Benefits of Emerging Transportation Technologies: Simulation Analysis and Policy Issues

by

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Submitted to the Engineering Systems Division
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Abstract

This thesis explores the quantification of transportation technology benefits, through simultaneous consideration of technical and policy issues. Benefits are first defined and identified based on current literature and discussions. Key benefits include delay impacts, safety impacts and environmental concerns.

A key element of such quantification and analysis is traffic simulation. MITSIMLab, a microscopic traffic simulator, has been recently enhanced to replicate transportation technologies and applications such as traffic signal priority and advanced vehicle location for transit. In addition, the existing capability for modeling incident detection and management is reviewed. These applications are tested on a traffic network on Stockholm, Sweden, about to undergo new construction and development. The implementations are demonstrated to be effective in a quantitative and qualitative manner, and successful in illustrating the benefits of signal priority for transit as well as the integration of different technologies in the simulation itself. Through the case study, this capability is contrasted with the ability of MITSIMLab to depict impacts of infrastructure changes. Benefits quantification is discussed through post-processing MITSIMLab output measures such as travel time statistics.

Benefits evaluation is necessarily intertwined with policy development. The technical analysis of the Stockholm network is framed with an investigation of transportation policy issues in the US and Sweden. Fundamental policy issues of stakeholder cooperation, technical integration and regional integration are identified, then explored in the context of benefits evaluation.

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Chapter 1

Introduction to Benefits Evaluation

1.1 Background

Technology has become essential to transportation. The importance and continued growth of the Intelligent Transportation Systems (ITS) industry attests to this strong relationship between technology and transportation. Different technologies such as location applications, control devices, smartcards and other emerging and still unforeseen technologies are deployed because of their benefits and ability to improve the transportation system.

Although the general benefits of an ITS application are clear, and technology is often cheaper and more effective than infrastructure expansion, construction is still necessary in areas where technology cannot solve a particular traffic problem. Benefits of all proposed transportation projects, whether consisting of roadway construction, technology deployments, or both, should be identified and quantified in order to:

- Justify present and future expenditures
- Optimize operation of the transportation system
Simulation tools have been and are being developed which can evaluate planned ITS deployments along with traditional evaluation of construction projects, to aid goals such as the above. The quantification of benefits has improved in the US with the tracking of actual ITS deployments and the creation of a deployment database (US JPO, 1996). However, such a tool evaluates projects already deployed. Furthermore, Thill (2001) points out that only a few benefits evaluation tools and models are currently available to planners, for comparing alternative construction developments, evaluating deployments of ITS technologies, or for comparing construction developments to technology implementations.

1.2 Objectives

The quantification of benefits of will be explored using a microscopic traffic simulator, MITSIMLab. MITSIMLab has been used to analyze impacts of various construction and ITS projects in the past, but it has recently been enhanced to replicate transportation technologies in transit, such as signal priority and advanced vehicle location. Thus, while still fulfilling the traditional role of simulation for analyzing benefits of physical infrastructure changes, MITSIMLab or any transportation analysis tool must continually possess the ability to assess emerging changes in technology. The role of MITSIMLab in assessing such technologies will be further tested and validated, while discussed in the context of current benefits evaluation methodologies. Policy issues will also be explored in conjunction with this benefits evaluation.

A case study in Stockholm, Sweden, will further serve to illustrate the relationship between technologies, benefits, and microsimulation.
1.3 Thesis outline

Chapter 2 will describe representative transportation technologies and current benefits evaluation methodologies. Chapter 3 will continue by illustrating how MITSIMLab can be used to extend these concepts of benefits evaluation using recent enhancements. Chapter 4 will enlighten the discussion further by investigating policy issues surrounding the quantification of transportation technology and its benefits. Chapter 5 will attempt to bring these concepts of technologies, benefits evaluation, and simulation together by applying them to an actual case study network in Stockholm, Sweden, and analyzing the results. Chapter 6 will conclude with recommendations and possibilities for further study.
Chapter 2

Literature Review

2.1 Introduction

This thesis seeks to investigate and extend the role of microscopic traffic simulation in quantification of transportation technology benefits, and to apply these findings to a real situation. As a starting point for investigating this role, recent work conducted in this area is outlined in the following literature review. In Section 2.2, a brief overview of the selected transportation technologies of interest is provided. This thesis focuses on technologies Section 2.3 follows with a discussion of the definition of transportation technology benefits, and why and how they may be quantified. Current methodologies for quantifying three specific transportation and technology benefits are investigated.

2.2 Overview of Transportation Technologies

A discussion of the evaluation of transportation technology benefits should begin with a very brief overview of the technologies themselves. While it is important to consider a system-wide and intermodal view of the transportation system, it is useful to narrow the study scope to
particular technologies for the purposes of analysis, and later to extend concepts learned to different modes. This thesis will analyze the effects of transportation technology benefits within the area of public transportation and incident management. Advanced Public Transportation Systems (APTS) impact all components of a transportation system and are defined, similar to Intelligent Transportation Systems in other modes, as technologies which increase the efficiency and safety of the entire system, from both the operator and user perspectives. Several useful emerging technologies have been developed for APTS, and simulation tools have been enhanced to reflect these developments. Incident management encompasses both incident detection and response, and related technologies which facilitate these tasks such as surveillance, video cameras, inductive loops, and also information dissemination methods, which assist with warning motorists of delays or detours.

The technologies of interest in this study include automatic vehicle location, traffic signal priority systems, and incident management systems. Although other technologies are not treated in detail within the scope of this thesis, the investigation using microsimulation can be extended to quantification of benefits for other technologies.

2.2.1 Automatic Vehicle Location

AVL systems are computer-based vehicle tracking systems which measure vehicle locations in real-time, and transmit that information along with information about the speed and vehicle load back to a central location. At this central location or dispatch center, the information appears on a computerized map. There are several different technologies that are used to perform the AVL function: Global Positioning System (GPS), signpost and odometer system, dead-reckoning, and combinations of these. As of early 1997 GPS is the most commonly used AVL technology (PBFI,
1997). Cain and Pekilis (1993) describe this movement from Loran C, Signpost and Dead reckoning to GPS with enhanced real time location tracking and schedule monitoring.

Vehicle location information may be used for a number of purposes. These include correcting on-time performance, improving operations and planning (scheduling and run-cutting), providing input to traveler information systems, and locating vehicles in times of emergencies (crimes in progress or medical emergencies).

2.2.2 Traffic Signal Priority

Traffic signal priority allows buses to have limited control over traffic signals. These systems extend the green phase or shorten the red phase (calling the green phase earlier than scheduled) upon the arrival of a vehicle, thus reducing transit trip times. Two methods are used for signal priority. The first employs a special transmitter on the transit vehicle and a companion receiver located at or near the signalized intersection. As the vehicle approaches the signal, the receiver identifies the vehicle from the transmitted waves and either extends the green phase or shortens the current phase to change the light to green until the vehicle passes clears the intersection. The second method integrates a transit agency’s AVL system with the traffic signal system. As the transit vehicle approaches the traffic signal, the AVL system recognizes the vehicle’s proximity and sends the traffic signal instructions to appropriately alter the signal phasing.

Signal priority allows more travelers to pass through an intersection during a light cycle, as the priority can be triggered based on the vehicle loads. It also helps with the management of bus routes that have short headways and helps to alleviate bunching (where buses too closely following one another), as the priority can be triggered based on preceding headways.
2.2.3 Incident Management Technologies

Rippeon et al (1999) give an overview of the possible incident detection and management technologies and methods. These include loop detectors embedded in the roadway or video detectors situated above the roadway which automatically transmit volume data, personnel in helicopters, and personnel with cellular phones situated along alternate routes. They further explain that a promising technology is an unmanned aerial vehicle, or UAV, that allows for a "bird's eye view" of an incident. The UAV is a lightweight helicopter with a camera attachment which can be launched quickly and provide video relay to an observer on the ground.

2.3 Definition of Benefits

The US Department of Transportation Joint Programs Office (JPO) for Intelligent Transportation Systems has already established a framework for evaluation of ITS benefits, using what it terms "A Few Good Measures". These six basic measures are directly related to the US National ITS Program Goals, and are "robust enough to represent the goals and objectives of the entire ITS program, yet are few enough to be affordable in tracking the ITS program on a yearly basis". These six basic measures are listed below, along with the related goals from the National ITS Program, and related metrics which can be physically measured from the transportation system deployment or from simulation methods (Table continues across two pages).

<table>
<thead>
<tr>
<th>ITS Benefit Measure</th>
<th>ITS National Goal</th>
<th>Related Metric</th>
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<tr>
<td>Effective Capacity Improvements</td>
<td>Increase Transportation System Efficiency and Capacity</td>
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<td>Volume to capacity ratio</td>
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<td>Vehicle hours of delay</td>
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<td>Incident-related capacity restrictions</td>
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<td>ITS Benefit Measure</td>
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<td>Vehicle operating costs</td>
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<td>Delay</td>
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<td>Customer Satisfaction</td>
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<td>Number of security incidents</td>
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<td>Exposure to accidents and incidents</td>
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<td>Safety</td>
<td>Improve Safety</td>
<td>Number of incidents</td>
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<td>Number of fatalities</td>
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<td>Time between response and arrival at scene</td>
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<td>Medical costs</td>
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<td>NOx emissions</td>
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<td>Environmental Costs</td>
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<td>VOC emissions</td>
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<td>Liters of fuel consumed</td>
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<td></td>
<td>Vehicle fuel efficiency</td>
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<td>Cost</td>
<td>Increase Economic Productivity</td>
<td>Travel time savings</td>
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<td>Operating cost savings</td>
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<td>Administrative and regulatory cost savings</td>
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<td>Labor cost savings</td>
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<td>Vehicle maintenance and depreciation</td>
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<td>Information-gathering costs</td>
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<td>Integration of transportation systems</td>
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</table>

Table 2-1: ITS Benefits Matrix  
Source: Adapted from (Lockheed Martin, 1996)
Other literature pinpoints categories which closely parallel the above, but further subdivides the above main areas into different levels, distinguishing between “fundamental” benefits (those characteristics that individuals and communities most want to consume) and “intermediate” benefits (those whose principal importance lies in the production of fundamental benefits) (TCRP, 1996). The research team identified economic measures, safety and security, and environmental dimensions as being “fundamental” benefits leading directly to improved quality of life.

In their study on benefits evaluation of ITS, especially information dissemination, Thill and Rogova (2001) pinpointed four primary benefit groups to quantify: delay, safety, emission, and fuel cost. These benefit groups are in alignment with the categories determined in Table 1.1 above. Thill and Rogova use these benefit groups to structure their analysis and develop a sketch planning tool, ITSOAM, for the New York State Department of Transportation.

Peng et al (1999) pinpoint benefits from different perspectives in their study of small- to medium-sized travel agencies (agencies with a fleet size of less than 50 vehicles). From their survey of a transit system in Wisconsin, they determine that the perspective of the transit user, the on-time performance of the bus service is the most important mode choice factor. Both regular and occasional riders tended to mark it as very important in their decision to ride a bus. The other user benefits ranked highly included low fares, corresponding to the customer satisfaction and cost measures in Table 2-1, and also the ability of the bus to be connected directly to emergency response services, which corresponds to the safety metric mentioned earlier. From the perspective of the transit agency, the measurable benefits from an AVL system include cost reduction by the elimination of staff and reducing response time to incidents, as well as increased efficiency of existing routes and greater productivity without increased staff or vehicles. These
measurable benefits again correspond to the main categories outlined above, namely the delay, safety, and cost metrics, while having indirect implications on the other metrics.

In their study on benefits of Transit AVL in the US, Gomez, Zhao and Shen (1998) point out that improving schedule adherence, emergency response and providing real-time travel information were the three most important factors for transit agencies' selection of AVL technology. They use examples from six transit agencies to determine the costs of AVL, considering factors such as different service configurations, fleet size, objectives, and other requirements. Again, schedule adherence corresponds to the delay, customer satisfaction and cost metrics above.

From the above examples, it appears that there is consensus among researchers, transit agencies and transit users on the important benefits to be derived from transportation systems and technologies. The following benefits are discussed in all the studies and appear to be the most indicative of transportation system performance:

- Reduced delay
- Increased safety and security
- Reduced environmental impacts

These specific benefits were explored in greater detail in the literature.

2.3.1 Delay

In ITSOAM (ITS Options Analysis Model) developed by the Calspan University at Buffalo Research Center for the New York State Department of Transportation, the delay model has two
roles. It estimates a delay-related measure of effectiveness, and it also predicts key measures of traffic operation before and after deployment (speed and volume) as input into the safety and environmental models (Thill and Rogova, 2001). For example, the benefit metric used to quantify the performance of VMS deployment is the change in overall user delay (defined as the aggregate increase in travel time resulting from the capacity reduction or flow increase).

ITSOAM models individual travel time in the impacted corridor is with the following components:

- The traversal time on the portion of the freeway with reduced capacity and/or flow increase
- A delay associated with the merging of traffic on blocked lanes (if any) with traffic traveling on free lanes (merge delay)
- A delay associated with the dissipation of vehicle queues formed upstream of the incident location (queue delay), and
- A delay associated with the decision to exit the highway corridor upstream of the incident location and to divert to an alternate route (diversion time).

The California Life-Cycle Benefit/Cost Analysis Model (Cal-B/C) used by Caltrans (1999) developed by offers a simple, practical method for preparing economic evaluations on prospective highway and transit improvement. Although Cal-B/C is a spreadsheet model, the methodology it uses to measure benefits may be useful. Among the four primary categories of benefits it measures resulting from highway and transit projects are the three measures highlighted above: travel time savings, safety benefits (accident cost savings), and emission reductions.
For each period by vehicle type, benefits of delay reduction for highway travel are calculated using the following formula:

\[
\text{Value of Time Savings = } \text{Value of Time} \times (\text{Travel Time Without Project} - \text{Travel Time With Project})
\]

Travel time with and without the project are calculated using the appropriate speed and average daily traffic (ADT) for the period and vehicle type.

\[
\text{Travel Time = Affected ADT} \times (\text{Affected Length}/\text{Speed})
\]

The affected length is the length of the highway that is affected by the project, which is usually the length of the highway segment.

For transit, travel time benefits for existing riders are calculated as the difference in travel times multiplied by the number of existing riders and the value of time.

IDAS is the ITS Deployment Analysis System developed by Cambridge Systematics. This model is a "sketch-planning analysis tool that will enable an analyst to estimate the impact and benefit/cost of a variety of different ITS components" (Cambridge Systematics, 1998). The software consists of five modules, one of which is a "Benefits" module. Within the benefits module, three sub-modules are present: a travel time/throughput submodule, a safety submodule, and an emissions/energy sub-module. These sub-modules are consistent with the benefit measures being explored in this section: delay, safety and the environment. The analysis is conducted at a regional level. The travel time/throughput submodule is capable of determining the impacts on traveler responses including route diversion, mode shift, temporal diversion, and induced/foregone demand. Just as with the ITSOAM model previously described, IDAS uses
outputs from the travel time submodule (namely updated link volumes and segment speeds) as inputs into the safety and environment submodules.

### 2.3.2 Safety and Security

Incident detection technologies provide benefits in terms of delay reduction and also in terms of increased safety. Incident management refers to several actions an operating agency may perform to mitigate negative traffic impacts of both planned and unforeseen events. These actions include identifying alternate routes and diverting traffic to these different routes, barring traffic from entering the incident area, or warning travelers of upcoming delays. Rippeon et al (1999) address the absence of an analytical model for evaluating the effectiveness of active incident management. The premise in their study is that studying one incident, in detail, allows one to determine the utility in observing alternate routes for the duration and the effect this “real-time” information has on delay faced by motorists. A tolerable level of speed and service for all detours should be maintained. To accomplish this, the operating agency can prevent an excessive number of vehicles from leaving the mainline and entering the detour, by observing the queue on various alternative routes and the mainline for the duration of the incident, and calculating the time it would take the number of vehicles necessary to saturate the route to enter the detour.

They use the microscopic simulation model CORSIM to determine under what conditions active incident management yields a significant reduction in delay. Four detour scenarios were simulated, and several factors were altered in the scenarios including volume reduction on the mainline of the detour. The following criteria were used to classify incidents:

- **duration**: the incident must last long enough to benefit from management
- **description of detours** used for rerouting traffic

25
- *date and time* of the incident – various hours of the day/months of the year
- *type of incident* – variety of work zone, tractor-trailer, single vehicle

They find that there are occasions when active management would allow a reduction in delay yet there are also occasions when congestion on the alternate routes prevents further delay reductions. The simulations also suggest instances where continuous monitoring gives the analyst sufficient warning prior to saturation, allowing him or her to alter detours accordingly.

Peng et al (1999) addressed the quantification of vehicle incident response benefits. The number of vehicle incidents including vehicle breakdowns, police/fire calls and medical calls and associated costs was be obtained from transit agencies. They explain that AVL can speed up the response time to those incidents by quickly locating the incidents and by reducing the time to inform the emergency response team. They used data from Wisconsin, and assumed a ten-percent reduction of incident costs and a cost per incident of $1000, this would save about $10,800 per year. The amount of savings is dependent on the current incident related expense and savings from adopting the AVL technology.

Thill and Rogova (2001) postulate that the relationship between accident rate and traffic volume is different for freeways and arterials; it depends on the road characteristics (e.g., number of lanes, geometry, number of traffic lights, road surface, etc.). They explain that since the accident rate depends directly on the traffic flow characteristics, every ITS element that can reduce traffic concentration, vehicle miles traveled, or duration of hazardous road conditions can provide safety benefits. Below is listed a range of explanatory variables in their safety benefits module as sources of accident reduction:
- Accident Rate
  - reduced congestion at the incident site (secondary accidents)
  - reduced congestion at the construction/planned event site
  - increased congestion on alternate roads
  - switch to the lower class alternatives

- Accident Duration
  - reduced congestion at the incident site due to faster dissipation of residual queues
    (secondary accidents)
  - reduced congestion at the construction/planned event site due to faster dissipation of residual queues

- Vehicle Miles Traveled
  - increased VMT due to switch to longer travel on alternate routes

The IDAS safety submodule uses performance output, such as traffic volumes, vehicle miles traveled, travel speeds, and accident rate look-up tables to determine changes in the number and severity of accidents. To determine safety impacts, new link volume and speed data segmented by market sector output by the travel time submodule are multiplied by the corresponding accident rate (Cambridge Systematics, 1998). The rates depend on the severity of the accidents, the type of roadway, and the type of vehicle. In addition, incident detection/verification technologies have been shown to have an impact on the severity of accidents (for example, shifting accidents from the “fatality” to the less severe “injury” accident category) without having an impact on the overall accident frequency. This effects of particular technologies such as these are incorporated into the model through the use of technology-specific factors.
2.3.3 The Environment

There are different dimensions to environmental impacts from transportation projects. These include disbenefits from construction activity, displaced wildlife and forestry where new infrastructure is located, and pollution from vehicles on the roadway. Most environmental analyses focus on air pollution and greenhouse gas emissions resulting from changes in travel behavior due to a new project as increased travel speeds, increased vehicle trips, or trip diversion. Caltrans explains the differences between both types of air pollution and greenhouse gas emissions. Air pollutant emissions occur when vehicles emit pollutants, such as carbon monoxide (CO), oxides of nitrogen (NOX), volatile organic compounds (VOC), particulate matter (PM), and oxides of sulfur (SOX).

These emissions can also form additional pollutants when they combine with each other. Ozone is formed through the combination of NOX and VOC in sunlight. NOX, VOC, and SOX can react in the atmosphere to form secondary particulates. Air pollutants can cause damage to human health, damage to buildings and vegetation, as well as impair mobility by limiting visibility (Caltrans, 1999).

Greenhouse gas emissions result from gases released during fuel consumption. The most common of these is carbon dioxide. Increasing concentrations of greenhouse gases in the atmosphere are believed to cause changes in the Earth’s climate which could have severe impacts in the form of crop loss, flooding, or health impacts such as increased disease.

The physical volumes of air-pollutants and greenhouse gas emissions resulting from travel are readily quantified, as the processes that result in these emissions are well understood (Caltrans, 1999).
The California Air Resources Board (CARB) has developed models such as the EMFAC model to estimate and forecast emission rates (Caltrans, 1999). It is important to note that emission rates change over time, as older vehicles are replaced with new vehicles that have improved emissions controls. Factors which affect the amount of highway vehicle emissions include in CARB’s model include:

- Vehicle miles traveled (VMT)
- Number of "cold start" vehicle trips (Starting a cold vehicle results in additional emissions because a vehicle's emissions control equipment has not reached its optimal operating temperature)
- Mix of vehicles in the fleet (e.g., light-duty gas vehicles, light-duty diesel vehicles, light-duty gas trucks, etc.), and changes in the mix—this allows for the effect of more or fewer trucks or buses.
- Age of the vehicle fleet
- Types of vehicle inspection and maintenance programs in place
- Ambient air temperatures
- Vehicle speeds and traffic flow—CARB states that speeds are of particular importance in determining vehicle emission rates. They explain that VOC emission rates tend to drop as speed increases, whereas NOX and CO emission rates increase at higher speeds (above 55 miles per hour). Emission rates are also higher during stop-and-go, congested traffic conditions than during free flow conditions at the same average speed. However, current emissions models do not address adequately the variations in the drive cycle, for a given average speed.
Different models use lookup tables to associate average speeds with emission rates for various pollutants. For example, emission rates tables by the Texas Research and Development Foundation are used in the StratBENCOST model. (FTA, 1982). The average travel speeds are used for the lookup tables, for each pollutant for each vehicle type, for both peak and non-peak periods. The model calculates the total volume of each pollutant by multiplying vehicle miles traveled by the emission rates (in grams per mile) for each vehicle class.

Cal-B/C computes emissions benefits by comparing the value of emissions with and without the transportation project. Air pollutant emissions are estimated based on travel volumes and a per-mile emissions rate. The emissions rates depend on travel speeds, and are estimated in the model based on emission rates generated from the California Air Resources Board (CARB) emissions model, EMFAC. Cal-B/C accounts for peak-period and non-peak period speeds and travel separately. The model also determines emissions for each period and vehicle class separately and then sums the results.

Emissions are calculated based on the following formula (Caltrans, 1999):

Total Emissions = (VMTPeak x RPeak) + (VMTOff x ROff)

where: R = the emissions rate (in grams per mile) and

VMT = vehicle miles of travel

The environment submodule in the IDAS model allows emissions and air pollution levels to be determined based on a series of lookup tables (Cambridge Systematics, 1998). The submodule uses as input the number of trips or vehicle miles traveled by facility type, vehicle type, speed range or time of day. The emissions tables then allow determination of the corresponding pollutant levels, by considering emission rates for California (the EMFAC model series
developed for the California Air Resources Board) and the rest of the United States (Mobile 5 Model).

Liu (2002) is develops a new method of estimating air pollution emissions. She pairs a microsimulator (in this case, MITSIMLab) which generates second-by-second vehicle trajectories with different second-by-second load-based emissions models (CMEM, EMIT (a statistical regression model), and emissions matrices). The new paired models are applied to three networks, with different traffic management schemes, and at different granularities (the network level, segment level, and vehicle level). Liu’s research will provide evidence that MITSIMLab can be paired with such existing emissions models to provide a much more reliable estimate of emissions. This thesis seeks to provide additional evidence for such an estimation of air pollution reduction benefits, in conjunction with the estimation of other transportation benefits, through the comprehensive case study of a network in Stockholm described in Chapter 5.

2.4 Summary

The preceding sections provided an overview of transportation technology examples, along with current methods of benefits quantification. Although current benefits evaluation frameworks differ in structure, they generally recognize the fundamental categories of benefits: throughput, delay, customer satisfaction, safety, emissions and productivity. The categories of delay, safety, and emissions will be the focus of this thesis, in conjunction with technologies such as advanced vehicle location, traffic signal priority, and incident detection technologies. Simulation was recognized as a key element in benefits evaluation, and the structure of one such simulator, MITSIMLab, will be summarized in the following chapter. Modules in MITSIMLab pertaining to the technologies described above will also be investigated.
Chapter 3

MITSIMLab Structure and Technology Representations

3.1 Introduction

This chapter focuses on the structure of MITSIMLab, descriptions of its recent enhancements and existing capabilities, and how those enhancements and capabilities allow one to explore quantification of transportation benefits. First, MITSIMLab will be described. Next, the modules of interest in MITSIMLab will be summarized. The modules of interest address three main areas: traffic signal priority, advanced public transportation systems, and incident management.

3.2 MITSIMLab structure

MITSIMLab is a simulation-based laboratory that was developed for evaluating and refining alternative traffic management system designs at the operational level. MITSIMLab contains state-of-the-art behavioral models, and is able to represent a wide range of traffic management system designs, to model the response of drivers to real-time traffic information and controls. MITSIMLab can also incorporate the dynamic interaction between the traffic management system and the drivers on the network.
The components of MITSIMLab are organized into three modules, demonstrated in Figure 3-1 below:

![Diagram of MITSIMLab Modules]

**Figure 3-1: MITSIMLab Modules**

The traffic flow simulator (MITSIM) is a microscopic simulator, which represents the network elements and layout along with the movements of individual vehicles. This level of detail is advantageous and necessary for technology evaluation at the operational level. Traffic controls and surveillance devices can be represented by objects in the network, which is represented by links and nodes. Links are further divided into segments (stretches of the link exhibiting uniform geometries) and lanes. Traffic volumes are represented by time-dependent origin-destination (OD) trip tables, which can be developed to represent expected future conditions, or a scenario for evaluation (for example, a hypothetical level of demand generated by a new development, or by a one-time large event such as the Olympics). Driver’s route choice decisions are represented using a probabilistic route choice model is used to capture route choice decisions and it has two forms: path- or link-based. The path-based model is path-size logit model (Ramming, 2001 ). The link-based model calculates the probabilities of choosing an outgoing link at each intersection. Drivers make route choice decisions either pre-trip or en-route (based on information received from Variable Message Signs (VMS) or in-vehicle devices). The expected travel time to one’s
destination for each alternative downstream link at an intersection can be time dependent. The expected travel time depends on the type of information the driver has access to. If no information is available habitual travel times are used.

The traffic management simulator (TMS) represents the traffic control and routing logic being evaluated. The control and routing strategies generated by the traffic management module determine the status of the traffic control and route guidance devices. Drivers respond to the various traffic controls and guidance while interacting with each other. TMS has a generic structure that can represent different designs of such systems. It can represent traffic control logic at various levels of sophistication; such as pre-timed to traffic actuated traffic signals. A wide range of control devices and logic has been implemented in the TMS. The modular structure of MITSIMLab allows the addition of other features in TMS without affecting other components of the laboratory. The following components are currently simulated:

- Ramp control
- Freeway control
  - lane control signs (LCS)
  - variable speed limit signs (VSLs)
  - portal signals at tunnel entrances (PS)
- Intersection control
- Variable Message Signs (VMS)
- In-vehicle route guidance

The graphical user interface (GUI) not only allows verification of the inputs into the simulation, but also facilitates viewing of different outputs such as flows, speeds, and path choices, and the state of signals and signs in the network. The GUI is also used for calibration purposes. Output from the simulation can be obtained both in text form as well.
The modular structure of MITSIMLab makes it extremely flexible, and able to accurately model different types of traffic networks and new traffic management technologies and applications. Key features of MITSIMLab include the separation of the microscopic simulator from the traffic management simulator; the capability of modeling traffic information systems, and the sophisticated representation of driving behavior.

First, the microscopic traffic simulator (MITSIM) and the traffic management simulator (TMS) can be run on separate processors since they are separate programs, allowing testing of different traffic control algorithms. This structure has been successfully used in the Boston Central Artery/Tunnel project among others to evaluate different ramp-metering algorithms, optimal placement and operation of lane use signs, and new incident detection algorithms and incident management strategies. Furthermore, the TMS can be replaced with existing traffic management software to allow evaluation of current systems. As agencies use and employ traffic management and incident management strategies to optimize network operations, including minimization of delays in the network, the capabilities of MITSIMLab to model management strategies are a key component of benefits evaluation.

Second, traffic information systems can also be represented, due to the modular structure of MITSIMLab. The models in MITSIMLab include explicit representation of a driver’s familiarity with a traffic network, access to traffic guidance and information, and the driver’s response to the traffic information. Thus, emerging information technologies can be incorporated into the simulation, and resulting benefits in terms of delay impacts and safety impacts can be evaluated.

Third, the sophisticated representation of driving behavior differentiates MITSIMLab from other traffic simulators. In MITSIMLab, new driving behavior models have been developed and
calibrated, and existing models have been enhanced. For example, MITSIMLab incorporates the state of the art in the following models:

- car following under multiple regimes
- mandatory and discretionary lane changing
- forced merging and courtesy yielding
- response to incidents and events
- compliance with signals and signs, and
- strategic lane choice (the lane choices of drivers which allow them to follow their paths downstream).

Rigorous econometric methods have been developed for the calibration of the different parameters of these driving behavior models. Again, the modular structure of MITSIMLab allows incorporation of and experimentation with new behavioral models, such as those related to new technologies, in addition to the models above.

Several transportation technologies can currently be represented in MITSIMLab; for example, electronic toll collection and variable message signs are incorporated into the models. More recently, enhancements have been made to MITSIMLab which better represent fleet management technologies such as automatic vehicle location and traffic signal priority. As well, as part of the incident management evaluation capability in MITSIMLab, the capability of representing incident detection technologies and evaluating incident impacts is also represented. The incorporation of these technologies facilitates the evaluation of key benefits of delay, safety, and environmental benefits identified in Chapter 2. The implementation of these technologies in MITSIMLab is described briefly below.
3.3 Transit Modeling Capabilities

Recently the capability of modeling transit supply and demand was implemented in MITSIMLab. Morgan (2002) wished to capture the complex interactions between different modes of an urban transport system, as well as between the transit system and its users. By capturing these complex interactions, MITSIMLab can now be used to simulate observed bus transit phenomena, such as bus bunching, and estimate their impacts on system-level and/or passenger-level measures of performance. He further states that the transit models also simulate the generation and distribution of real-time bus operations data from field-deployed technologies such as Automated Vehicle Location (AVL) and automatic passenger counters. The modular structure of the transit representation allows for the simulation of emerging APTS technologies (Morgan, 2002).

Morgan divides the requirements for modeling and evaluating APTS in a simulation framework into the following categories:

- Transit System Representation
- Transit Vehicle Movement and Interaction
- Transit Demand Representation
- APTS (Advanced Public Transportation Systems) Representation
- Measures of Effectiveness

Of particular interest to this thesis are the APTS representation and the measures of effectiveness which Morgan establishes.
Within the APTS representation lies the ability to model AVL, or Advanced Vehicle Location, described in Chapter 2. Morgan accomplishes this through the extension of MITSIMLab's representation of data ownership (which vehicle or object possesses operational data), storage (how long an object holds the data before acting upon it or disseminating the data to another object) and distribution (how and to whom the data is disseminated).

With regard to data ownership, vehicles in MITSIMLab are aware of their type (car, bus, truck, or other vehicle), location in the network, and path through the network. Morgan extends this by adding the capability for separate bus vehicles to retain records of their current bus route, design headway and prevailing headway, next scheduled arrival time and schedule deviation, and passenger load. Different types of buses can be represented in the simulation; for example, buses equipped or not equipped with AVL. Furthermore, since a bus maintains records of its current trip and route, a bus can provide information which is route-based in addition to the network-based information retained by all vehicles in the simulation. Headway information is important as an input to various traffic signal priority strategies; for example, if a vehicle is behind schedule with longer than usual headways, a traffic signal priority strategy can be invoked in order to speed the vehicle through its route to bring it closer to its scheduled arrival times.

Data storage does not play a large role in the transit representation. MITSIMLab usually stores the latest information from each bus, and transit operations centers usually need the latest information for operational strategies. Data distribution becomes important in modeling transit control strategies, however. Morgan establishes this representation of information distribution in MITSIMLab for transit vehicles, such as the passenger load and schedule deviation information that an approaching bus might deliver by radio signal to a signal controller to request priority, by using sensors embedded in the network. The sensor represents the communication between the vehicle and the roadside device. A sensor can be placed in the network at a distance upstream of
the field-installed device (e.g. signal controller) that corresponds to the range of the transmitting and receiving devices. A sensor can be configured to respond only to certain vehicles (e.g. GPS-equipped buses). This capability is utilized in the signal priority strategy in the case study in Chapter 5.

Morgan establishes new measures of effectiveness appropriate to the new representation of transit operations. Where MITSIMLab already yields output measures of performance at system-wide and link or segment levels, new dimensions had to be added to properly give an idea of how the transit system is performing. New measures of effectiveness include passenger-level outputs such as aggregate travel times and waiting times, stop-level outputs such as headway, dwell time, and the numbers of boarding and alighting passengers, and bus-specific outputs or data such as route ID, bus ID, location in relation to origin, passenger load, and schedule deviation at the previous stop.

With the implementation of this more sophisticated representation of transit operations, benefits such as delay (in terms of network delay, individual vehicle delay, and now passenger delay) can be analyzed, and by extension input into models which analyze safety measures and environmental measures.

3.4 Traffic Signal Priority

A generic traffic signal controller was implemented in MITSIMLab with a flexible logic that allows it to simulate a wide range of traffic signal control types and strategies. These control strategies include both isolated and coordinated intersection control, with fixed-time and demand-responsive logic. The controller is also designed with a modular structure that allows specialized
features of advanced control strategies to be implemented within the controller framework. This framework is used to implement transit signal priority in MITSIMLab, allowing the simulation of both passive and active signal priority strategies (Davol, 2001). In particular, the PRIBUSS system in operation in Stockholm was modeled using the generic traffic signal controller module.

Davol reduced the logic to its basic form: the decision of whether to hold the current indication (color on a signal face) or to change it. He also reduces the inputs to their basic form, including time-based inputs, data from sensors on the network, and data from other signals and controllers.

He extends this logic and instead of representing controller operation through time progressions (or signal phases), he develops a method of representing signal operation through vehicle movement progressions (or signal groups). The signal group thus becomes the "structural unit" of the generic signal controller. As part of the controller logic, different conditions are evaluated for each signal. He specifies four different conditions, corresponding to different actions: general conditions perform miscellaneous functions, change conditions advance the signal group to the next period, hold conditions keep the group in the current period, and skip conditions indicate that the next specified number of conditions should be skipped.

The controller again illustrates the flexibility and modularity of MITSIMLab. It provides a foundation for future modeling of adaptive control strategies, which optimize operations in the network in real-time according to current traffic volumes. This can be accomplished by directly coding the logic using the generic controller, or by connecting the generic controller physically to an external logic module. Furthermore, different types of controllers, such as the NEMA controllers in use in the US, or European controllers, can all be represented. Of relevance to this thesis is the capability of the generic signal controller to model traffic signal priority, which in conjunction with the advanced public transportation systems modeling capability discussed in
Section 3.3, allows evaluation of traffic signal priority implemented in Stockholm, as part of the case study in Chapter 5. Thus, the possible reduction of network delays and by extension, the impacts on the benefits of safety and environmental consequences, can be explored.

3.5 Incidents and Incident Management

Incidents are lane blockages or capacity reductions caused by disabled vehicles, road construction, and other unforeseen events. Yang (1997) establishes a mechanism for representing incidents in MITSIMLab. Incidents simulated in MITSIMLab can be placed anywhere in the network and activated and cleared at any particular time. Each incident may be specified as affecting one or more lanes.

Incident data is read from a scenario definition file. The information for an incident includes: visibility, number of lanes affected, and location (segment and longitudinal position). Lane specific information for an incident includes the severity of the incident and its length, maximum speed, start time, and expected duration. The maximum speed of an incident sets the upper bound on the speed of the vehicles passing the incident, which can be used to simulate the rubber-necking effect of partial blockage incidents. The start time of an incident may differ from the time that the incident is detected by the traffic management system. The clearance time of an incident is its start time plus duration by default, but it can be shortened by IMS to a time before the “scheduled” clearance time. Thus, different incident detection and management schemes can be evaluated.
3.5.1 Incident Management

Along with the simulation of incidents in MITSIMLab, the a rule-based incident management scheme is included in the TMS module. Currently this incident management scheme applies only to the operations of traffic signals and signs, and not to the emergency units. The response plans are pre-determined and response delay is user defined.

Yang explains that incident management in TMS is represented by response plans, which specify the states of the signals and signs in the network at various stages. In the current implementation, incident response plans are designed only for lane use signs, portal signals at the entrance to a tunnel, variable speed limit signs, and variable message signs.

Each response plan consists of one or more response phases and a final clearance phase. Each phase is assigned an activation delay and a set of predefined actions to be taken at various situations. In the first response phase, the activation delay is defined as the interim time between when an incident is detected/confirmed and the actions are implemented. The delay for subsequent response phases is the elapsed time since the implementation of the previous phase. The final phase of a response plan is called clearance phase, which defines the actions to be taken when an incident is cleared. These final actions usually restore the devices to their default state. The corresponding activation delay indicates how long the system will wait before it restores the devices to their default state after the incident is cleared.

In implementing incident management in TMS the following parameters have been defined to select appropriate actions: (i) situation code; (ii) device type; (iii) affected region; and, (iv) signal/sign state.
The situation code determines whether or not the corresponding action applies to a particular situation. Situations are characterized by the severity of the incident and how any emergency vehicles will access the incident site. These situations can include lane blockage, where an incident can cause a partial or full blockage of a lane, and emergency vehicle access, specifying if emergency vehicles approach the incident, and if they approach the incident from upstream or downstream. If the full blockage situation is in effect, downstream access may be the only choice.

The device type specifies the types of signals or signs a given action affects. The following control devices can be used in the current incident management module: (i) lane use sign (LUS); (ii) variable speed limit signs (VSLs); (iii) variable message signs (VMS); and (iv) portal signals (PS).

The affected region defines the area where signals or signs are of relevance to the given action. Four variables are used in defining an affected region. Two of them define the reference points (e.g. incident position, upstream, or downstream portal signals), and the other two define the relative distance from the specified reference point to the start and end points of the region.

The signal/sign state specifies a designated state, depending on the device type, representing a signal color (LUS or PS), message ID (VMS), or a speed limit (VSLs), for each of the signals or signs in the affected region. For VSLs actions that change speed limits gradually over the space, the state is specified by two variables: an initial state and a step size. In this case, the speed limit is set to the initial state for the first sign and varies for the remaining signs in the region, according to the step size and predefined upper and lower bounds for speed limits.
When an incident occurs in MITSIMLab in the current implementation, a message is sent to TMS to describe the characteristics of the incident such as position, severity, duration, etc. A detection delay is added to the activation delay of the first phase of the incident response plan. This detection delay is a function of the method used for incident detection.

After an incident is confirmed, the activation time for the first phase of each response plan is scheduled. This response phase is activated at the scheduled time, and after its activation, the next phase is scheduled again. These operations proceed phase by phase until all phases specified in the response plan are completed. When a response phase is activated, all related actions are executed. In searching the signals and signs that are of interest to an action, a breadth-first search algorithm is used. The search begins from the start point and moves toward the end point(s) of the affected region. All the control devices of the given type found in the affected region are then set to the designated state (Yang, 1997).

The detailed capability of modeling incidents and incident management schemes in MITSIMLab as described above, along with the microscopic modeling properties of the simulator, allow the full delay impacts of an incident to be represented. The effects of the incident on different segments of the vehicle population (at the network level, by vehicle type, or the delays by origin-destination pairs of interest) can be identified and quantified through the travel time delays and link or segment densities. Once these measures are obtained, impacts on increased safety in the network and also reduced environmental impacts can also be quantified.

Furthermore, Thill and Rogova (2001) point out that although benefits evaluation usually focuses on systems consisting of multiple elements (for example, an incident management system or a traffic management control center), it is often desirable or necessary to evaluate benefits independently of other elements. For this, an understanding of the interactions between the ITS
elements is necessary, so that interactions between elements can be captured and double-counting of errors minimized. In MITSIMLab, when considering the measures of effectiveness and benefits evaluation for different technologies and capabilities such as those mentioned above, a system- or network- wide view can be taken where all the technology elements are simulated at once, so that their collective impacts may be ascertained. In addition, elements may be simulated independently of other elements, allowing one to pinpoint impacts of particular technologies.

3.6 Summary

This chapter summarizes the structure of MITSIMLab and its new and existing modules which represent technologies and applications such as advanced vehicle location, traffic signal priority, and incident management. The following chapter describes some policy issues of interest to the case study in Chapter 4, followed by the case study in Chapter 5 where many of the elements described in this chapter are implemented with relation to a real situation in Stockholm, Sweden.
Chapter 4

Policy Issues

4.1 Introduction

This chapter supplements the benefits simulation methodology developed in Chapter 3 by discussing policy implications in the context of transit agency operations in Stockholm, Sweden. By comparing and contrasting perspectives on ITS and ITS applications in the US and in Sweden, and exploring key policy issues of interest to the Stockholm transit agency, background will be developed for quantification of technology benefits in Chapter 5 through the case study in Stockholm.

Section 4.2 provides general background on SL, the Stockholm transit agency, and introduces key policy issues of interest to SL. Section 4.3 explores these issues in greater detail and surmises how each of them respectively might fit in with the benefits evaluation framework established in Chapter 3. The discussion culminates in Section 4.4 with a recap of these policy issues as illustrated by SL’s current activities, and how they can be introduced into the benefits evaluation framework.
4.2 Background: Storstockholms Lokaltrafik

In order to give context to the following policy discussion, a description of SL structure and goals is described. This information in this chapter was obtained from transit agency employees, Stockholm Transportation Department employees, and from local publications.

Storstockholms Lokaltrafik (SL) is the public transportation agency which serves the Stockholm metropolitan area. This area comprises 26 municipalities and covers an area of 6,500 square kilometres. The population of the metropolitan area is approximately 700,000. In the year 2000, SL's bus fleet comprised approximately 1680 buses, and 1.5 billion passenger kilometres were traveled by bus (EMTA, 2002).

The goals in SL's strategic plan closely parallel those outlined in the general ITS Goals for the US outlined in Chapter 2 (Table 2.1), especially in the areas of throughput and mobility. SL would like to significantly increase market share of public transport, aiming for an increase in the number of daily travelers on SL from 640,000 passengers per day in the year 2000 to 700,000 in the year 2004. Attainment of this market share goal would reflect both increased service levels and increased capacity due to new technologies. SL also states that it would like to increase the "satisfaction of passengers” from 58% in 1998 to 75% in 2004 (EMTA, 2002). Satisfying passengers includes a commitment to provide passengers with "simple and fair" trips.

A recent addition to the SL system has been the "trunk route" network. The new buses on these five routes which traverse the inner city area are given priority over other traffic. Bus stops for the trunk route network are located to minimize distances to other trunk routes, local bus routes,
the subway or commuter trains. In addition, to decrease passenger travel times, bus stops on the
trunk network are spaced at greater distances from each other than for local routes. This system
makes use of the technologies described in previous sections: AVL, signal priority, and
automatic passenger counters. Furthermore, SL has plans to incorporate modern electronic
payment systems into its fleet. These improvements further illustrate SL’s commitment towards
achieving the benefits discussed and identified in Chapter 2 – improvements such as faster and
more reliable travel times (in the “delay” category identified in Chapter 2), more comfortable,
easily navigable and user-friendly bus services (in the “customer satisfaction” category), and the
deployment of ethanol-powered, low-floor, articulated buses (in the “energy/emissions”
category).

4.3 Key policy issues pertaining to technology deployment

Key policy issues were identified through discussions with SL officials, City representatives,
consultants, and through recent publications and websites. At first glance, key policy issues
pertaining to public transportation technology deployment and benefits quantification in
Stockholm appear to parallel policy issues of APTS deployment in the US. These issues include
stakeholder relationships, technology integration and regional integration. The general simulation
methodology developed in Chapter 3 can be extended to include these policy issues (and others)
and illustrate how simulation can be used to illuminate policy decisions pertaining to technology
deployment. The issues are explored below each followed by their roles and representations in
the simulation process.
4.3.1 Stakeholder Perspectives and Interests

Different stakeholders must communicate, interact and cooperate for effective deployment of transit technologies and realization of benefits. In general, the stakeholders include the following:

- Agency
- System users
- Contractors/operators
- Vendors
- Public agencies
- Non-users

The transit agency, SL, is an "umbrella" brand in Stockholm for different subsidiaries and contractors, described in detail below. The agency is responsible for data collection, operations and planning, new transit projects, intermodal projects and cooperation with other agencies. The system users perceive the benefits of the system, and in turn their perceptions and usage affect the level of service of the system. The contractors must design, install, build, test, and operate the system or system components. The level of quality experienced by the customer is a result of dealings with the particular contractor of the transit services. Thus, in order to attain a high degree of customer satisfaction, it is crucial that the contractors strive for certain goals which will be translated into both perceived and actual benefits for the customer. Service agreements between SL and the contractors emphasize punctuality, information about service delays, coordination between trains and buses, vehicle on-time performance, staff behavior, and safety. There is continuous adaptation of services to reflect passenger requirements and needs. The interplay between the users, the agency and the contractors is important in establishing both
standards and feedback regarding which and what level of benefits should be realized by SL’s services.

Stockholm is an interesting field study because, unlike many U.S. cities, SL is a brand of public transportation and through tendering procedures, operates services through five large traffic contractors. These contractors include Busslink, which operates over half of SL’s bus services; Citypendeln, responsible for all the commuter train services; Connex Tunnelbanan, responsible for subway services; Linjebuss, responsible for bus service, and Swebus, responsible for bus services. Thus, benefits quantification by SL is important not only for bus services, but for all elements of the transportation system including train and subway. The benefits quantification framework must be applicable to different transportation services and different technologies used for those services.

The contractors not only cooperate amongst themselves, but must negotiate and talk about benefits with other stakeholders. For example, Takyi (2001) observes: “Integrating sub-systems – or components of hardware or software – is handled by a system integrator through a public-private contracting process. Managing the integrator (or contractor) and ensuring that the integration is completed successfully in an open-modular form are the keys to a successful multi-regional transportation management system”. Thus, this issue not only illustrates the importance of cooperation among stakeholders, but it touches upon two other policy issues, technology integration and regional integration, discussed in Sections 4.3.2 and 4.3.3 below.

Vendors must also be aware of technology benefits in order to maintain and improve their products. Are there quicker ways to perform vehicle location, or more efficient manners of performing electronic payment? The vendors must have a manner of assessing the effects of new
technologies on SL before mass deployment; conversely, an assessment or evaluation must take
the vendors' product quality and functionalities into account.

Non-users include drivers, pedestrians, and other citizens. A key benefit of importance to these
stakeholders is safety. For example, Stockholm's "Peace in the Streets" project is a cooperative
venture between SL, schools, the police, Stockholm's Traffic Department and the City Council
(TRB, 1998). This project shows cooperation between SL and other entities, the good reputation
of SL as perceived through high safety levels), and the importance of safety as a benefit. The
BEST (Benchmarking Experience in Scanadanavia) project, described further in Section 4.4
below, illustrates the importance of the entire system, including passengers and non-passengers,
to SL. The BEST project is an ongoing survey of Stockholm residents, both users of transit and
users of other modes, regarding different measures of effectiveness of the transit system.

Thus, stakeholders in SL's effective operation encompass a wide range of groups: users, the
agency itself, contractors, vendors, public agencies, and non-users. When quantifying benefits of
the transportation system, simulation can take into account attributes of different stakeholders.
For example, transit passengers (users) and other drivers and pedestrians (non-users) can be
assigned various behavioral attributes in the simulation (personal attributes such as aggressive or
non-aggressive, or technology-related attributes such as informed (about travel time information
and incidents) or not informed), and their choice behavior replicated through various models in
the simulation. The transit agency itself is represented by the Transit Management Center in the
simulation (illustrated in Figure 3.1 in Chapter 3), which can replicate certain operational
decisions made by the transit agency (for example, what to do in response to an incident). The
technology itself is replicated to a high degree (for example, bus attributes can be defined in the
simulation, as can traffic signal priority parameters), reflecting the interests of the vendors and
public agencies (such as the state or local agencies who govern the right-of-way on which traffic
signal priority is located). Parameters might also reflect behavior of the contractors, represented by the drivers of the transit vehicles in the simulation.

Furthermore, benefits obtained from new technologies are perceived differently by different stakeholders. A common example in signal priority is that the transit passengers experience less delay, yet non-users of transit may experience higher delay. When quantifying benefits, these differing perceptions should be taken into account. These concepts will be illustrated through the case study in Chapter 5.

4.3.2 Technology Integration

SL must deal with several issues as it improves its services and deploys different and newer technology components throughout the system. In his classification of different levels of integration, Takyi (2001) observes that technology integration is time-sensitive and market-based. Dissimilar technologies developed at different times with different capabilities can present problems when being integrated; for example newer versions of hardware or software may not easily interface with components previously linked to older components. Although simulation can never replace actual field tests preceding technology deployment, simulation can be used to assess the effects of different technologies and combinations of technologies at larger scales, and to compare technologies under different conditions. Takyi further points out that “there is the challenge of building large databases of technological systems for individual units while ensuring jurisdictional independence”, providing the example of New York City Transit where the bus stop management GIS database needs to be maintained and operated independently of the scheduling and AVL databases, yet the three databases must be coordinated.
In addition to hardware and software interoperability, data compatibility must also be considered when integrating different technologies. In the US, the National System Architecture provides standards upon which to build ITS systems. When representing these technologies, this data compatibility and data flow should likewise be represented in the simulator as closely as possible. Thus, considerations pertaining to hardware, software, jurisdiction and cooperation between agencies, and data compatibility affect SL's perception of benefits from new technologies.

There are several examples of technology integration in SL's operations and how simulation can be used for analysis of this integration and subsequent benefits. For example, the SL bus trunk network consisting of five bus lines traversing the city with reserved lanes has signal priority throughout the network. Equipped buses transmit information to the intersection signal controller to trigger priority. Alternatively, in order to trigger signal priority based on load levels, the system might eventually be integrated with automatic passenger counters, or eventually, electronic fare payment systems which can capture demand data. In his enhancement of MITSIMLab, Morgan implements the capability of representing such integration: conditional signal priority which can be triggered by load levels, schedule deviation, or headway (Morgan, 2002).

This capability of representing the integration of signal priority and passenger counters or electronic fare payment applications might further be extended. At SL bus stops, customers have electronic displays informing them of the time of an oncoming bus. With additional information regarding bus loads, customers might choose to take a different route or mode, or to cancel their trip altogether. Thus, this customer information system, (technology giving passengers information regarding bus loads) coupled with models regarding choice behavior, might later be integrated with the representation of signal priority, and demand data-collecting devices such as automatic passenger counters and electronic smartcards.
4.3.3 Regional Integration

Regional integration is a key planning issue in Stockholm. Regional integration is important because the functional region of Stockholm extends beyond county boundaries. People commute to jobs from outside the county, and the housing problem can be partially solved outside county boundaries. Residents of Stockholm can choose to study outside the county, and residents from outside Stockholm may partake in cultural events within the city. Thus, there is a pronounced need for integration of services across county lines (ORPUT, 2000). Current infrastructure projects traversing the region also illustrate the need for regional planning and strategic public transport planning. These include the construction of a new outer ring road linking the northern part of the region with the southern part, and the construction of a complete ring road around the inner city. A tunnel under the center of Stockholm will enclose two additional tracks for commuter trains, and several train lines will be expanded (RTK, 2001).

There is thus clearly a need for larger coordination between Stockholm and surrounding regions. One mechanism for, and outgrowth of, achieving this integration is the planned SL smartcard system discussed by SL officials. The system within Stockholm is a zone-based system, where a flat fare for each of five zones is in effect for both rail and bus services, regardless of which mode is chosen within SL services. The majority of SL’s passengers use season tickets or passes. SL is planning on introducing a smartcard payment system by 2003 which may coordinate several different services pertaining to, and outside of, public transportation such as retail and commercial applications. The card would be rechargeable.
Lessons from the US would be useful as Stockholm prepares for these applications, so that SL might capitalize on the opportunity for improved regional operations. In the US, development has been coordinated with other local information systems and technology applications. In order for this system to succeed, it has been suggested that implementers be able to develop specifications or an architecture, and also demonstrate a proven ability to work across different sectors, such as retail and commercial applications, navigation and congestion information from the public and private sectors, and entertainment information.

Partnerships for these types of applications have been established in the US; for example, in the Bay Area in California, the Metropolitan Transportation Commission (MTC) wants to introduce non-transit partners to its TransLink smartcard program, ranging from merchants and sports teams to a possible collaboration with San Francisco's department of parking and traffic to accept the card on parking meters (Mass Transit, 2002). Coordinating multiple fare structures also calls for concessions from participating transit agencies. For example, although SL operates as an umbrella manager for the transit providers, there can still be issues pertaining to fare levels, and technology integration throughout the system. The smartcard should be readable throughout SL on its different vehicle types (buses, subways, commuter rail), while modular in order to incorporate future unknown applications.

When looking at regional integration issues, it is difficult to use microscopic simulation by itself to analyze regional policy implications, because regional models have a more aggregate representation of activity and demand. However, SL's goal of increasing ties across regions affects transit representation in a simulation model. For example, technology deployments such as the new smartcard system in 2003 would affect dwell times at stops, passenger mode choice and thus transit market share, and signal priority (due to possible capability of the smartcard system to transmit load levels to the signal controller, thus triggering priority).
4.4 Current Directions

The above sections briefly illustrated three policy issues of great interest to SL: stakeholder relationships, technology integration and regional integration. In each section it was observed how simulation fits in with the evaluation of technologies germane to that particular policy. Thus, the discussion has been developed along the dimensions of benefits, technologies, and policies. A discussion of SL’s treatment of various benefits measures as defined in Chapter 2 will demonstrate that SL is perceived as leader among transit agencies in Europe. Since an enhanced benefits quantification framework must show the interplay between benefits quantification and policy decisions, SL is a good subject for application of this framework due to its high profile and leadership role among transportation agencies in Europe. The discussion below culminates in this enhanced framework. Such a framework could assist SL or another transportation entity in maintaining and further enhancing this reputation among various stakeholders (customers, operators, and vendors), and in making improved operational and planning decisions including funding decisions, technology procurement decisions, and regional integration efforts.

As with many transit agencies, customer satisfaction is the umbrella consideration under which SL measures other benefits pertaining to throughput, delay, safety, the environment and productivity. SL aims to offer customers a “fully developed transport system – easy to use, reliable, pleasant, and affordable, with reasonable journey times” (SL, 2002). Quality management focuses on areas such as customer satisfaction, product development as related to customer’s needs, and contractor role in delivering customer satisfaction. Again, we see the different stakeholder perspectives outlined in Section 4.2.1 above. This commitment to customer satisfaction is further illustrated by SL’s Travel Warranty, which is SL’s offer to pay for a
customer’s taxi fare in “larger disturbance” situations (EMTA, 2001). Furthermore, SL designed a campaign entitled “Operation Safety” to create a safer environment in the SL transit system by reducing vandalism and violence. Along with installing an alarm and surveillance system, SL doubled its security force and established closer ties with the police department (TRB, 1997).

A “quality barometer” is performed bi-annually consisting of automated counts, on-board surveys, household surveys by telephone and more recently, SL is experimenting with collecting data through internet surveys. Data collected is standard statistical data such as number of boarding and alighting passengers, running times, stop times at bus stops and traffic signals and schedule adherence (Hardis, 2002).

The central importance of customer satisfaction is underlined by an ongoing competition designed and administered by SL. The “SL Challenge”, also known as “BEST” (Benchmarking Experience in Scandanavia) started in 1999 and focuses on citizen and passenger experiences in various European cities. The goal of the competition is to be the best transit agency in Europe as measured through annual rounds of comprehensive questionnaires to citizens (users and non-users of the transit agency) in each respective city. Participants now include Stockholm, Helsinki, Oslo, Copenhagen, Turin, Munich, Barcelona and Vienna. The finals and prize distribution will take place in Stockholm in June, 2005.

The survey questions probe dimensions such as traffic operation, travel time reliability, traveler information, staff behavior, safety, comfort, social benefit, value, and general satisfaction (Lausten, 2001). Aside from these direct measures of customer perceptions of benefits, the process itself of administering this project has led to several benefits on a larger, region-wide scale. These benefits shared by the European participants in BEST include lessons that may be used in other fields of transport (for example, fare policy lessons carry over into pricing of other
transportation services), methodologies from other industries (for example, to incorporate current thinking regarding the issue of branding, the BEST group used experience from the food industry, that of Arla Foods), and also close network ties among the participants themselves. These ties within the BEST network will lead to technological cooperation, sharing of ideas on operations and planning, and ongoing innovation as the cities continue friendly competition to be the best transit agency by 2005.

Although other, perhaps larger-scale, benchmarking initiatives have been launched (for example, the benchmarking effort started by the European Commission in 2001 comparing transport networks in 50 cities, along dimensions such as intermodality, ITS accessibility, and value for money (Eltis, 2001)), this SL effort is relevant to discussion because it measures similar benefits, yet illustrates other policy issues through the benchmarking process itself.

Tying these lessons with the discussion in previous sections, it is clear that going the next step after identifying and rating technology benefits, to quantifying them, is closely intertwined with policy decisions made by the transit agency. Not only do policy decisions impact the benefits of interest to be quantified (for example, security and safety is a predominant theme in this age), but conversely, the actual quantification of benefits can have a strong impact on policy decisions. As explained in Chapters 2 and 3 of this thesis, simulation is a key tool for the benefits quantification process. The general evaluation procedure followed in most of the literature surveyed, and used as a starting point in this thesis, is illustrated in Figure 4.1. MITSIMLab is the microsimulation tool which will be used to illustrate the benefits for a particular network in Stockholm in the following Chapter. The policy discussion generated in this chapter enhances the benefits evaluation framework for a more complete understanding of the impacts from and on the procurement of emerging technologies.
4.5 Summary

Thus, in Chapters 2, 3, and 4, connections were made between a transportation network, ITS technologies, benefits identification, simulation, benefits quantification and subsequent policy analysis. A feedback loop between policy decisions and quantified benefits is important as it recognizes the interdependence between these elements. In the following chapter, a comprehensive case study in Stockholm using data from SL, the City of Stockholm, and using MITSIMLab as a simulation tool will illustrate evaluation of transportation benefits for which informed policy development by SL is so important.
Chapter 5

Case Study

5.1 Introduction

The results of this case study will show the effectiveness of MITSIMLab as a tool for quantification of the benefits of reduced delay, reduced environmental impacts and increased safety, discussed in the previous sections. These benefits can ensue from either alternative construction, or from usage of new technologies (ITS), or from both, and the results from MITSIMLab simulations can be used as a basis for recommendations in all cases.

The primary benefit metric used will be the change in overall user delay, as well as the change in delay (or change in travel times) for various origin-destination (OD) pairs of interest. The change in overall user delay is defined as the aggregate increase or decrease in travel time resulting from the infrastructure change or technology implementation. Certain OD pairs are selected because they travel through areas pinpointed by local residents and also pinpointed during preliminary MITSIMLab simulations as being problem areas. These problem areas are defined in Section 5.4. Segment statistics are also analyzed in order to depict network operations and possible problem areas.
Two simulation networks of an actual area in Stockholm, Sweden are developed using current data from the Stockholm Traffic Department. The first network is the existing infrastructure. The second network is an infrastructure expansion consisting of a tunnel diversion and rotary combination ("tunnel network") underneath the main motorway. Three scenarios are explored. Taken together, these analyses will illustrate the usefulness of MITSIMLab in assessing the benefits of traditional infrastructure projects, along with the benefits of emerging technologies.

The first section of this chapter will describe simulation setup, including the project networks and data. The main part of the chapter describes the results of the simulations.

5.2 Project Description

This network, which we will refer to as the North West Kungsholmen (NVK, in Swedish) network, was chosen for several reasons. First, the City of Stockholm has targeted this area for heavy redevelopment within the next few years. Several transit lines pass through this area, and numerous PRIBUSS signals which invoke signal priority are present in the network. The network will be described in more detail in the following sections. Second, MITSIMLab was calibrated to traffic conditions in Stockholm under a different project in 2001 (MIT ITS Lab, 2001). The network for that project was just northwest of Stockholm, in the Brunnsviken area, and consisted of over 8 kilometres of roadways. Calibration was performed using methodology developed by MIT based on aggregate traffic data. This NVK network is much smaller in scale than the Brunnsviken network, and will be used to assess the benefits of transit technologies in an urban network setting unlike the motorway setting of the Brunnsviken project. Third, transit enhancements have been implemented in MITSIMLab using a second network in Stockholm, just
southeast of the NVK network, in the Hornstull area. This network was used for testing of signal priority and transit modeling and behavior enhancements.

The North West Kungsholmen network is located in the western part of Stockholm and covers an area of approximately 4 square kilometres. Two main motorways traverse the network. Essingeleden (Motorway E4) runs in a north-south direction, and Drottningholmsvägen runs in an east-west direction. The network is bordered by bridges ("bron" in Swedish): Ekelundsbron to the north, Tranebergsbron to the west, and Fredhällsbron, Mariebergsbron, and Västerbron to the south. Central Stockholm is located 2 kilometres east of the network. This section of Stockholm consists of industrial and residential developments. The area is highlighted in Figure 5-1 below.

![Figure 5-1: Project Location](image)

Public Transportation in Stockholm is provided by SL, or Storstockholms Lokaltrafik. The system has a fleet of blue and red buses, and a subway system cutting through the city. The Stockholm public transit system serves the area with Blue Lines 1, 3 and 4, and Red Lines 49, 57,
59, 196, 197, 198 and 396. Signal priority is present in the network, along Lindhagensgatan.
Two signals operate under PRIBUSS, a signal priority strategy developed for use in Stockholm.
A diagram of the area, including transit routes and signal priority locations, is shown in Figure 5-2 below.

![Diagram of transit routes and signal priority locations](image)

Figure 5-2: Signals and Transit in NVK Network

Numerous residential and industrial developments are being planned in order to spur economic growth in the area. In conjunction with these developments, transit services must be adjusted or expanded accordingly (for example, bus frequency can be increased or decreased, or service area and routes can be adjusted according to the new development densities and new employee/resident travel patterns).
At present, there is no manner in which drivers through the network can reach Drottningholmsvagen westbound directly from E4 southbound. Drivers currently follow a circuitous route (current route shown in Figure 5-3), along Lindhagensgatan and then through the rotary and back onto Drottningholmsvagen, due to the lack of a direct off ramp from E4 to Drottningholmsvagen.

![Diagram](image)

Figure 5-3: Existing Route through NVK Network

Several plans are under discussion to allow direct connection between the two motorways. The main plan involves construction of a rotary and tunnel to replace the Kristineberg interchange (in the center of the network), thus allowing E4 southbound drivers to obtain direct access to Drottningholmsvagen westbound (the tunnel route in Figure 5-4).
Thus, the NVK project can be analyzed along several different scenarios:

- Infrastructure expansion: tunnel network vs. existing network (Section 5.4)
- Increased demand: Impacts of new residential and commercial developments on both networks (Section 5.5)
- Transit operations: Effectiveness of new technologies such as transit and signal priority (Section 5.6)

Traffic microsimulation provides an excellent method for analysis of the future construction in the context of expected benefits of reduced delay, increased safety, and reduced environmental impacts. The recommendation of appropriate transit services and technologies can also be accomplished, because by evaluating the signal control logic and transit service capabilities which exist or are desired, the City and SL can assess benefits under various construction designs.
The project provides an opportunity to test recent enhancements to MITSIMLab: technology modeling capabilities in signals and transit, and also a new module to developed to estimate OD-flows. The section will conclude with operational and policy recommendations.

5.3 MITSIMLab representation of networks

Two separate networks were developed in MITSIMLab for the analysis:

1. existing NVK network
2. proposed future NVK network with tunnel under E4

The network was coded in MITSIMLab using information provided by GFK, including construction drawings, transit maps and schedules, aerial photographs, and initial studies from subconsultants. Roadway geometry was determined from the drawings and photographs where possible; elsewhere, minor roadways within the network were assumed to consist of one lane in each direction. The existing network has a total of 126 links and 68 nodes. The future network has a total of 135 links and 75 nodes. As previously described, two PRIBUSS signals are included in the network along with a total of 10 SL bus routes. The simulation networks as represented in MITSIMLab are shown in Figures 5-5 and 5-6 below.
Figure 5-5: Existing NVK Network in MITSIMLab

Figure 5-6: Future NVK Network in MITSIMLab
Twelve replications were run for each scenario. Statistics on travel time, and segment flows, speeds and densities were collected so that a picture of network operation could be obtained. Furthermore, simulation and analysis of the operation of the bus routes through the network, in conjunction with the signal priority on Lindhagensgatan, will illustrate quantification of benefits of these transit technologies.

5.3.1 Traffic Volumes

Bidirectional 1996 daily traffic volumes on selected links were provided by GFK. Preliminary origin-destination data and unidirectional link volumes for the year 2000 for the morning peak hour were taken from EMME/2 output and provided by Scandia Consult. These two data sets were used to develop the OD matrix to input into MITSIMLab, using the OD estimation procedure described in Section 5.3.3. The GFK data was normalized to the year 2002 for analysis, using growth rates determined by annual population statistics for the Stockholm area. This growth rate was calculated to be 1.99% annually. As the morning peak hour (7:00-8:00AM) was simulated for the NVK network, peak hour volumes were extracted from the daily GFK volumes using a peak hour traffic/daily traffic ratio (peak hour factor) of 10%, the accepted value used by GFK. A warm-up period of 15 minutes was built into the simulation to allow vehicles to load onto the network. Where traffic volume distributions over a typical weekday were provided (such as at the Kristineberg and Fredhall junctions), the demand was varied accordingly over the time period of the simulation using a similar distribution pattern. After this preliminary procedure, traffic volume data was thus estimated for the weekday morning peak hour in the year 2002 at various point locations throughout the network. The total volume on the network over the peak hour was determined to be about 3,800 vehicles. Paths were generated using preliminary simulations, and the resulting path set was inspected manually. Paths were added
where necessary, and infeasible paths were eliminated, thus ensuring that only feasible paths were included in the path set.

5.3.2 OD Estimation Methodology

Because data was provided at point locations (sensor locations) within the network, and MITSIMLab requires origin-destination (OD) volume data as input, an OD estimation process developed by Darda (2002) was used to determine the network traffic volumes for MITSIMLab input. In this process, an OD estimation module is one of three interacting modules (the other two being a steady state travel time table module, and a parameter calibration module) developed to achieve joint calibration and estimation of OD flows in any MITSIMLab. The three modules interact in order to achieve objective criteria, such as minimization of deviation between simulated and observed counts and/or speeds.

The inputs to the OD estimation module are:

-an a priori seed matrix.

-traffic field counts

-an assignment matrix obtained from the simulator.

In this case, the a priori seed matrix was output from EMME/2 and provided by SCC, and the traffic field counts were the 1996 bidirectional volumes provided by GFK. Forty-eight sensors on the network were used. The basic framework followed to estimate the new OD flows, using fixed parameter values and steady state travel time, is shown in Figure 5-7.
The OD estimation problem can be stated as a constrained optimization problem in which the link counts, seed-OD matrix and an assignment matrix generated by the simulation model are used to get the new estimates of the OD flows. The constraint being imposed is that OD flows are non-negative (Darda, 2002).

The error covariance matrices of both the counts and the OD flows were initially assumed to be identity and then were adjusted. The module started by computing the steady state travel time, using five iterations. Five iterations for OD estimation were then carried out. After each iteration, the new set of steady state travel times was computed and fed back to MITSIMLab. The results of this process are shown in Figure 5-8 below, and are the basis for the demand file used in the rest of the analyses.
Figure 5-8: Results of OD Estimation
5.4 Results

Upon preliminary observation of the running simulations, confirmed by discussions with GFK and SCC, it was noted that there were four main problem areas or areas of interest in the network. These key locations are shown below in Figure 5-9.

![Diagram showing key locations in network]

Circled Areas = areas of interest for observation and analysis

Kristineberg Interchange/ (Tunnel in Future case)

E4/Drottningholmsvägen Interchange

Lindhagensplan Rotary

Lindhagensgatan Intersection

Figure 5-9: Key Locations in Network
<table>
<thead>
<tr>
<th>Key Location</th>
<th>Description of Traffic Movement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kristineberg Interchange</td>
<td>on-ramp to E4 northbound</td>
</tr>
<tr>
<td></td>
<td>E4 SB</td>
</tr>
<tr>
<td></td>
<td>E4 NB</td>
</tr>
<tr>
<td>Lindhagensgatan Intersection</td>
<td>off-ramp to E4 SB</td>
</tr>
<tr>
<td></td>
<td>NB</td>
</tr>
<tr>
<td></td>
<td>SB</td>
</tr>
<tr>
<td>E4/Drottningholmsvagen Interchange</td>
<td>EB from E4 off-ramp</td>
</tr>
<tr>
<td></td>
<td>Drottningholmsvagen WB</td>
</tr>
<tr>
<td></td>
<td>E4 off-ramp to Drott. WB</td>
</tr>
<tr>
<td>Lindhagensplan Rotary</td>
<td>Drottningholmsvagen EB into rotary</td>
</tr>
<tr>
<td></td>
<td>rotary weaving with Drottning. EB</td>
</tr>
<tr>
<td></td>
<td>rotary into Drottningholmsvagen WB</td>
</tr>
<tr>
<td></td>
<td>Lindhagensplan SB into rotary</td>
</tr>
</tbody>
</table>

Table 5-1: List of Key Locations in Network

5.4.1 Travel Times, Existing vs. Tunnel networks

The travel times through the network were thus collected for origin-pairs of interest according to the above selection of key locations in the network. These travel times on both the existing network and the tunnel network are detailed in Table 5-2.
<table>
<thead>
<tr>
<th>Description</th>
<th>O</th>
<th>D</th>
<th>EXISTING network (Kristineberg Junction)</th>
<th>FUTURE network (Tunnel under E4)</th>
<th>Percentage difference between Future and Existing networks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>THROUGH KRISTINEBERG JUNCTION OR TUNNEL</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E4 SB to Drottningholmsvagen WB</td>
<td>5</td>
<td>18</td>
<td>123</td>
<td>74</td>
<td>-39%</td>
</tr>
<tr>
<td>E4 SB</td>
<td>5</td>
<td>48</td>
<td>51</td>
<td>52</td>
<td>+2%</td>
</tr>
<tr>
<td>E4 SB to Ralambshovsleden (rotary)</td>
<td>5</td>
<td>59</td>
<td>74</td>
<td>60</td>
<td>-18%</td>
</tr>
<tr>
<td><strong>EASTBOUND TO ROTARY</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drottningholmsvagen EB</td>
<td>18</td>
<td>79</td>
<td>63</td>
<td>62</td>
<td>-2%</td>
</tr>
<tr>
<td>Drottningholmsvagen EB to Ralambshovsleden (rotary)</td>
<td>18</td>
<td>59</td>
<td>58</td>
<td>58</td>
<td>+0%</td>
</tr>
<tr>
<td>Ralambshovsleden NB to Lindhagensgatan NWB</td>
<td>59</td>
<td>83</td>
<td>49</td>
<td>51</td>
<td>+4%</td>
</tr>
<tr>
<td><strong>THROUGH INTERSECTION AT LINDEHAGENS GATAN AND ON-RAMP TO E4</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ralambshovsleden NB to E4 NB</td>
<td>59</td>
<td>5</td>
<td>54</td>
<td>58</td>
<td>+7%</td>
</tr>
<tr>
<td>Kristinebergsvagen SWB to E4 NB</td>
<td>87</td>
<td>5</td>
<td>41</td>
<td>40</td>
<td>-2%</td>
</tr>
<tr>
<td>Geijersvagen SB to E4 NB</td>
<td>31</td>
<td>5</td>
<td>52</td>
<td>50</td>
<td>-4%</td>
</tr>
<tr>
<td>Ralambshovsleden NB to Ekelundbron</td>
<td>59</td>
<td>6</td>
<td>63</td>
<td>57</td>
<td>-9%</td>
</tr>
</tbody>
</table>

Table 5-2: Comparison of Travel Times on the Existing and Tunnel Network Configurations

The main journey of interest, from E4 southbound to Drottningholmsvagen westbound, indeed shows a remarkable reduction in travel time – a reduction of 39%. Although this result is expected due to the new configuration, it is useful to have a quantifiable measure of the reduction. Similarly, related traffic paths which were affected by the previous configuration (namely other drivers who had to pass through the Kristineberg junction, but whose destinations were elsewhere in the network and not Drottningholmsvagen westbound) also improve, as shown by the 18%
reduction in travel time by the E4 drivers headed towards Ralambshovsleden through the existing rotary.

The overall user delay in the network for the existing network and the tunnel network at existing demand levels is as follows:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Aggregate Travel Time for all vehicles output from MITSIMLab at existing demand levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing Network</td>
<td>54.0 seconds</td>
</tr>
<tr>
<td>Tunnel Network</td>
<td>52.7 seconds</td>
</tr>
</tbody>
</table>

Table 5-3: Aggregate Travel Times on Existing Network and Tunnel Network

The average aggregate travel time for all vehicles decreases by approximately 2% in the tunnel network as compared to the existing network. Thus, coupled with the travel time improvements for the travelers diverted through the new tunnel, and the travel time improvements for the travelers continuing along the Lindhagensgatan route southeastbound discussed above, the simulation results show that the tunnel construction provides system-wide benefits by reducing the aggregate delay time along with reducing delay times along Lindhagensgatan.

5.4.2 Segment Statistics, Existing vs. Future Networks

Segment statistics were also analyzed for the key locations in the network. Results showing densities at key locations are shown in Figure 5-10.
Comparison of Segment Densities at Key Locations

![Graph showing comparison of segment densities between existing and future networks at different locations.]

Figure 5-10: Segment Densities at Key Locations

(Segment descriptions appear in Table 5-1)

There are revealing results from the segment densities shown in Figure 5-10. Segment densities on the future network are higher than those on the existing network for two of the key segments: (1) the off-ramp to E4 southbound from the Kristineberg interchange (existing) or the rotary (future) and (2) the stretch of Drottningholmsvägen westbound before the off-ramp from E4. The first location shows an increase in density on that segment of 52%. This can be explained by the configuration of the rotary just upstream of the ramp; in the future configuration, the rotary necessitates several weaving and merging decisions which may slow traffic, which were not present in the existing configuration (in which drivers simply have an uninterrupted path from the signalized intersection at Lindhagensgatan to the off-ramp). The second location shows an increase in density of 80% over the existing network. The increase in density is anticipated due to the new merging of both E4 northbound and now E4 southbound (from the tunnel) traffic, at a point just upstream of the segment. In both of these cases, the MITSIMLab simulations serve to both pinpoint the problem locations and to quantify the disbenefits of increased congestion at those places in the network.
5.5 Increased Demand Levels

New NVK developments are expected to bring economic revitalization to this part of Stockholm. These new developments consist of residential, commercial and industrial buildings. The new total expected demand for these developments was calculated by SCC to be approximately 27,400 vehicles per day. As explained in Section 5.3.2, peak hour volumes were extracted from these daily volumes using a peak hour traffic/daily traffic ratio (peak hour factor) of 10%, the accepted value used by GFK, translating into additional demand of 2,700 vehicles for the peak hour. The existing traffic volume was previously determined to be approximately 3,800 per hour. Using the OD matrix developed in the previous scenario with the OD estimation module, the new traffic was assigned to both the existing and future networks by allocating the vehicles according to the assignment shown in Figure 5-11, distributed among the locations of the developments. The origins are represented by six different nodes in the network, illustrated in Figure 5-12. Because data for the increased demand was provided directly by SCC, and the additional volumes simply overlay the existing and future volumes according to the distribution below, further estimation of an OD matrix is not necessary.

![Diagram](image)

**Figure 5-11: Assignment of New Demand from NVK Development**
The behavior of the vehicles in the network is depicted by the travel time results shown in Tables 5-4 to 5-9 for the following four scenarios:

- 100% of additional demand from NVK development, compared to base case of existing demand on existing network
- 120% of additional demand from NVK development, compared to base case of existing demand on existing network
- 100% of additional demand from NVK development, compared to base case of existing demand on tunnel network
- 120% of additional demand from NVK development, compared to base case of existing demand on tunnel network
Again, 12 replications were performed for each scenario.

### 5.5.1 Travel Times, Existing Network with Increased Demand

The overall user delay in the network when loaded with additional demand is as follows:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Aggregate Travel Time for all vehicles output from MITSIMLab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing Case</td>
<td>54.0 seconds</td>
</tr>
<tr>
<td>Existing Network with Existing Demand + 100% of NVK Demand</td>
<td>54.1 seconds</td>
</tr>
<tr>
<td>Existing Network with Existing Demand + 120% of NVK Demand</td>
<td>55.1 seconds</td>
</tr>
</tbody>
</table>

Table 5-4: Aggregate Travel Times on Existing Network

Thus, overall, the user delay would increase slightly with the additional vehicles, although imperceptibly to the average user. To obtain a better picture of network operations, then, the delays are measured by area of interest and particular OD pairs in the following sections.

The results for the different demand scenarios (100% of NVK demand and 120% of NVK demand) for the existing network are shown in Tables 5-5 and 5-6.

As shown in the results, except for two movements originating from Ralambshovsleden to the north of the network, there is no appreciable change in travel times on the network for the key OD pairs due to the increased demand from the NVK development. The change of highest magnitude is the increase by 5% in travel time from the Ralambshovsleden rotary to the north of the network, Ekelundsbron (the bridge east of the E4 motorway). This is followed by an increase of 4% in travel time from the Ralambshovsleden rotary to Lindhagensgatan, also traveling northbound. These increases can be explained because of the locations of some access/egress
points to and from the developments along Lindhagensgatan; thus, egressing vehicles from the developments will cause longer wait times for through vehicles, additional conflicts at intersections, and longer travel times.

<table>
<thead>
<tr>
<th>Description</th>
<th>O</th>
<th>D</th>
<th>Average Travel Time Through Existing Network (seconds)</th>
<th>Percentage difference between 100% NVK Demand and Existing Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>EXISTING DEMAND Condition</td>
<td>EXISTING DEMAND + 100% NVK DEMAND Condition</td>
</tr>
<tr>
<td><strong>THROUGH KRISTINEBERG JUNCTION</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E4 SB to Drottningholmsvagen WB</td>
<td>5</td>
<td>18</td>
<td>123</td>
<td>121</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-1%</td>
</tr>
<tr>
<td>E4 SB</td>
<td>5</td>
<td>48</td>
<td>51</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+0%</td>
</tr>
<tr>
<td>E4 SB to Ralambshovsleden (rotary)</td>
<td>5</td>
<td>59</td>
<td>74</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+0%</td>
</tr>
<tr>
<td><strong>EASTBOUND TO ROTARY</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drottningholmsvagen EB</td>
<td>18</td>
<td>79</td>
<td>63</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0%</td>
</tr>
<tr>
<td>Drottningholmsvagen EB to Ralambshovsleden (rotary)</td>
<td>18</td>
<td>59</td>
<td>58</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+0%</td>
</tr>
<tr>
<td>Ralambshovsleden NB to Lindhagensgatan NWB</td>
<td>59</td>
<td>83</td>
<td>49</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+4%</td>
</tr>
<tr>
<td><strong>THROUGH INTERSECTION AT LINDDHAGENSGATAN AND ON-RAMP TO E4</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ralambshovsleden NB to E4 NB</td>
<td>59</td>
<td>5</td>
<td>54</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+2%</td>
</tr>
<tr>
<td>Kristinebergsvagen SWB to E4 NB</td>
<td>87</td>
<td>5</td>
<td>41</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+0%</td>
</tr>
<tr>
<td>Geijersvagen SB to E4 NB</td>
<td>31</td>
<td>5</td>
<td>52</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+2%</td>
</tr>
<tr>
<td>Ralambshovsleden NB to Ekelundsbron</td>
<td>59</td>
<td>6</td>
<td>63</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+5%</td>
</tr>
</tbody>
</table>

Table 5-5: Comparison of Travel Times on the Existing Network at 100% NVK Demand
The results for 120% of the projected demand are as shown in Table 5-6. Again, the large reduction in travel time for the Ralambshovsleden to Ekelundsbron movement is present, and can be explained by the locations of the development exits along Lindhagensgatan. The increase in travel time for the Ralambshovsleden to Lindhagensgatan NWB movement increases from 4% (Table 5-5) to 8% (Table 5-6) with the additional demand, as compared to the base case. The most revealing result is the 9% increase in travel time (from 2% seen in Table 5-5 to 11% seen in Table 5-6) for the Ralambshovsleden NB to E4 NB movement. One would deduce that based on these quantifications, if the NVK demand is more than projected at the time of build-out (here, 120% more demand is being assumed), that congestion problems may occur along this path (Ralambshovsleden NB to E4 NB) due to changing interactions in the network. The builders should be careful to monitor traffic flows at different levels of build-out.
<table>
<thead>
<tr>
<th>Description</th>
<th>O</th>
<th>D</th>
<th>Average Travel Time Through Existing Network (seconds)</th>
<th>Percentage difference between 120% NVK Demand and Existing Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>EXISTING DEMAND Condition</td>
<td>EXISTING DEMAND + 120% NVK DEMAND Condition</td>
</tr>
<tr>
<td><strong>THROUGH KRISTINEBERG JUNCTION</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E4 SB to Drottningholmsvagen WB</td>
<td>5</td>
<td>18</td>
<td>123</td>
<td>119</td>
</tr>
<tr>
<td>E4 SB</td>
<td>5</td>
<td>48</td>
<td>51</td>
<td>52</td>
</tr>
<tr>
<td>E4 SB to Ralambshovsleden (rotary)</td>
<td>5</td>
<td>59</td>
<td>74</td>
<td>75</td>
</tr>
<tr>
<td><strong>EASTBOUND TO ROTARY</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drottningholmsvagen EB</td>
<td>18</td>
<td>79</td>
<td>63</td>
<td>62</td>
</tr>
<tr>
<td>Drottningholmsvagen EB to Ralambshovsleden (rotary)</td>
<td>18</td>
<td>59</td>
<td>58</td>
<td>58</td>
</tr>
<tr>
<td>Ralambshovsleden NB to Lindhagensgatan NWB</td>
<td>59</td>
<td>83</td>
<td>49</td>
<td>53</td>
</tr>
<tr>
<td><strong>THROUGH INTERSECTION AT LINDHAGENSGATAN AND ON-RAMP TO E4</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ralambshovsleden NB to E4 NB</td>
<td>59</td>
<td>5</td>
<td>54</td>
<td>60</td>
</tr>
<tr>
<td>Kristinebergsvagen SWB to E4 NB</td>
<td>87</td>
<td>5</td>
<td>41</td>
<td>42</td>
</tr>
<tr>
<td>Geijersvagen SB to E4 NB</td>
<td>31</td>
<td>5</td>
<td>52</td>
<td>51</td>
</tr>
<tr>
<td>Ralambshovsleden NB to Ekelundsbron</td>
<td>59</td>
<td>6</td>
<td>63</td>
<td>68</td>
</tr>
</tbody>
</table>

Table 5-6: Comparison of Travel Times on the Existing Network at 120% NVK Demand
5.5.2 Travel Times, Tunnel Network with Increased Demand

The overall user delay in the tunnel network when loaded with additional demand is as follows:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Aggregate Travel Time for all vehicles output from MITSIMLab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel Network, Existing Demand</td>
<td>52.7 seconds</td>
</tr>
<tr>
<td>Tunnel Network with Existing Demand + 100% of NVK Demand</td>
<td>52.9 seconds</td>
</tr>
<tr>
<td>Tunnel Network with Existing Demand + 120% of NVK Demand</td>
<td>54.0 seconds</td>
</tr>
</tbody>
</table>

Table 5-7: Aggregate Travel Times on Tunnel Network

Again, as with the existing network, the overall user delay would increase slightly with the additional vehicles, although imperceptibly to the average user. To obtain a better picture of network operations, then, the delays are measured by area of interest and particular OD pairs in the following sections.

The results for the different demand scenarios (100% of NVK demand and 120% of NVK demand) for the tunnel network are shown in Tables 5-8 and 5-9.

In the demand scenarios on the tunnel network, results differ from the travel time measurements on the existing network in Section 5.5.1. Thus, the changes in travel behavior caused by the new tunnel/rotary configuration are quantified. In the 100% NVK demand scenario, the most telling figures are the 18% (Table 5-8) and 19% (Table 5-9) increases in travel time for the same Ralambshovsleden NB to E4 NB movement previously discussed. Again, due to the large amount of congestion expected along this path, even with the absence of diverted traffic which now travels through the tunnel instead of along Lindhagensgatan, planners must be careful of monitoring traffic activity at the development exits and entrances, at different levels of build-out.
<table>
<thead>
<tr>
<th>Description</th>
<th>O</th>
<th>D</th>
<th>Average Travel Time Through Tunnel Network (seconds)</th>
<th>Percentage difference between 100% NVK Demand and Existing Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>EXISTING DEMAND Condition</td>
<td>EXISTING DEMAND + 100% NVK DEMAND Condition</td>
</tr>
<tr>
<td>THROUGH KRISTINEBERG JUNCTION</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E4 SB to Drottningholmsgvagen WB</td>
<td>5</td>
<td>18</td>
<td>74</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+2%</td>
</tr>
<tr>
<td>E4 SB</td>
<td>5</td>
<td>48</td>
<td>52</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+0%</td>
</tr>
<tr>
<td>E4 SB to Ralambshovsleden (rotary)</td>
<td>5</td>
<td>59</td>
<td>60</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+2%</td>
</tr>
<tr>
<td>EASTBOUND TO ROTARY</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drottningholmsgvagen EB</td>
<td>18</td>
<td>79</td>
<td>62</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+0%</td>
</tr>
<tr>
<td>Drottningholmsgvagen EB to Ralambshovsleden (rotary)</td>
<td>18</td>
<td>59</td>
<td>58</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+0%</td>
</tr>
<tr>
<td>Ralambshovsleden NB to Lindhagensgatan NWB</td>
<td>59</td>
<td>83</td>
<td>51</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+2%</td>
</tr>
<tr>
<td>THROUGH INTERSECTION AT LINDHAGENSGATAN AND ON-RAMP TO E4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ralambshovsleden NB to E4 NB</td>
<td>59</td>
<td>5</td>
<td>58</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+2%</td>
</tr>
<tr>
<td>Kristinebergsvagen SWB to E4 NB</td>
<td>87</td>
<td>5</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+0%</td>
</tr>
<tr>
<td>Geijersvagen SB to E4 NB</td>
<td>31</td>
<td>5</td>
<td>50</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+4%</td>
</tr>
<tr>
<td>Ralambshovsleden NB to Ekelundbron</td>
<td>59</td>
<td>6</td>
<td>57</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+18%</td>
</tr>
</tbody>
</table>

Table 5-8: Comparison of Travel Times on the Tunnel Network at 100% NVK Demand

84
<table>
<thead>
<tr>
<th>Description</th>
<th>O</th>
<th>D</th>
<th>Average Travel Time Through Tunnel Network (seconds)</th>
<th>Percentage difference between 120% NVK Demand and Existing Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>THROUGH KRISTINEBERG JUNCTION</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E4 SB to Drottningarholmsvagen WB</td>
<td>5</td>
<td>18</td>
<td>74</td>
<td>77</td>
</tr>
<tr>
<td>E4 SB</td>
<td>5</td>
<td>48</td>
<td>52</td>
<td>52</td>
</tr>
<tr>
<td>E4 SB to Ralambshovsleden (rotary)</td>
<td>5</td>
<td>59</td>
<td>60</td>
<td>62</td>
</tr>
<tr>
<td><strong>EASTBOUND TO ROTARY</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drottningarholmsvagen EB</td>
<td>18</td>
<td>79</td>
<td>62</td>
<td>63</td>
</tr>
<tr>
<td>Drottningarholmsvagen EB to Ralambshovsleden (rotary)</td>
<td>18</td>
<td>59</td>
<td>58</td>
<td>58</td>
</tr>
<tr>
<td>Ralambshovsleden NB to Lindhagensgatan NWB</td>
<td>59</td>
<td>83</td>
<td>51</td>
<td>51</td>
</tr>
<tr>
<td><strong>THROUGH INTERSECTION AT LINDHAGENSGATAN AND ON-RAMP TO E4</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ralambshovsleden NB to E4 NB</td>
<td>59</td>
<td>5</td>
<td>58</td>
<td>64</td>
</tr>
<tr>
<td>Kristinebergsvagen SWB to E4 NB</td>
<td>87</td>
<td>5</td>
<td>40</td>
<td>41</td>
</tr>
<tr>
<td>Geijersvagen SB to E4 NB</td>
<td>31</td>
<td>5</td>
<td>50</td>
<td>52</td>
</tr>
<tr>
<td>Ralambshovsleden NB to Ekelundbron</td>
<td>59</td>
<td>6</td>
<td>57</td>
<td>68</td>
</tr>
</tbody>
</table>

Table 5-9: Comparison of Travel Times on the Tunnel Network at 120% NVK Demand

### 5.6 Analysis of Transit Operations and Signal Priority

As described in Chapter 3, MITSIMLab has been enhanced to include technology representations such as Automatic Vehicle Location and traffic signal priority. With these elements in the network, simulation runs can be made and technologies evaluated. Thus far, the analysis of
network traffic has been of all vehicles, to demonstrate the differences between the existing and future network configurations.

The generic signal controller in MITSIMLab was applied for the PRIBUSS intersections. Signal group timings were provided by GFK, with a 110-second cycle and signal priority for buses turning from Lindhagensgatan to the on-ramp for northbound E4. MITSIMLab inputs for signal control require the signal locations and signal group timings, along with network sensors for invoking transit priority. The generic controller allows priority to be invoked for both phase shortening, where the current signal phase is shortened to allow approaching buses an early green phase, and phase extension, where a green phase about to end is extended to allow the bus to proceed through the intersection.

The transit routes were also implemented in the network, along with their routes, schedules (provided by SL) and bus stops. Headways for the routes along Lindhagensgatan are typically about 9 or 10 minutes, long headways due to the frequency of different routes on that road (routes 196, 197, 198 and 396). As detailed demand information was unavailable, passenger demand was represented by dwell times at bus stops uniformly distributed between an upper and lower bound (of 45 and 30 seconds). MITSIMLab inputs for transit require definitions of bus types, bus schedules, routes, bus stop locations, and passenger demand.

Scenarios were set at this main intersection (Lindhagensgatan and Kjellgrensgatan, for buses heading toward E4 northbound), where bus routes did and did not experience signal priority. The locations of the signals and bus routes is shown in Figure 5-13. The effectiveness of the generic signal controller and transit implementations in MITSIMLab were also qualitatively verified. For
example, when buses leave a bus stop, lane changing behavior was modified so that buses can now nose into traffic. Results are given in the next section, along with observations.

![Diagram of signals and transit in NVK Network](image)

Figure 5-13: Signals and Transit in NVK Network

### 5.6.1 Results for Buses and Signal Priority

The simulation was run with and without signal priority in order to assess the effects of the PRIBUSS implementation, and to verify the transit capabilities of the model. The results are as follows.

With no signal priority capability implemented, the transit vehicles on routes 196, 197, 198, and 396 experience a mean travel time of 209 seconds through their portions of the network, over 12
simulation runs. With signal priority, the transit vehicles’ mean travel time decreases to 189 seconds, a decrease of 11%. Over each replication comprising one AM Peak hour, the signal priority for the Lindhagensgatan-Essingeleden movement was invoked an average of 9 times per hour. Both phase shortening and phase extensions were invoked during all runs.

These results show that the PRIBUSS signal priority at the Lindhagensgatan/Kjellgrensgatan/Kristineberg intersection leads to only a slight decrease in travel time for the buses on those routes. The shorter travel time in the signal priority scenario could also be due to other factors, including the traffic distribution over the course of the hour leading to high traffic at that time a particular bus is running on the network. However, signal priority is hoped to be more effective in reducing transit vehicle travel times and thus increasing passenger throughput. An extended network would be instructive in assessing the technologies in more detail. Implementations were also verified qualitatively by observing the graphical simulation. Signal priority was invoked at the appropriate windows during the signal cycle, and different transit capabilities, such as noses behavior, were observed. Thus, the integration of traffic signal capabilities with the new transit capabilities in MITSIMLab was further verified.

5.7 Conclusions and Recommendations

This Chapter illustrates the capabilities of the recently enhanced MITSIMLab for quantifying benefits, especially as measured through delay impacts, through a case study involving four different scenarios for the North West Kungsholmen Project in Stockholm. MITSIMLab is especially suited to these analyses since it has previously been calibrated for Stockholm driving conditions. The scenarios are as follows:
• Tunnel construction vs. existing configuration (Section 5.4)
• Increased demand due to new development (Section 5.5)
• Transit operations: Effectiveness of new technologies such as transit and signal priority
  (Section 5.6)

An assessment is made of the suitability of a tunnel construction project under the E4 motorway
using MITSIM as a tool for quantifying delay impacts. The simulation results show that the
travel times for the drivers to be diverted through the tunnel are significantly decreased, by 39%,
as are the travel times for drivers who used to share the interchange with those who are now
rerouted through the tunnel (a travel time reduction of 18%). Thus, the first scenario seems to
support the investment in the tunnel construction. Segment statistics at key locations were also
analyzed and helped pinpoint possible problem locations (the on-ramp from Kristineberg to E4
southbound, and also the section of Drottningholmsvagen westbound upstream of the E4/tunnel
off-ramp).

Several observations are made through different scenarios involving demand. Among these are
the verification that diverted traffic through the tunnel, along with other traffic which still travels
along Lindhagensgatan, still enjoy travel time savings under all increased demand scenarios, as
expected. The changes in travel times under the different demand scenarios are as shown in
Table 5-10.

Even with the high demand scenarios resulting from the new development, the travelers diverted
through the tunnel with enjoy travel time savings of at least 35% over the times on the existing
network. Another observation involves pinpointing possible problem locations through changes
in travel times for certain OD pairs; for example, the Ralambshovsleden NB to E4 NB movement,
which experiences a large increase in travel time (2%-11%%) on both networks, and the
Ralambshovsleden NB to Ekelundsbron movement, which also experiences an increase in travel time on both networks (5%-19%) with the new demand. This large increase for the through movement can be explained by the presence of the new development access and egress points along Lindhagensgatan. Thus, since the delays around problem locations are pinpointed, the negative impacts of the development are highlighted, and the benefits of reduced delay due to other strategies (monitoring demand, changing intersection logic, etc) can be pursued.

<table>
<thead>
<tr>
<th>Network</th>
<th>Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Existing demand</td>
</tr>
<tr>
<td>Existing Network</td>
<td>123</td>
</tr>
<tr>
<td>Tunnel Network</td>
<td>74</td>
</tr>
<tr>
<td>Percentage decrease on</td>
<td></td>
</tr>
<tr>
<td>tunnel network over</td>
<td>-39%</td>
</tr>
<tr>
<td>existing network</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-10: Travel time savings for traffic from E4 SB to Drottningholmsvagen WB, Both Networks, under different demand scenarios

Further investigation is made into the impacts of new or modified transit technology using recent enhancements to the simulator. These enhancements were described in Chapter 3 and include signal priority enhancements, and bus modeling capabilities. Travel times on the network were calculated without and with signal priority for transit vehicles. The results from utilizing these implementations show that the signal priority at the main PRIBUSS intersection at Lindhagensgatan/Kjellgrensgatan in fact does not provide significant benefit to transit vehicles tagged for priority. A travel time reduction of 11% is achieved for transit vehicles on the
northbound Lindhagensgatan routes, which is consistent with the range of percentage reduction in travel times found in the literature for signal priority. Travel time reductions have from 5 to 15% have been assessed in field tests in European cities such as France, Italy, Sweden and Germany (European Commission, 1998). When designed, new PRIBUSS signal timings can also be tested in MITSIMLab; for example, before introduction of a proposed bus route on Lindhagensgatan southbound from Nordenflychtsgången (a new proposed bus route to travel from the northwest corner of the network to the Lindhagensplan rotary at the southeast corner).

Further insight could be obtained if detailed demand data for transit were available, in addition to pedestrian movement data. In addition to vehicle-delay for various scenarios, person-delay could also be computed, and thus different stakeholders in the network could be considered.
Chapter 6

Conclusions

This thesis explored the quantification of transportation technology benefits using a microscopic traffic simulator. Benefits were first defined and identified based on current literature and discussions. Benefits generally fall into the main categories cited by the US Department of Transportation: capacity improvements, delay, customer satisfaction, safety, the environment (energy and emissions) and costs. Based on existing frameworks and literature, most benefits evaluation methodologies which relate to the fundamental benefits of delay, safety, and the environment are dependent on traffic statistics pertaining to travel times in the network. Transportation technologies such as advanced vehicle location, traffic signal priority, and incident detection and management were reviewed as a basis for future analysis of emerging technologies. The capability of modeling each of these technologies has already been implemented in MITSIMLab. This thesis takes these implementations and further tests them simultaneously with real data, while leveraging MITSIMLab’s strength in modeling capacity improvements.

A case study in Stockholm, Sweden allowed several applications to be tested and goals to be achieved. Two extensive networks were implemented in MITSIMLab based on real data. These networks, one an existing network and the other a proposed tunnel diversion, allowed analysis of the benefits or disbenefits of capacity improvements. It was verified through the simulation that
travel times between the existing and tunnel networks would differ significantly for the movements of interest. Those drivers diverted through the tunnel experience average delay reductions of 39%, and those who previously shared a path with these diverted trips and now enjoy an average delay reduction of 18%. The investment in the construction of the new tunnel is thus supported.

The technology representations in MITSIMLab were further tested. Transit modeling and signal priority were implemented in the network simulation to reflect real-life operations. The combined transit modeling and signal priority scenario forecasts a delay reduction of 11% for transit vehicles on a selected route through the network. This percentage reduction is within the same range as the reduction obtained in other studies, as discussed in Chapter 5 (European Commission, 1998).

Benefits were quantified by analyzing the change in overall user delay, as well as the change in delay (or change in travel times) for various origin-destination (OD) pairs of interest. The change in overall user delay is defined as the aggregate increase or decrease in travel time resulting from the infrastructure change or technology implementation. Certain OD pairs are selected because they travel through areas pinpointed by local residents and also pinpointed during preliminary MITSIMLab simulations as being problem areas. This metric of either overall or origin-destination (OD)-specific user delay was determined to be the building block for other benefits evaluation modules, such as methodologies evaluating safety or environmental benefits.

The OD estimation module in MITSIMLab was successfully used to generate the traffic volumes for the simulation, as explained in Section 5.3.2. Thus, another enhancement to MITSIMLab was tested with real-life data.
Policy issues specific to the transit and transportation agencies in Stockholm were discussed in
the context of user benefits. Three main issues were pinpointed in the discussion: stakeholder
cooperation, technical integration and regional integration.

Through the simulation process, discussions with transportation officials, and the literature
review, it was determined that further investigation could take the following forms:

- Other benefits in addition to those stemming directly and indirectly from delay reduction
  measures should be investigated. For example, many studies discuss intangible measures
  such as customer satisfaction. MITSIMLab has many tools (for example, the capability of
  modeling the dissemination of traveler information) which would provide a good framework
  for such an investigation.

- An economic analysis (relating to the benefit of productivity) can be incorporated into the
  benefits evaluation framework. For example, many cost-benefit models take the delay
  outputs further and assign values of time to delays. Some studies have determined the value
  of time to be 50 percent of the wage rate for the value of in-vehicle travel time and 100
  percent for walking and waiting time (US DOT, 1997). This is consistent with Miller’s
  (1996) finding that many studies value highway travel time as falling between 50 to 75
  percent of the prevailing wage rate. He determines that 55 percent of the wage rate should be
  used for drivers (all trip purposes) and 40 percent should be used for for passengers, whether
  in autos or in transit vehicles. With regard to safety and the environment, different models
  compute a cost per accident as cost per accident multiplied by accident rates in that area and
  vehicle miles traveled on the roadway (for example, using data in the annual Data on
  California State Highways volume published by Caltrans) or and monetary values of air
  pollution emissions (Wang et al, 1995).
As the number of enhancements to MITSIMLab increase, one can measure new benefits. For example, as the demand models for transit are refined, the benefits resulting from new transit systems will be more accurate as (for example) the delay benefit for transit users is measured using the number of riders multiplied by the number of existing riders and the existing value of time. As another example, as mode choices of riders is better represented, different values of time can be assigned to the total travel time for users of different modes.

In closing, better methods of benefits quantification are constantly being sought. It has been shown that MITSIMLab, through this application to a new transportation network using recent enhancements of technology representation, is a useful tool for benefits quantification. It is foreseen that MITSIMLab will be further enhanced as new technologies emerge, and a benefits quantification package would be a useful add-on to the measures of effectiveness already output, not only in terms of transportation planning but also in terms of transportation development.
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