..., |A| \tag{20}$$

$$TV_i \le \frac{D^* u_f k_j}{1 + D^* \frac{u_f}{L_i}} \quad i = 1, 2, ..., |A| \tag{21}$$

We denote by A the set of links in the downtown, and by $|A|$ the total number of links in the downtown area. We make a summation over all links and obtain the following:

$$\sum_{i=1}^{|A|} TV_i \le \sum_{i=1}^{|A|} \frac{D^* u_f k_j}{1 + D^* \frac{u_f}{L_i}} \tag{22}$$

The maximum number of vehicle MV that could be on the streets of the downtown area equals:

$$MV = \sum_{i=1}^{|A|} \frac{D^* u_f k_j}{1 + D^* \dfrac{u_f}{L_i}} \qquad (23)$$

We denote by P the total number of parking places downtown. The maximal number of vehicles in the downtown area equals:

$$D_{max} = MV + P \qquad (24)$$

$$D_{max} = \sum_{i=1}^{|A|} \frac{D^* u_f k_j}{1 + D^* \dfrac{u_f}{L_i}} + P \qquad (25)$$

The maximal number of vehicles in the downtown area depends on the free flow speed, jam density, link lengths, maximum acceptable delay and the total number of parking spaces. Relation (25) is easy to implement, and we use this relation when calculating the maximal number of vehicles in downtown D_{max}.

Some calculated D_{max} values are given in the following example.

Example:

There are $|A| = 10$ links in the downtown area. The length of every link equals $L_i = 1 km$ $(i = 1,2,\ldots,10)$. The jam density on every link equals $k_j = 165 [veh/km]$. The free-flow speed at any link equals $u_j = 60 [klm/hr]$. The maximum allowed delay at any link equals $D^* = 2$ min. The maximum number of vehicles on the streets of downtown equals:

$$MV = \sum_{i=1}^{|A|} \frac{D^* u_f k_j}{1 + D^* \dfrac{u_f}{L_i}}$$

$$MV = \sum_{i=1}^{|10|} \frac{\dfrac{2}{60} [hr] \cdot 60[km/hr] \cdot 165[veh/km]}{1 + \dfrac{2}{60} [hr] \cdot \dfrac{60[km/hr]}{1[km]}}$$

$MV = 1,100$ *vehicles*

Table 1 shows few MV values for various values of D^*.

Solving the Downtown Area Time Slot Auction Problem

The downtown time slot auction problem is combinatorial by its nature. Combinatorial optimization problems could be solved by *exact*

Table 1. The *MV* values for various values of *D**

Maximum allowed delay at any link D* *[min]*	Maximum number of vehicles on the streets *MV*
1	825
2	1,100
3	1,238
4	1,320

or *heuristic* algorithms. Heuristic algorithms can be described as a combination of science, invention and problem-solving skills.

The exact algorithms always find the optimal solution(s). The wide usage of the exact algorithms is limited by the computer time needed to discover the optimal solution(s). In some cases, this computer time is enormously large.

Optimization Approaches

In the past five decades, linear, non-linear, dynamic, integer and multi criteria programming have been widely used to solve various engineering, management and control problems. Mathematical programming techniques have been used to attack the problems dealing with the most efficient allocation of limited resources (supplies, capital, labor, etc.) to meet defined objectives. The downtown area time slot auction problem considered in this paper belongs to the class of problems related to the most efficient allocation of limited resources.

The problem defined by relations (3)–(5) is an *integer programming* problem. There are numerous software systems that solve linear, integer, and mixed-integer linear programs (CPLEX, Excel and Quattro Pro Solvers, FortMP, LAMPS, LINDO, LINGO, MILP88, MINTO, MIPIII, MPSIII, OML, OSL).

The downtown area time slot auction problem should be solved by using some of these software systems.

Heuristic Algorithms

A combinatorial explosion of possible solutions could appear in the downtown area time slot auction problem. In the cases when the number of integer variables in the problem is very large, finding optimal solution becomes very difficult, if not impossible. In such cases, various heuristic algorithms are used to discover 'good' solutions. These algorithms do not guarantee optimal solution discovery. A good heuristic algorithm should generate quality solutions in an acceptable computer time. Good heuristic algorithms are capable of discovering

optimal solutions for some problem instances. On the other hand, heuristic algorithms do not guarantee optimal solution discovery.

'Greedy' heuristic algorithms. 'Greedy' heuristic algorithms build the solution of the studied problem in a step-by-step procedure. In every step of the procedure the value is assigned to one of the variables in order to maximally improve the objective function value. In every step, the greedy algorithm is looking for the best current solution with no consideration of future costs or consequences. Greedy algorithms use local information available in every step. In the problem considered, a simple greedy algorithm could be formulated in the following way. The total number of time intervals D_{ij} in a collection of visits c_{ij} created by the agent a_i equals:

$$D_{ij} = \sum_{t=1}^{T} d_{ij}(t) \tag{26}$$

The ratio a_{ij} between the number of monetary units m_{ij} and the total number of requested time intervals D_{ij} equals:

$$a_{ij} = \frac{m_{ij}}{D_{ij}} \tag{27}$$

The ratio a_{ij} represents the offered unit price per one requested time interval. The list of calculated ratios a_{ij} is created and sorted in a descending order. Allocation of available time slots could be done according to the formed list. Available time slots must be updated all the time.

Meta heuristic approaches. Meta heuristics can be defined as general combinatorial optimization techniques. These techniques are designed to solve many different combinatorial optimization problems. Known meta heuristics are based on local search techniques (Simulated Annealing, Tabu Search, etc.), or on population search techniques (Genetic Algorithms). The problem considered in this paper could be solved by various meta heuristic approaches.

Internet Downtown Time Slot Auction Issues

There are no internet downtown area time slot auctions in operation at this moment. The following account is our educated guess about future downtown area time slot auction implementation issues.

Agents (drivers) will continuously (whenever web bid collecting service is available) make bids for downtown visits during observed time periods (one week). Every agent should have full information about the availability of time slots, before creating the bid. For

example, the Matrix A with seven rows (seven days) and 14 columns (14 time slots) should be displayed to potential bidders. The matrix element a_{ij} should indicate the available 'downtown capacity', i.e. the total number of vehicles that still could be accepted to enter the downtown area on the i-th day during j-th time interval (The case when $a_{ij} = 0$ is related to the situation when vehicles are not accepted any more to enter the downtown area on the i-th day during j-th time interval). At the time point 00:00 it is not possible any more to make bids that include the current day. At this moment the considered time period is updated (the second day is the new first day, the third day becomes the new second day, etc.). Auction software is activated periodically, for example, every 60 minutes. All requests that appear in the last 60 minutes are considered. All agents are informed by email about acceptance or rejection of their bids. The agents whose bids are not accepted can send the new, modified bids to be considered during the next round.

The web bid collecting service should not be available to the agents while auction software is running. This is the standard procedure related to the available data. The data base is always 'locked' for new transactions whenever one transaction is in progress. 'Early bids' in an auction have a good chance to obtain the requested collection of visits for a reasonable amount of money. This could force a fraction of the driver population to plan their activities and visits to downtown on time. The auction software could solve the optimization problem related to bids that showed up in last 60 minutes. In this way, it is possible to obtain the optimal solution in a reasonable CPU time, since the dimensions of the problem are not so large.

A Numerical Example

The proposed concept was tested on a few different numerical examples. The data required for solving these hypothetical examples are generated based on certain assumptions and procedures discussed below.

a. We consider one week and divide a one-week period into 98 smaller time intervals (we consider 14 smaller time intervals within one day).
b. Drivers (agents) make up to three bids for one or more down town visits during observed time period (one week).
c. The operator (traffic authority) is the auctioneer who makes the decision whether to accept or reject particular bids sent by the drivers.
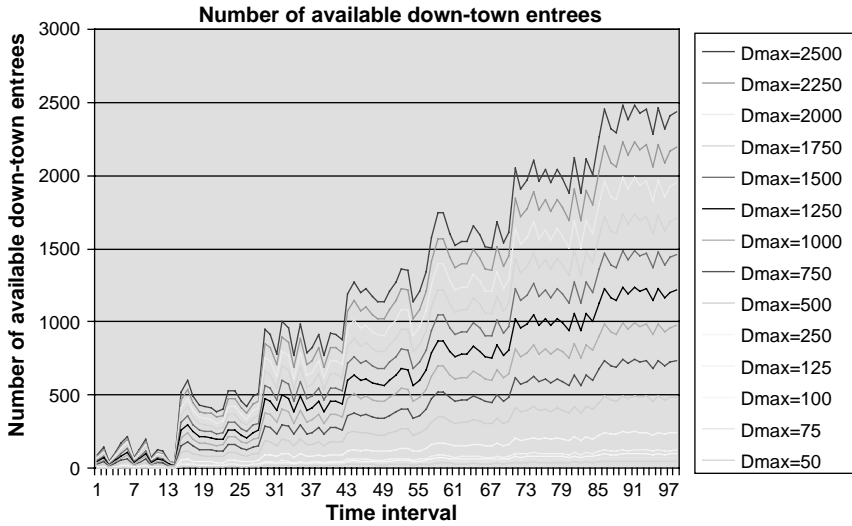d. The maximum numbers of vehicles on the streets (numbers of available downtown entries) is known (Figure 5).

Figure 5. Maximum numbers of vehicles on the streets (numbers of available downtown entries)

Figure 5 shows the maximum numbers of vehicles on the streets (number of available downtown entries) during the time of one week. The values shown in Figure 5 were generated in a random manner. It is logical to expect that D_{max} values will be higher at the end of a week.

We illustrate the proposed auction-based congestion pricing concept using the following numerical example (Table 2).

The total number of agents that participate in the auction equals 100. Every agent generates three bids (first column of the table). Every bid is characterized by the requested time intervals and the number of offered monetary units.

We found the optimal solution of the problem considered. The auctioneer's decisions (acceptance/rejection) and the auctioneer's revenue achieved are shown in the last two columns of the table. The table corresponds to the case when there is $D_{max} = 125$ available entries in downtown area.

The average CPU time, the revenue achieved and the percentage of accepted agents for the various D_{max} values are shown in the Table 3 and Figures 6 and 7.

The achieved CPU times to reach the optimal solution are shown in Figure 8.

Table 2. Bids, auctioneer's decisions and the revenue achieved

Agent/Bid	Day I		Day II		Day III		Day IV		Day V		Day VI		Day VII		Number of monetary units	Accepted / Rejected	Revenue
	From	To	From	To	From	To	From	To	From	To	From	To	From	To			
1/1	0	0	0	0	1	5	0	0	0	0	0	0	0	0	7	0	0
1/2	0	0	4	7	4	12	0	0	1	2	0	0	0	0	8	0	0
1/3	0	0	0	0	6	14	8	12	7	14	8	9	0	0	10	1	10
2/1	7	8	0	0	0	0	0	0	2	10	3	7	0	0	11	0	0
2/2	0	0	0	0	1	3	1	8	0	0	7	14	0	0	11	1	11
2/3	6	7	7	7	10	11	0	0	0	0	4	13	11	14	9	0	0
3/1	0	0	0	0	0	0	0	0	4	8	5	6	8	11	9	1	9
3/2	5	11	5	13	1	14	10	14	1	5	9	14	0	0	10	0	0
3/3	0	0	0	0	1	3	0	0	0	0	4	11	0	0	8	0	0
72/1	4	10	11	13	0	0	0	0	7	10	1	11	9	11	9	0	0
72/2	6	9	7	10	0	0	2	12	7	10	0	0	0	0	8	0	0
72/3	7	13	0	0	7	12	3	12	0	0	0	0	0	0	10	0	0
98/1	9	9	0	0	0	0	12	14	1	4	1	8	5	11	6	0	0
98/2	0	0	0	0	8	13	0	0	0	0	0	0	4	4	7	1	7
98/3	0	0	2	14	6	14	0	0	0	0	0	0	0	0	8	0	8
99/1	1	9	0	0	0	0	5	13	8	13	0	0	1	3	10	0	0
99/2	2	9	9	13	2	10	12	13	0	0	5	14	6	12	10	0	0
99/3	0	0	2	12	0	0	0	0	2	10	0	0	6	11	9	1	9
100/1	0	0	0	0	3	4	1	3	9	11	2	11	5	7	12	1	12
100/2	1	13	4	8	10	12	4	8	10	13	1	5	0	0	9	0	0
100/3	9	13	5	14	3	12	7	14	4	11	0	0	1	14	11	0	0
Total																94	956

Table 3. The average CPU time, the revenue achieved and the percentage of accepted agents

D_{max}	CPU time [s] in average	Revenue	Number of accepted agents
2500	0.76	1124	100
2250	0.65	1124	100
2000	0.81	1124	100
1750	0.93	1124	100
1500	0.74	1124	100
1250	0.61	1124	100
1000	0.66	1124	100
750	1.02	1117	100
500	0.64	1100	100
250	0.62	1045	100
125	0.64	954	94
100	0.65	908	89
75	0.70	865	84
50	0.78	777	77

We considered numerical examples of a smaller size. The achieved CPU times to reach the optimal solution are practically negligible. A combinatorial explosion of possible solutions could appear when the downtown area time slot auction problem is considered. In such cases, the problem could be successfully solved by heuristic or metaheuristic approaches.

Conclusions

A new demand management concept – *Auction-based Congestion Pricing* – has been proposed and modeled in this paper. The basic principles of auctions have also been described. The downtown time
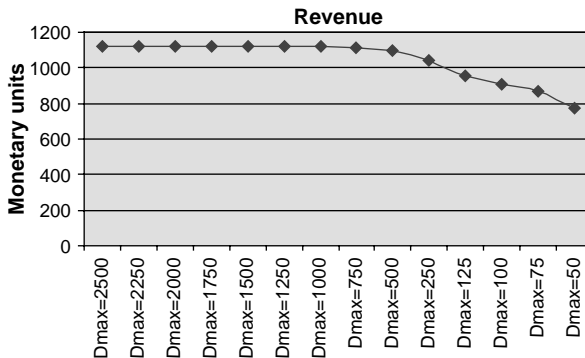

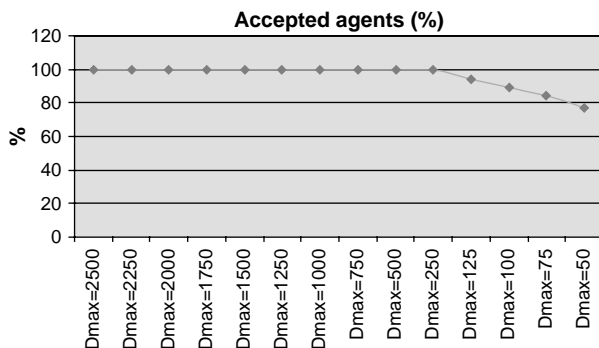**Figure 6.** Revenue achieved as a function of D_{max}

Figure 7. The percentages of accepted agents as a function of D_{max}
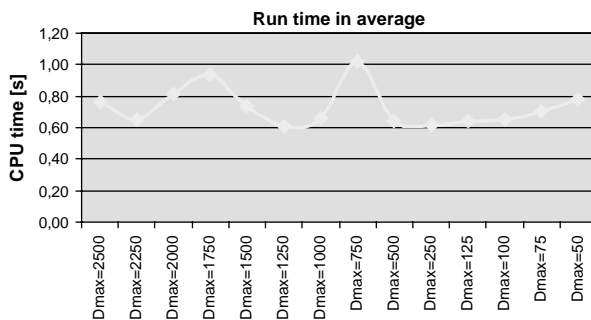
Figure 8. The CPU times to reach the optimal solution

slot auction model is proposed, as well as potential solution approaches. The most important issues to be addressed in future research are one-shot auction versus multiple round auction, payment determination (first price versus second price), information flows between bidders and the auctioneer, bid language, public acceptance, etc.

The auction software could be developed in such a way to enable *automatic bidding* and/or *straight bidding*. In the case of automatic bidding, the agents request from the auction software to bid up to specific amount in his/her behalf. The auction software increases incrementally starting with the bid amount. In the case of straight bidding, the agent enters the exact amount that they wish to bid. This type of bidding happens at live auctions.

In future research, the problem considered could also be expanded by considering downtown congestion simultaneously with the congestion on the major highways leading to the downtown area.

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