TravTek Evaluation
Modeling Study

TravTek Evaluation Modeling Study

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FOREWORD

This report is one of eight reports produced as part of the evaluation of the TravTek operational field test, conducted in Orlando, Florida, during 1992-1993. TravTek, short for Travel Technology, was an advanced driver information and traffic management system that provided a combination of traveler information services and route navigation and guidance support to the driver. Twelve individual but related studies were conducted during the evaluation. Evaluation goals and objectives were represented by the following basic questions: (1) Did the TravTek system work? (2) Did drivers save time and avoid congestion? (3) Will drivers use the system? (4) How effective was voice guidance compared to moving map and turn-by-turn displays? (5) Was TravTek safe? (6) Could TravTek benefit travelers who do not have the TravTek system? (7) Will people be willing to pay for TravTek features?

Evaluation data were obtained from more than 4,000 volunteer drivers during the operation of 100 specially equipped automobiles for a l-year period. Results of the evaluation demonstrated and validated the concept of in-vehicle navigation and the provision of traveler information services to the driver. The test also provided valuable results concerning the drivers' interaction with and use of the in-vehicle displays. This project has made many important contributions supporting the goals and objectives of the Intelligent Transportation Systems Program.

Samuel . Tignor, Ph.D., P.E.
Acting Director, Office of Safety and
Traffic Operations Research and
Development

NOTICE

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16. Abstract

The following report describes a modeling study that was performed to extrapolate, from the TravTek operational test data, a set of system wide benefits and performance values for a wider-scale deployment of a TravTek-like system. In the first part of the modeling study, the INTEGRATION simulation model was enhanced and calibrated to produce a model whose driver and in-vehicle system parameters were representative of the behavior that was quantified by various TravTek field tests in Orlando, Florida. In the second part of the study, a coded traffic network was created with properties that were representative of the traffic conditions observed in Orlando during the course of the TravTek operational field test. Nine Measures of Performance (MOP's) of the TravTek system were then estimated using the model: the total trip travel time; the total distance traveled; the number of stops incurred; and the number of missed turns experienced; as well as the average estimated fuel consumption; vehicle emissions of hydrocarbon (HC); carbon monoxide (CO) and oxides of nitrogen (NOx) per vehicle; and the expected accident risk.

The simulated Orlando TravTek network consisted of 2,670 uni-directional links, 87 zones, 49 traffic signals and 783 lane-km. During a typical modeling run, of the PM peak, 62,899 individual vehicles were traced through a total of 679,111 veh-km or 11,882 veh-h. The Level of Market Penetration (LMP) was found to improve most of the nine MOP's by up to 12, 5, 32, 37, 13, 16, and 7 percent for the average trip duration, average trip length, number of vehicle stops, number of wrong turn maneuvers, level of fuel consumption, HC and CO emissions, respectively. The total travel time, the travel distance, the number of vehicle stops, the number of wrong turn maneuvers, the level of fuel consumption and the HC emissions were observed to improve monotonically for all LMP's. Emissions of CO were found to increase by no more than 3 percent for an LMP of 10 percent and decreased by up to 7 percent for LMP's beyond 10 percent. Emissions of NOx were found to increase by no more than 5 percent for all LMP's below 90 percent and were found to decrease by 1 percent for an LMP of 100 percent. For LMP's up to 100 percent the traffic fleet as a whole, during the PM peak, experienced changes in accident risk that were less than ± 1 percent. However, at virtually all LMP's, during the PM peak, the equipped vehicles experienced an accident risk that was greater than that of background traffic, that benefited from the diversion of the equipped vehicles. However, this was not the case during off-peak traffic conditions. The majority of the benefits increased at a decreasing rate for higher LMP's, but benefits accrued at lower LMP's were never subsequently reversed or negated.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd ❑ 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2 = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2 = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (Lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp ❑ 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] ^{o}F ❑ y ^{o}C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliters (ml) ❑ 0.03 fluid ounce (fl oz)
1 liter (1) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] ^{o}C ❑ x ^{o}F

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES: 0 1 2 3 4 5 6 7 8 9 10

CENTIMETERS: 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 25.40

QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10286.

OVERVIEW

The TravTek operational field test involved the deployment of 100 Advanced Traveler Information Systems (ATIS) equipped vehicles in Orlando during a period of time from March 1992 to March 1993. During this time a combination of visitors and local drivers drove in excess of 1.6 million vehicle-km using one of three main variations of a basic ATIS. An integral part of the operational field test' was a comprehensive evaluation which consisted of a combination of field experiments, surveys and subsequent modeling architecture studies. This report describes the latter modeling study.

The modeling study had three main objectives. In the first instance, the modeling study attempted to extrapolate from the available field data the expected performance of a TravTek type system for levels of market penetration ranging from 1 percent to 100 percent. In addition, the modeling study attempted to extrapolate the expected performance of a TravTek system in terms of measures such as vehicle stops, fuel consumption, vehicle emissions, and accident risk, that were not always directly observed during the field test. Finally, the modeling study attempted to estimate the potential impact on the benefits of the TravTek system for conditions not necessarily encountered in Orlando during the field test, such as different levels of traffic congestion, different incident durations and different levels of routing quality for either the TravTek or the non-TravTek vehicles.

The INTEGRATION simulation model was employed as the primary means based on which the modeling estimates were derived. This model is microscopic, in that it considers traffic in terms of individual entities, each with its own unique characteristics. The basic model combines traffic simulation and traffic assignment, and is highly dynamic. In addition to time-varying demands and capacities, dynamic changes in traffic controls can also be considered. Of special interest to the TravTek evaluation was the ability to model different vehicle sub-populations, each with their own unique routing characteristics, and the ability to estimate a wide range of measures of performance, such as travel time/distance, queue sizes and the expected number of stops per vehicle. In addition, the individual vehicle's fuel consumption and emissions of HC, CO and NOx, as well as expected accident risk per vehicle trip were estimated.

In order to perform the TravTek modeling evaluation, the basic INTEGRATION simulation model was customized and calibrated to the TravTek architecture and Orlando network in several ways, Specifically, the Orlando road network that was modeled was converted directly from the navigation (NavTech) data base in the TravTek vehicle to a format compatible with the INTEGRATION input files. Subsequently, the speed-flow and capacity characteristics of the freeway links were refined using statistical analyses of the I-4 Freeway Management Center (FMC) loop data. These same FMC data were also utilized to derive the link traffic flows from which the dynamic network synthetic O-D's were estimated.

Abstractions of the actual TravTek routing logic were incorporated in the model, as were abstractions of the data fusion and transmission logic at the TMC. The relative efficiency, in terms of travel time/distance and number of wrong turns were also included in the model, as were the fuel consumption characteristics of the TravTek vehicle based on performance characteristics that were measured directly in Orlando.

Nearly 175 different simulation runs were performed on a combination of a series of Personal Computers (PC's) and RISC-6000 workstations, where each run required approximately 10 h of Central Processing Unit (CPU) time. During a typical run, the movement of roughly 65,000 vehicles was traced across the network of 2,700 links and 90 Origin-Destination zones. The total network travel distance driven was nearly 700,000 veh-km, corresponding to an average trip duration of about 11.3 min. Most of the simulation runs concentrated on the analysis of that portion of Orlando for which real-time loop detector data were available and on the PM peak traffic conditions as observed in Orlando during the winter of 1993. A small number of sensitivity analyses examined increased as well as reduced levels of traffic demand to represent both future and off-peak conditions, respectively. Finally, while most analyses were conducted for recurring congestion scenarios, representative freeway incidents were also analyzed.

An analysis of the impact of the Level of Market Penetration (LMP) indicated that total travel times can be expected to decrease for all LMP's, but that the most significant marginal benefits can be expected at the lower LMP's. A maximum network travel time saving of 15 percent was found for an LMP of 100 percent. Benefits in travel time savings were obtained by both the TravTek vehicles and the background traffic, as the latter experienced less residual congestion following the diversion of the initial TravTek vehicles. The above travel time benefits were found to increase as the base level of traffic congestion was increased beyond the current levels. Furthermore, it was found that for these higher levels of traffic congestion, a smaller fraction of TravTek vehicles was needed to obtain a similar percentage of the ultimate benefits that might be achieved at an LMP of 100 percent. It was also found that the travel time benefits associated with increased levels of market penetration have the potential to offset a considerable amount of new traffic demand that may be generated by the reduced level of traffic congestion.

Travel distance savings, that were 7 percent at an LMP of 100 percent, were found to be positive but less than the savings in travel time. This finding arose from the fact that part of the rather significant reductions in navigational waste were offset by diversions away from congestion which typically involves reductions in travel time but increases in travel distance. The reduction in number of vehicle stops, however, was greater than the reduction in travel time. This effect was considered to arise from the TravTek vehicle's ability to avoid congested routes and the accompanying stop/go conditions.

Fuel consumption decreased for the various LMP's in a manner which was roughly equal to the reduction in travel time. Part of this reduction in fuel consumption arose from the more efficient travel during uncongested versus congested conditions, while another component was derived from the reduction in navigational waste. The overall reduction in fuel consumption might have been greater, except for the fact that diversions often have associated with them small increases in travel distance, as noted earlier.

The rather complex and non-linear relationship between vehicle emissions, and vehicle speed and fuel consumption, lead to equally complex relationships between these emissions and the LMP, as indicated below. In the first instance, the rather consistent relationship between hydrocarbons (HC) emissions and speed resulted in a reduction of HC emissions for all LMP's reaching a maximum of 16 percent at an LMP of 100 percent. The less consistent relationship between carbon monoxide (CO) and vehicle speed resulted in an initial increase of 3 percent for an LMP of 10 percent, which was followed by a subsequent reduction in CO emissions of 7 percent for LMP's up to 100 percent. Finally, the fact that oxides of nitrogen (NOx) emissions increase rapidly as a vehicle's speed increases, resulted in an increase in NOx emissions up to a maximum of 5 percent for intermediate LMP's, but decreased by 1 percent at an LMP of 100 percent.

The overall impact of the TravTek system on accident risk can be broken down into impacts during uncongested versus congested conditions. During uncongested conditions the TravTek system has a predominately positive effect on accident risk as TravTek reduces risk exposure by reducing navigational waste and by favoring higher class (and safer) versus lower class (less safe) routes. Also travel per unit of similar exposure with a TravTek in-vehicle system was shown in the camera car study to be intrinsically safer than travel without a system. However, some of the above benefits are partially offset for TravTek vehicles during congested conditions in Orlando when diversions away from freeway congestion results in both increased exposure, through increased travel distance, and increased risk per unit of exposure when the diversion route results in increased travel on lower road class facilities. During these diversions, non-TravTek vehicles do incur some spin-off benefits because without diverting they experience travel on less congested facilities without changing to lower class or increasing travel distance. The net effect of the above interactions was that the total vehicle fleet did not experience changes in accident risk in excess of 1 percent during the PM peak. However, while those TravTek vehicles that diverted to longer distance alternative routes on lower class facilities experienced measurable increases in accident risk, the background traffic received offsetting risk benefits. During non-peak conditions, however, the fleet accident risk as well as the TravTek accident risk reduced for all LMP's.

In conclusion, the INTEGRATION simulation model permitted the quantification of many of the complex interactions that arise when a TravTek type of system is deployed at increasing LMP's. This quantification measured the different types of impacts on travel time, distance, stops, fuel consumption, vehicle emissions and accident risk, and characterized how these differences change for different traffic demand levels. The findings suggest that the TravTek ATIS can clearly be expected to achieve its primary objectives, namely the reduction of travel time, distance, number of vehicle stops, number of wrong turns, and navigational waste. In addition, reductions in fuel consumption and HC emissions can also be expected, even though these Measures of Performance (MOP's) are not explicitly targeted by the TravTek system's routing or design objectives. However, it must be noted that while CO emissions and total fleet accident risk can be expected to remain essentially constant, small increases in NOx emissions and the accident risk of the TravTek vehicle sub-population may be expected under congested road conditions in a network similar to the Orlando network. However, for metropolitan areas where the opportunity for freeway-to-freeway or increased arterial-to-arterial diversion exists the actual accident risk exposure may be reversed.

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CHAPTER 1: INTRODUCTION

TravTek was a joint public and private sector operational field test of an Advanced Traveler Information System (ATIS) and Advanced Traffic Management System (ATMS).“. 2) Public sector participants were the City of Orlando, the Federal Highway Administration (FHWA), and the Florida Department of Transportation (FDOT). The American Automobile Association (AAA), and General Motors (GM) were the private sector participants.

The TravTek Evaluation consisted of a series of behavioral, engineering, and modeling studies designed to evaluate the TravTek system from multiple perspectives. This report, which describes the Modeling Study of the TravTek system, is one of several reports that were developed describing the various analytical approaches and results from the TravTek evaluation.

Initially, this chapter overviews the TravTek architecture that was utilized in the evaluation study. Subsequently, the TravTek operational field test is described together with the goals of this field test. After describing the specifics of the TravTek architecture and the various components of the TravTek operational field test, the specifics of the Modeling Study that will be discussed in the remainder of the report are overviewed. Finally, the layout of the Modeling Study report is presented.

OVERVIEW OF TRAVTEK SYSTEM ARCHITECTURE

The TravTek system architecture was composed of three primary components: the TravTek vehicles, the TravTek Information and Service Center (TISC), and the Traffic Management Center (TMC). These three components are described briefly here with reference to figure 1 which provides a graphical overview of the TravTek system architecture. Based on the data links, that are indicated by arrows, it can be seen that the vehicle both received and transmitted data. Data transmitted by the vehicle included travel times across TravTek network roadway segments.

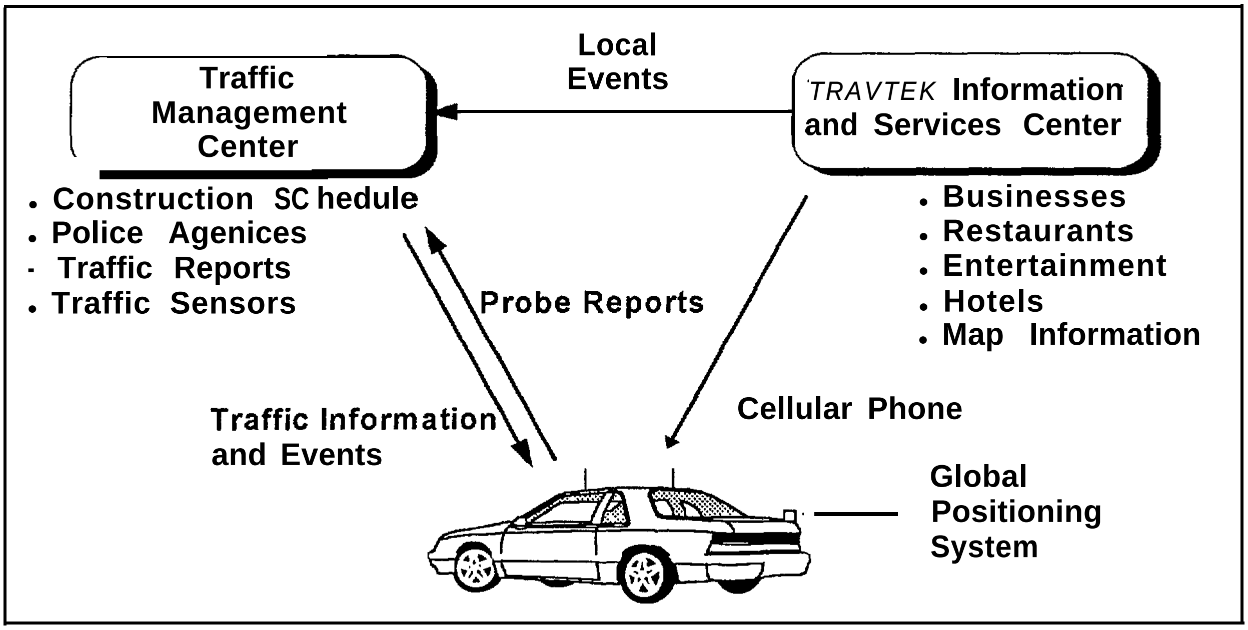

Figure 1: Overview of the TravTek system

TravTek also made a wealth of information available to drivers. This information included: route planning, turn-by-turn route guidance, real-time traffic reports, and real-time re-routing advisories. Some of the features of the TravTek system are described next.

Navigation

A variable-scale color map was displayed on a 127-mm (5-in) video display. The video display, an option on the Oldsmobile Toronado, was positioned high on the dashboard and to the driver's right. The navigation system used a combination of dead-reckoning, map-matching, and Global Positioning System information to indicate the vehicle's position on the map. The vehicle's position was indicated by an icon that was horizontally-centered three-fourths of the distance from the top of the screen. When the vehicle was in DRIVE the map was displayed in a heading-up format.

Route Selection

An in-vehicle routing computer provided the minimum-time route from the vehicle's current position to a selected destination. The minimum-time criterion was subjected to constraints such as turn penalties, preference for higher level roadways, and avoidance of short-cuts through residential areas.

Route Guidance

When a route had been computed, a sequence of guidance displays provided maneuver-by-maneuver driving instructions. The visual guidance display could be augmented by synthesized voice that provided the next turn direction, distance to the turn, and the name of the street on which to turn. The driver could switch between the maneuver-by-maneuver *Turn-by-Turn Display* and a *Route Map.* The Route Map showed the planned route as a magenta line traced over the map display. Buttons on the steering wheel hub were used to swap between the Guidance Display and the Route Map, and to turn the voice guidance function off or on.

Real-Time Traffic Information

Real-time traffic information was broadcast to TravTek vehicles once every minute. To limit the quantity of information broadcast, only exceptions to normal traffic flows were reported. The real-time information could be used in route planning, Also, if conditions changed while the vehicle was en-route, a new, faster, route could be offered to the driver. The real-time traffic information was collected from a variety of sources and fused together. The fused traffic conditions available to the system via broadcasts from the TMC included:

- Historical travel times as a function of time-of-day and day-of-week.
- Roadway sensor data (e.g., loop detectors).
- Police reports.
- City reports of maintenance and road closures.
- Probe reports from other TravTek vehicles of travel times across TravTek traffic links (roadway segments).

When the real-time information function was active and a route was planned, the routing computer made a continual search for a significantly faster route. If a faster route was found, it was offered to the driver for acceptance or rejection. Traffic congestion and incidents were represented on both the Turn-by-Turn Display and Route Map screens. Synthesized voice announcement of traffic information was toggled on or off by a TRAFFIC REPORT button on the steering wheel hub.

Help Desk Telephone Assistance

When the vehicle was in PARR, a *HELP* function was available by pressing a touch sensitive key on the video display. One feature of the *HELP* function was free cellular telephone calls to the TISC.

The TISC was operated by the American Automobile Association. Help desk operators had access to a TravTek simulator that replicated the TravTek functions in the vehicles. This enabled the help desk operators to replicate problems encountered by drivers, or to plan routes just as they are planned in the vehicle. Participants in this study's Control condition (drivers using TravTek vehicles but not using TravTek functions) were permitted to call the help desk for assistance in finding their destination.

Figure 2 provides an overview of the TravTek in-vehicle architecture. Compass, wheel sensor, and Global Positioning System data were used by the navigation computer to position the vehicle relative to a map data base. A second computer, the routing computer, used a different data base to plan routes and to provide navigation assistance. The driver could interact with the system via touch sensitive buttons on the video display, steering wheel buttons, and buttons on the video display bezel.

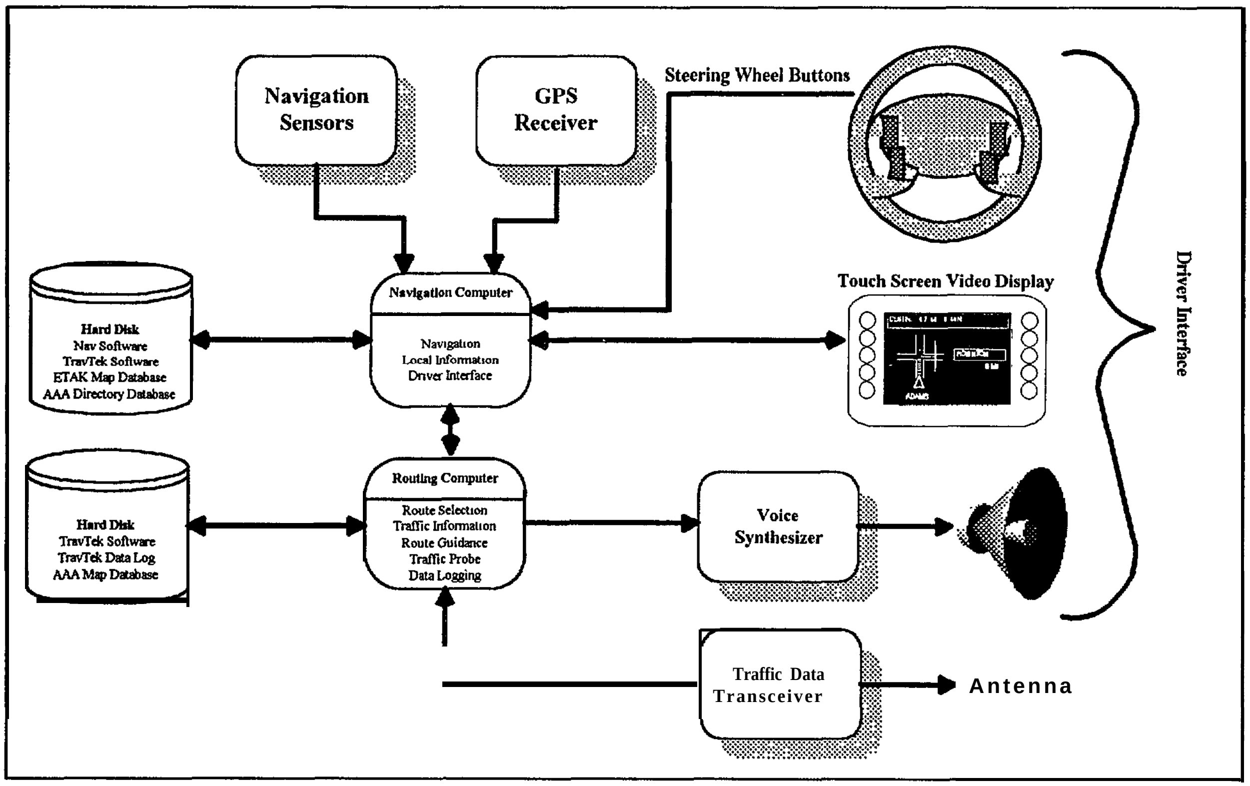

Figure 2: Schematic representation of the TravTek vehicle architecture

OVERVIEW OF TRAVTEK EVALUATION

A hallmark of the TravTek operational field test is the TravTek partnership's early emphasis upon the comprehensive evaluation of issues pertaining to advanced driver information systems and associated traffic management systems.(1) The TravTek partners established evaluation goals and objectives for the TravTek operational field test early on in the program. They agreed that achievement of the major evaluation goals and objectives could be determined by an approach that answered the following basic questions:

- Did the TravTek system work?
- Did drivers save time and avoid congestion?
- Will drivers use the system?
- How effective was voice guidance compared to a Route Map and Turn-by-Turn guidance displays?
- Was TravTek safe?
- Could TravTek benefit travelers who do not have the TravTek system? and
- Will people be willing to pay for TravTek features?

Each partner agreed in advance of building TravTek that data collection systems would be designed into the cars, the TMC, and the TISC to help answer these questions that were critical to understanding the ultimate feasibility of an IVHS prototype like TravTek. Moreover, the evaluation was expedited by making each TravTek car easily programmable to one of three alternative configurations. The Services (S) configuration provided drivers with: free cellular telephone access to the TISC and “911” emergency services; a Services and Attractions feature; cellular phone auto-dialing to any service or attraction at a push of a touch-screen button; and, a pre-drive map that showed the location of selected services and attractions. The Services configuration was an experimental control, or baseline condition for evaluating navigation and route guidance provided by the other configurations. Accordingly, it provided neither navigation (i.e. a moving map or vehicle location information) nor route guidance information. The Navigation (Nav) configuration provided all of the features in the S configuration as well as routing options based on in-vehicle storage of nominal travel times. The Navigation Plus (Nav+) configuration provided all of the features of the Nav configuration plus the addition of real-time traffic information factored into the routing algorithm.

Other evaluation data sources included: a one-of-a-kind TravTek camera car; personal debriefings of car users; questionnaires for every volunteer driver; in-vehicle observations during special controlled experiments; and driver logs for those TravTek drivers not accompanied by an observer desiring to help by logging origins and destinations.

To answer a whole gamut of questions, including the seven basic ones presented above, the TravTek partners established an evaluation program consisting of separate studies integrated into an overall evaluation approach. Figure 3 illustrates the major classes of studies (see boxes) performed, and types of data (see circles) that the studies yielded. These studies were conducted over a one year period beginning in March 1992 and ending in March 1993. The following sub-sections describe the nature of each study (i.e. the boxes in figure 3)

Naturalistic User Field Studies

There were two naturalistic field studies in the TravTek evaluation: The *Rental User Study* that employed a fleet of 75 TravTek cars and recruited over 3,900 drivers who rented through AAA/Avis and the *Local User Study* which provided cars to 53 high mileage local drivers. These studies capitalized on the realism of a naturalistic setting whereby drivers were able to use the cars as they would outside of an experimental setting. Accordingly, participants in these two TravTek field studies were unconstrained in the routes they chose or their methods of getting there. For the *Rental User Study,* drivers were assigned either to the Nav+, Nav or Services (S) configuration of TravTek, and used the cars for an average of between 5 and 6 days. For the *Local User Study,* selected drivers used the car for an average period of 6 weeks. These drivers experienced both the Nav+ and Nav configurations for roughly equal time periods. Local Users were not provided cars in the S configuration.

Design and Effectiveness Field Experiments

The manipulation of independent variables and the possibility of randomization are the most important characteristics of the field experiment, whereby casual relationships between independent and dependent variables can be better established through controlled experiments. Three controlled experiments were performed. The *Yoked Driver Study* focused on differences among Nav+, Nav, and S configurations as they affected travel time and navigational waste during peak traffic conditions. Forty-one driver triplets (123 drivers), participated in this study. Each driver within a triplet was assigned a different vehicle configuration and drove the same route within 2 min of each other. Those with the S-configured vehicles used conventional methods (e.g. paper map) of route planning and navigation compared to the capabilities of those in the Nav and Nav+ configurations. The *Orlando Test Network Study* (OTN) focused on relative advantages and disadvantages of alternative methods of communicating routes to drivers in day or night. Performance and preference data for 3 13 drivers were analyzed for six alternative navigation display combinations. Each driver drove one origin-destination pair with the Route Map Display, one with the turn-by-turn Guidance Display, and one with no visual display. Half of the drivers drove with voice and the other without. Half of the drivers drove in the day, and half drove at night. The *Camera Car Study* used 30 volunteer drivers for the primary purpose of examining safety issues related to the use of in-vehicle ATIS displays, and to how driver age and experience with in-vehicle systems may relate to ATIS safety. The design of the camera car enabled collection of very detailed driver behavior data from four video camera views; the face, for measurement of locus of gaze; over the shoulder, for control usage; out the windshield, for recording the traffic environment; and, a left-front, outside view for recording lane tracking. Other special data, collected only in the camera car, included, 2-axis acceleration, steering wheel position, and brake light status (on, off).

Interview and Questionnaire Studies

A total of 486 drivers were interviewed just after turning in their TravTek cars to AVIS at the Orlando International Airport. These interviews sampled drivers' immediate impressions about TravTek. A total of 1,608 drivers filled out and returned questionnaires about their TravTek experience. Specific questionnaire items addressed were: drivers' perception about TravTek features; self reports of how participants drive with the TravTek system; drivers' future intentions including willingness to pay; and, background information about the drivers.

Traffic Modeling and Safety Studies

The *Traffic Modeling Study,* which is presented in this report, consisted of a number of traffic simulations using data from TravTek studies. These data were input to the INTEGRATION model to derive more reliable and comprehensive estimates of the potential traffic impacts of a fully deployed in-vehicle route guidance system of the TravTek type. Objectives included the use of INTEGRATION to predict network-wide travel time benefits, fuel consumption and emission statistics, changes in the number of network-wide collisions, and to predict how such measures are affected by different levels of market penetration of TravTek-like vehicles.

The Safety *Study* had three basic objectives: 1) to determine if drivers drive more, or less safely, in ways related to the use of TravTek; 2) to determine if the TravTek system affected drivers' performance in terms of safety and accidents; and 3) to determine if there would be a decrease, or an increase, in the total number of network-wide collisions if a large fraction of the fleet were equipped with TravTek-like systems.

Architecture Evaluation

This study focused on hardware and software system performance, with some coverage of the ergonomic evaluation of the TMC operator's console. Numerous issues were examined by this study. For example: How accurate was the TMC travel time information? How reliable were the TMC hardware and software? How well might alternative architectures have worked compared to TravTek? Were levels of processing appropriately allocated to the vehicle, TMC automation, and the TMC operator? How well did the overall TravTek system work? Were data bases accurate? Was network coverage sufficient?

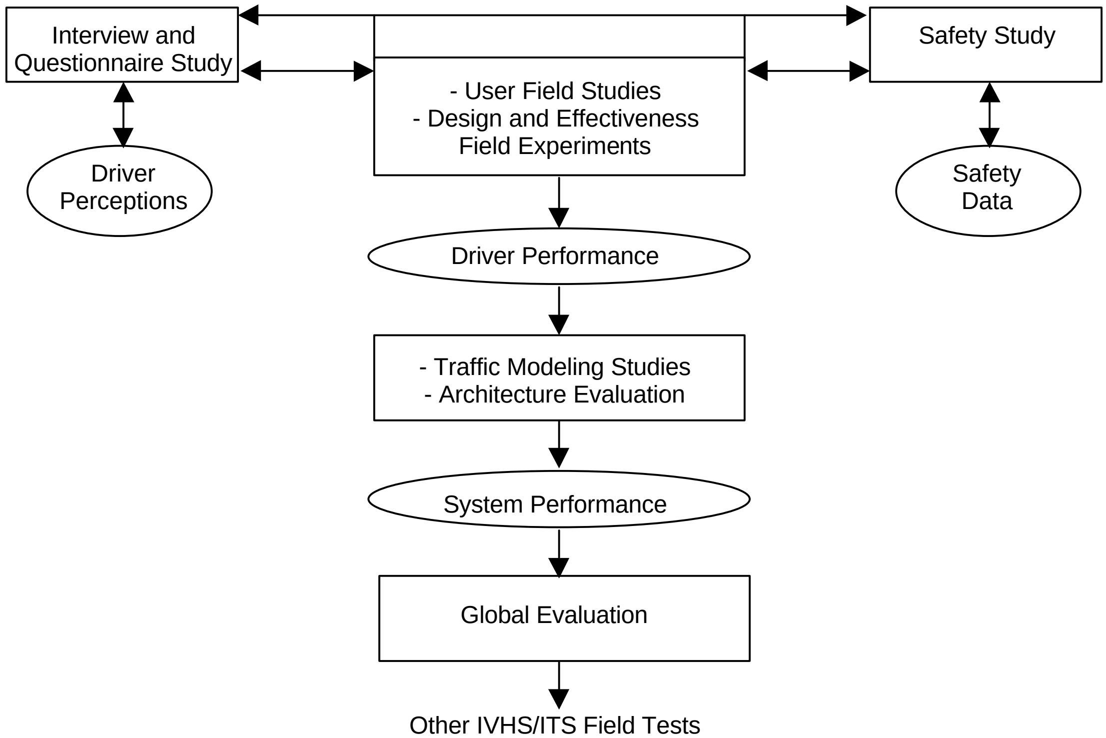

Figure 3: Relationships among TravTek evaluation studies (boxes) and the data yielded (ellipses)

OVERVIEW OF MODELING STUDY

The field experiments and surveys, described earlier, collected data and information on the performance of the test vehicles and the drivers in them. These data indicated how the system performed for the configuration that was tested and for the conditions that were encountered in Orlando by the vehicles during the time frame of the operational field test. It was not always possible to systematically collect all types of potential data on all test driver trips. It was also not possible to observe the system's performance for conditions that were not encountered in the field. Examples of the former data gaps are the fuel consumption, emissions and risk exposure of all of the 100 test vehicles, whereas examples of the latter are the potential performance of the TravTek system for higher levels of market penetration and/or with improved real-time data inputs.

The desire to examine these unobservable factors resulted in the inclusion of a comprehensive modeling activity as part of the TravTek evaluation using the microscopic INTEGRATION simulation/assignment model. This modeling activity was intended to permit an objective and systematic extension of the findings from the operational field test to generate performance estimates for a range of other conditions and configurations that would be of interest to those contemplating the deployment of similar systems on a wider scale.

To date the use of traffic simulation models remains the main and virtually only means to extrapolate Level of Market Penetration (LMP) effects from field studies on a limited number of subjects, While these traffic models have advanced rapidly during the past decade, many deficiencies remain. The INTEGRATION microscopic simulation/assignment model was selected because of its rather unique traffic features that provided the flexibility for modeling the traffic engineering features of the TravTek Traffic Management Center and Route Guidance System (RGS) units.

Figure 4 illustrates, in a flow chart form, the nature of the flow of data from the various data sources to the INTEGRATION model. As demonstrated in figure 4, the fuel consumption and vehicle emission models were incorporated in the INTEGRATION model using the Environmental Protection Agency (EPA) driving cycles as defined by the Federal Test Procedures (FTP). The wrong turn probability of both background and TravTek vehicles were estimated based on the results of the *Yoked Field Study.* In addition, the error in link travel time estimates of the TravTek vehicles were estimated from field tests. Furthermore, the Freeway Management Center (FMC) data were utilized to generate speed-flow relationships for the freeway links, and were also utilized in generating the synthetic Origin-Destination matrix.

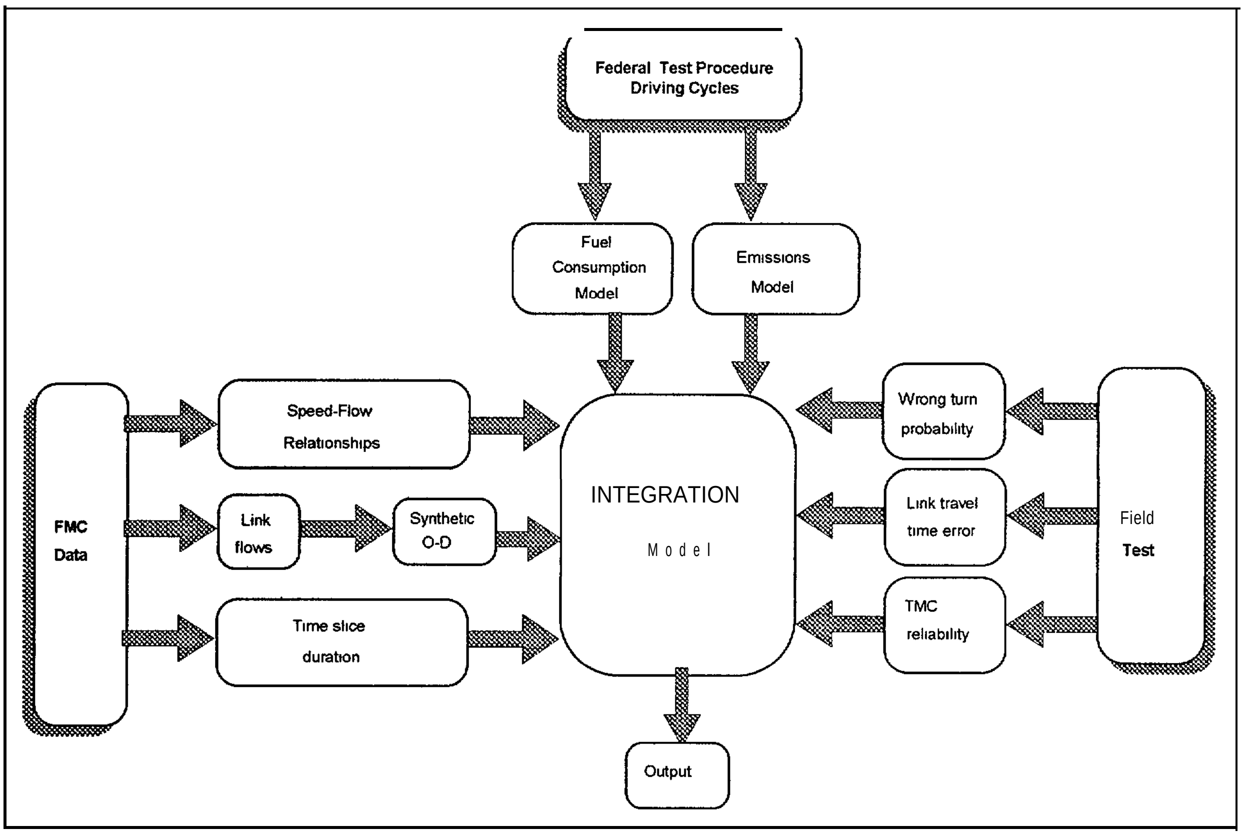

Figure 4: Data flow to/from INTEGRATION model.

OVERVIEW OF MODELING STUDY REPORT

Initially the configuration of the INTEGRATION model and the network utilized in the simulation study are described in chapter 2. The objective of this description is to provide the reader with a general overview of the INTEGRATION model and thus understand why the model was selected as the evaluation tool. Chapter 2 also describes how the input parameters to the INTEGRATION model were derived. These input data include the generation of the Origin-Destination demands, the derivation of the demand time slice duration, and the derivation of the link characteristic parameters from loop detector measurements.

Chapter 3 focuses on deriving the TravTek specific modeling and network features. Prior to discussing these TravTek features, a brief overview of the data transmission cycle is presented in chapter 3. Initially, the accuracy of probe data is discussed based on data collected from a few limited field studies in Orlando. Subsequently, the accuracy of the data fusion task is discussed together with the spatial and temporal availability of real-time information. Chapter 3 also presents how the TravTek and background traffic routing were modeled within the INTEGRATION model. Finally, chapter 3 describes how the modeling of fuel consumption, vehicle emissions of HC, CO and NOx and the accident risk estimation were incorporated in the INTEGRATION model.

In chapter 4 the INTEGRATION model, in the absence of TravTek, is calibrated to the existing traffic network conditions. It is anticipated that inadequate model calibration can produce model biases that could exceed the potential benefits of the TravTek route guidance system. Consequently, chapter 4 describes how the calibration of INTEGRATION to the existing traffic conditions in Orlando was conducted.

In chapter 5 the impact of increasing the level of market penetration of the TravTek system is studied on the nine Measures of Performance (MOP's). During this examination, the base runs are modeled with proportions of TravTek equipped vehicles ranging from 1 percent to 100 percent. The nine MOP's are compared for the different levels of market penetration. In addition, chapter 5 investigates the impact of different random number seeds on the overall simulation results.

Chapter 6 studies the impact of the level of congestion and the likely existence of incidents on the potential benefits of a TravTek system for different LMP's. The total PM traffic demand is varied from 90 percent to 110 percent of the base demand at 5-percent increments. In addition, two freeway incidents are studied. In the first instance the incident occurs on a congested portion of the I-4 freeway, while in the second instance the incident occurs on an uncongested portion of the I-4 freeway. The incident duration is varied from 5 to 30 min for both incident scenarios. In addition, chapter 6 studies the impact of the simulated link travel time error for both background and TravTek vehicles on the potential benefits of the TravTek system.

Finally, chapter 7 presents the conclusions of the report in addition to some recommendations for future analytic and modeling studies.

CHAPTER 2: THE INTEGRATION MODEL AND NETWORK CONFIGURATION

INTRODUCTION

In this chapter the configuration of the INTEGRATION model and the network utilized in the simulation study are described in detail. Subsequently, chapter 3 describes how the TravTek specific features were modeled within INTEGRATION followed by a description of the calibration process of the INTEGRATION model in chapter 4.

The general characteristics of the INTEGRATION model are briefly discussed in this chapter as are the characteristics of the Orlando network that was simulated. As the INTEGRATION model requires, as one of its input files, an Origin-Destination (O-D) demand file the following section describes the derivation of this demand file from the link flow measurements provided by the Freeway Management Center (FMC). In addition, the derivation of the typical traffic conditions that were computed from the observed loop detector measurements are described followed by a description of how the time slice durations for O-D demand rates were selected. In addition, the procedure that was utilized in estimating the link free-speed, speed-at-capacity, capacity and jam density is described in this chapter. Finally, this chapter provides the reader with a concise summary of the chapter.

CONFIGURATION OF THE INTEGRATION SIMULATION MODEL

Figure 5 illustrates, in a flow chart form, the nature of the flow of data from the various data sources to the INTEGRATION model. As demonstrated in figure 5, the fuel consumption and vehicle emission models were incorporated in the INTEGRATION model using the Environmental Protection Agency (EPA) driving cycles as defined by the Federal Test Procedures (FTP), as will be discussed in one of the forthcoming chapters. The wrong turn probability of both background and TravTek vehicles was estimated, as indicated in chapter 3, based on the results of the Yoked field experiment. In addition, the error in the link travel time estimates provided to the TravTek vehicles, as described in chapter 3, were estimated from field tests. Finally, the Freeway Management Center (FMC) data were utilized to generate speed-flow relationships for the freeway links, and were also utilized in generating the synthetic Origin-Destination matrix as will be discussed in further detail in this chapter.

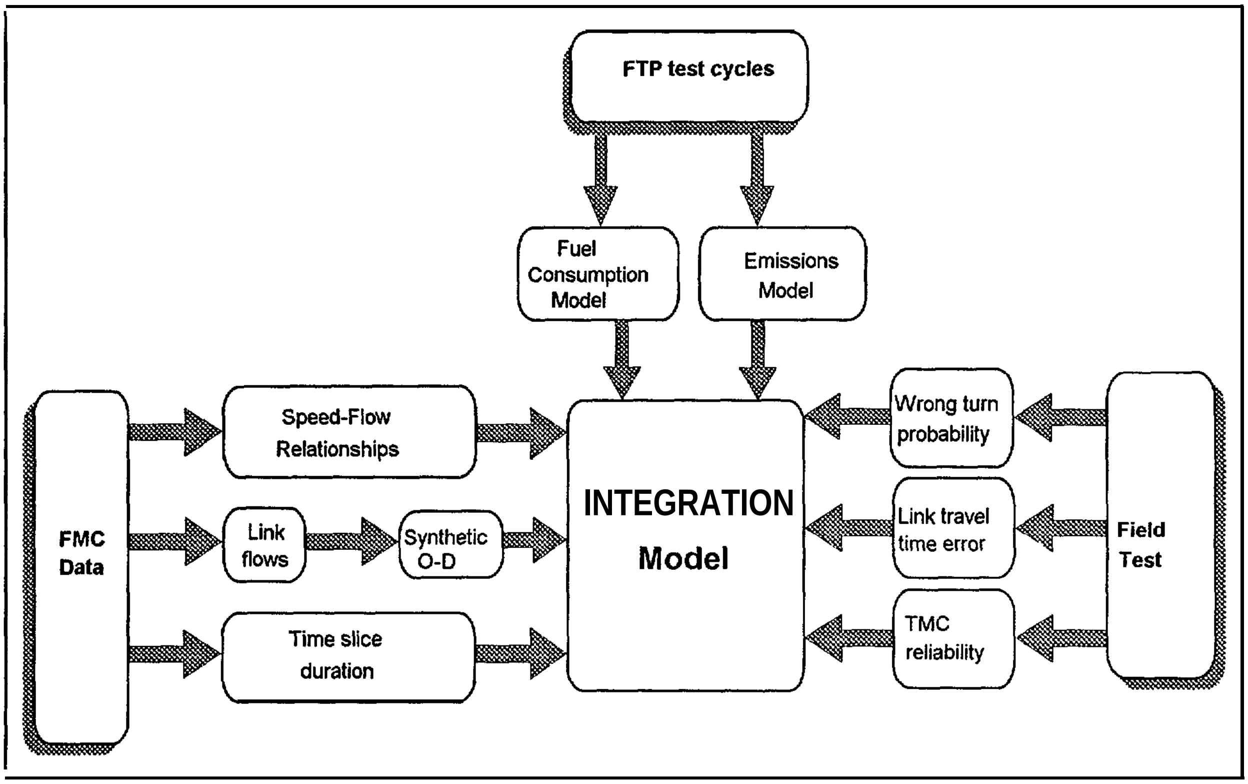

Figure 5: Organization of INTEGRATION model calibration

Characteristics of the INTEGRATION Traffic Flow and Routing Model

INTEGRATION is a microscopic simulation and traffic assignment model which can model the dynamics of an integrated freeway and traffic signal network in a setting within which Intelligent Vehicle Highway Systems/Intelligent Transportation Systems (IVHS/ITS) technologies may be deployed.(3) The model is microscopic, in that it traces the behavior of individual vehicles as they traverse a network from their origin to their destination. However, the model may be viewed as macroscopic in the sense that it can consider networks consisting of several thousands of links and potentially several hundred thousands of individual vehicles.

The number of vehicle trips that must occur in each time slice is specified as an external input to the model in terms of an aggregate dynamic time varying O-D matrix. This dynamic O-D matrix is then parsed into a series of individual vehicle departures that correspond, in a discrete fashion, to the desired aggregate and continuous departure rate. When the simulation clock reaches a vehicle's scheduled departure time, the vehicle is entered into the network along the first link towards its destination. The speed of the vehicle along that first link, as well as any subsequent links, is updated every deci-second. Each such update reflects the distance headway between the vehicle in question and the vehicle immediately preceding it. The exact desired speed for any given distance headway is based in a deterministic fashion on a link-specific car-following relationship that reflects the link's free-speed, capacity, speed-at-capacity and jam density.

When a vehicle reaches the end of a given link, it selects the next link to take based on a set of look-up tables. These look-up tables indicate, for a given vehicle on a given link and which is destined to a particular destination, which downstream link should be taken next. The use of a single look-up table results in an all-or-nothing traffic assignment, while the availability of multiple concurrent look-up tables for a given vehicle class (during a single time period) results in a static multipath traffic assignment. Different sets of look-up tables for different vehicle types permit multivehicle class traffic assignments, in which each vehicle class may have its own unique set of desired routings. Similarly, when, during the course of a simulation, temporal adjustments are made to a given set of look-up tables, a full multipath dynamic traffic assignment can be emulated. The extent to which vehicles actually adhere to the prescribed routes is also modeled as a stochastic process with parameters that are vehicle configuration specific. Probabilistic selection of look-up tables can be used to model expected rates of missed turns or other stochastic variabilities in driver navigation behavior compliance.

Beyond the speed restrictions, that arise from the above car-following logic, a vehicle's progress can also be delayed at traffic signals, ramp meters, queues and/or other capacity bottlenecks. These effects can be time varying and usually interact both spatially and temporally.

Generation of Measures of Performance

The identification of individual vehicles as distinct entities permits a unique vehicle ID to be associated with each vehicle and a unique list of vehicle attributes to be associated with each vehicle ID. One of these attributes is the vehicle's time of entry onto a link, a quantity that can be queried when the vehicle leaves the link. This query can be utilized in order to derive a very accurate estimate of the current link travel time. Link travel time samples can also be logged for output of link travel time statistics. In addition, travel time samples can be shared with a central data base of link travel times that may be passed to a centralized or decentralized minimum path algorithm and used to update the routing look-up tables for particular vehicle classes. This feature permits the simulation of probe vehicles and the modeling of the effects of real-time travel information on system performance.

During the course of the simulation, a vehicle's speed during the current and the immediately preceding second, are always stored. The average of these two values provides a direct input for estimating the likely steady-state fuel consumption of that vehicle, while the difference between these two values permits a similar estimate of the additional fuel being consumed by any accelerations/decelerations, as will be discussed in further detail in chapter 3. These second-by-second fuel estimates are sensitive to the prevailing ambient temperature and to the extent to which the car's engine has reached its hot stabilized temperature. The stabilization process of a vehicle's engine and catalytic converter are modeled as a function of a particular vehicle's cumulative trip distance and trip time at any instant.

Similarly, speed, ambient temperature and the extent to which the catalytic converter has already warmed up are also utilized to estimate the vehicle's emissions of hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NOx), as will be discussed in detail in chapter 3. The number and magnitude of the decelerations and accelerations can also be utilized to estimate an index which reflects the number of full or partial stops a vehicle experiences during a particular trip. Although field measures of fuel consumption and emissions are known to be dependent on the particular acceleration and deceleration profile of a vehicle, factors such as driver aggressiveness and acceleration preferences, that are known to affect these profiles are held constant among the various simulation runs in order to limit the sources of variance in the output data. Only the impact of route guidance on driver characteristic variability (i.e. TravTek versus non-TravTek driver behavior) are evaluated later in this report.

The road class a vehicle is traveling on, coupled to the traffic flow conditions the vehicle experiences (either congested or uncongested), permits an appropriate accident risk factor to be computed for each vehicle at any instant in time as will be discussed in chapter 3. This accident risk factor, which is facility and congestion level sensitive, is first accumulated for each vehicle for the entire length of the link. Subsequently, it is further aggregated either for all the vehicles that traverse a particular link, or for all the links that are traversed by a particular vehicle. Table 1 lists the other measures of performance that are collected for each vehicle and for each link.

Table 1: Typical vehicle and link measures of performance

Vehicle Statistics	Link Statistics
Total Trip Time	Total Link Flow
Total Trip Distance	Average Link Travel Time
Total Number of Stops	Average Link System Time
Total Number of Missed Turns	Maximum Queue Size
Total Fuel Consumption	Maximum Vehicle Density
Total HC Emissions	Average Link Speed
Total CO Emissions	Average Link Occupancy
Total NO_x Emissions	Average Volume/Capacity Ratio
Total Accident Risk	Link Cumulative Fuel Consumption
	Link Cumulative Vehicle Emissions
	Average Effective Green Duration
	Link Cumulative Accident Risk

Configuration of the Simulation network

The Orlando area was represented using several overlapping network data bases, as discussed next.

The TravTek traffic network

The most aggregate of all the traffic data bases is the TravTek Traffic Network data base. It consists of approximately 750 two-way links. It represents the set of links for which real-time data were collected and disseminated electronically by the TMC each minute. This traffic network was developed by Florida Department of Transportation (FDOT) and contains all the major arterials and freeways in the Orlando area for which off-line travel time estimates had been estimated using floating car studies.

The NavTech vehicle location network

The NavTech vehicle location network was developed and maintained by Navigation Technologies for AAA. It is the actual data base that was present in the TravTek vehicles for purposes of tracking individual vehicles.

This data base, which consists of approximately 80,000 one-way links, provides a much greater level of detail of the road network than the TravTek data base. It considers all the local streets and navigable roadways in the Orlando area that could be utilized by TravTek vehicles and which would be tracked by the navigational data base.

The NavTech navigation network

The NavTech navigation network consisted of a subset of the NavTech vehicle location network, that excluded all local streets and alleys but retained all roads that corresponded to highways and arterials/collectors in Orlando. This entire network was composed of approximately 18,000 one-way links and was utilized for any routing functions or minimum path calculations.

The traffic simulation network

The simulated network was subsequently further reduced from 18,000 to 2,670 links by geographically cropping the original link data base. The reasons for selecting this smaller network were as follows. First, continuous automated updates of travel time information were available for only 12 percent of the links in the TravTek network. All of these links were located in the area immediately surrounding the downtown area of Orlando and along the I-4 freeway. Secondly, the Yoked Driver study, which provided specific information on the travel time estimates along specific routes for different TravTek configurations, also exclusively traversed the area immediately surrounding the downtown of Orlando. Consequently, the final INTEGRATION simulation network consisted of a smaller network which encompassed all navigational links surrounding the downtown core of the City of Orlando and all of the detectorized portions of the I-4 freeway, as illustrated in figure 6.

Origin-Destination zones and dummy connector links were added to the above network in order to represent all main traffic movements within and through the network that potentially would be subject to routing and diversion decisions. Specifically, external origins were coded to represent all main entering and exiting links around the periphery to the network. In addition, internal to the network all major land use areas within the network and all off- and on-ramps to freeways were assigned zone connectors. The final network resulted in a total of 2,670 links, 87 Origin-Destination zones, 1,295 nodes, and 49 traffic signals, as summarized in table 2. Appendix A lists the different input files that were utilized in the simulation study.

All traffic signals were modeled as operating at a cycle length of 80 s with a 50:50 phase split as many signals operated in a responsive mode and as further information on the exact signal settings at a particular instant in time was therefore not available. However, because these same signal settings were common to all the runs, these fixed settings would likely not affect the relative results from one scenario to another to a significant extent.

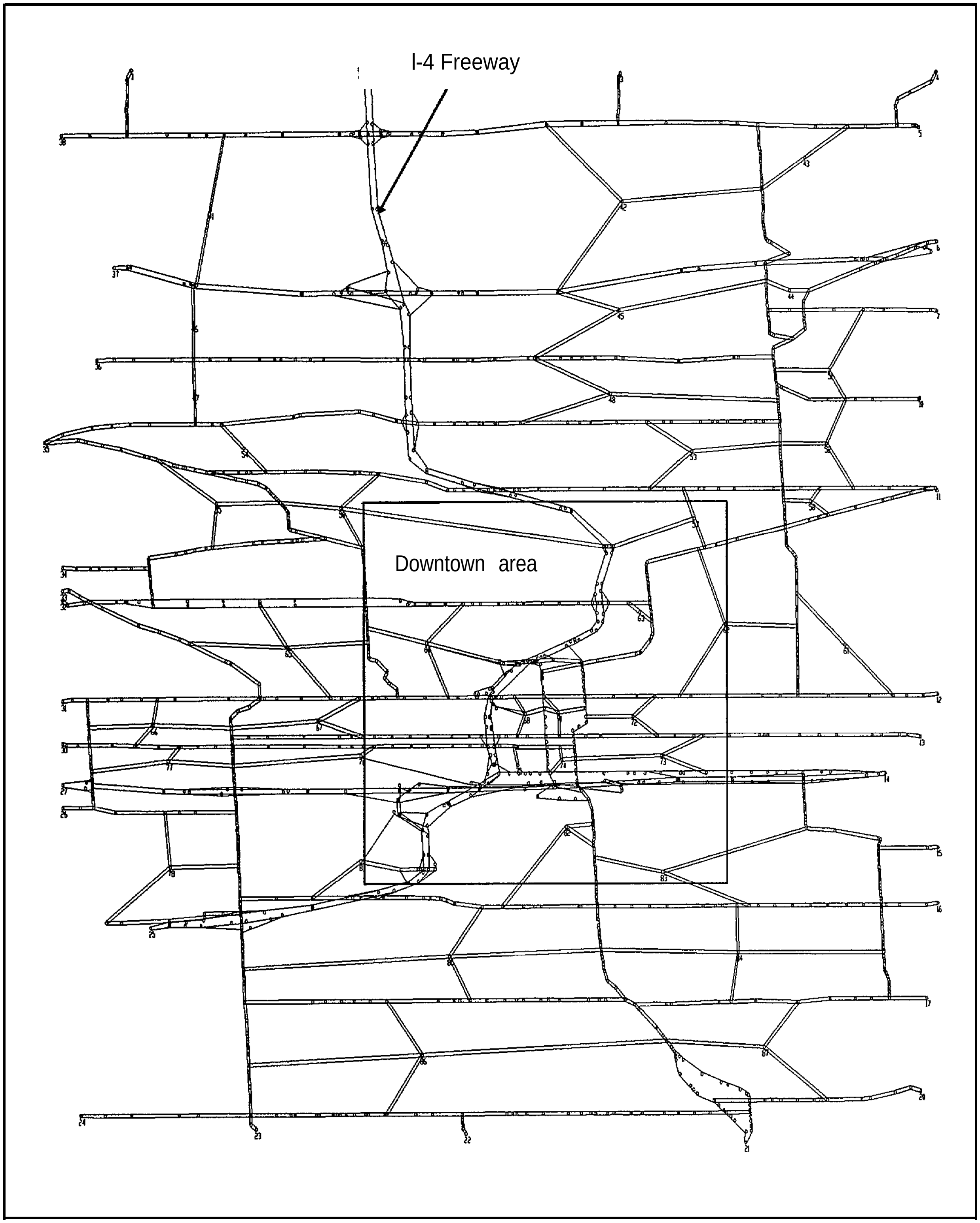

Figure 6: The Orlando network utilized in the simulation studies using INTEGRATION

Table 2: Summary of Orlando network characteristics

#' nodes	# zones	# macro zones	#links	# signals
1295	87	87	2670	49

TRAFFIC DEMAND GENERATION

The generation of the Origin-Destination demands using the QUEENSOD model utilized all available real-time traffic counts from the FMC and a volume equal to 25 percent the saturation flow for the remaining arterial links for which no on-line data were available as will be discussed in this section."'

FMC Data

The detectorized portion of the I-4 freeway was located in the downtown of Orlando extending from 33rd street to the South-West and ended downstream of Maitland Boulevard to the North-East as illustrated in figure 7. There was a total of 24 loop detector stations located along I-4 numbered from 1 to 25 with data for station 10 missing. The spacing of the detector stations range from 0.4 to 0.87 km.

The analysis period included traffic data for portions of a 4 month time period during the winter of 1992 and 1993. The actual days are indicated by the highlighted cells in table 3. The data included 11 days in November 1992, 29 days in January 1993, 26 days in February 1993, and 11 days in March 1993. This amounted to a total of 75 days of 30-s data with approximately 10 different days of data for each day of the week, as illustrated in table 4.

The FMC dual loop detectors measured and logged the flow, occupancy and space mean speed for each of the three lanes at 30-s intervals. These data were aggregated into 5-min data summaries in order to reduce the stochastic level of random noise, while still capturing most of the deterministic trends in the time varying traffic conditions. An average lane flow, occupancy and space mean speed estimate was generated from the individual loop detector measurements for each lane at each station. In estimating the average lane speed at a specific station, the individual loop speeds were weighted by the volume on each set of dual loops.

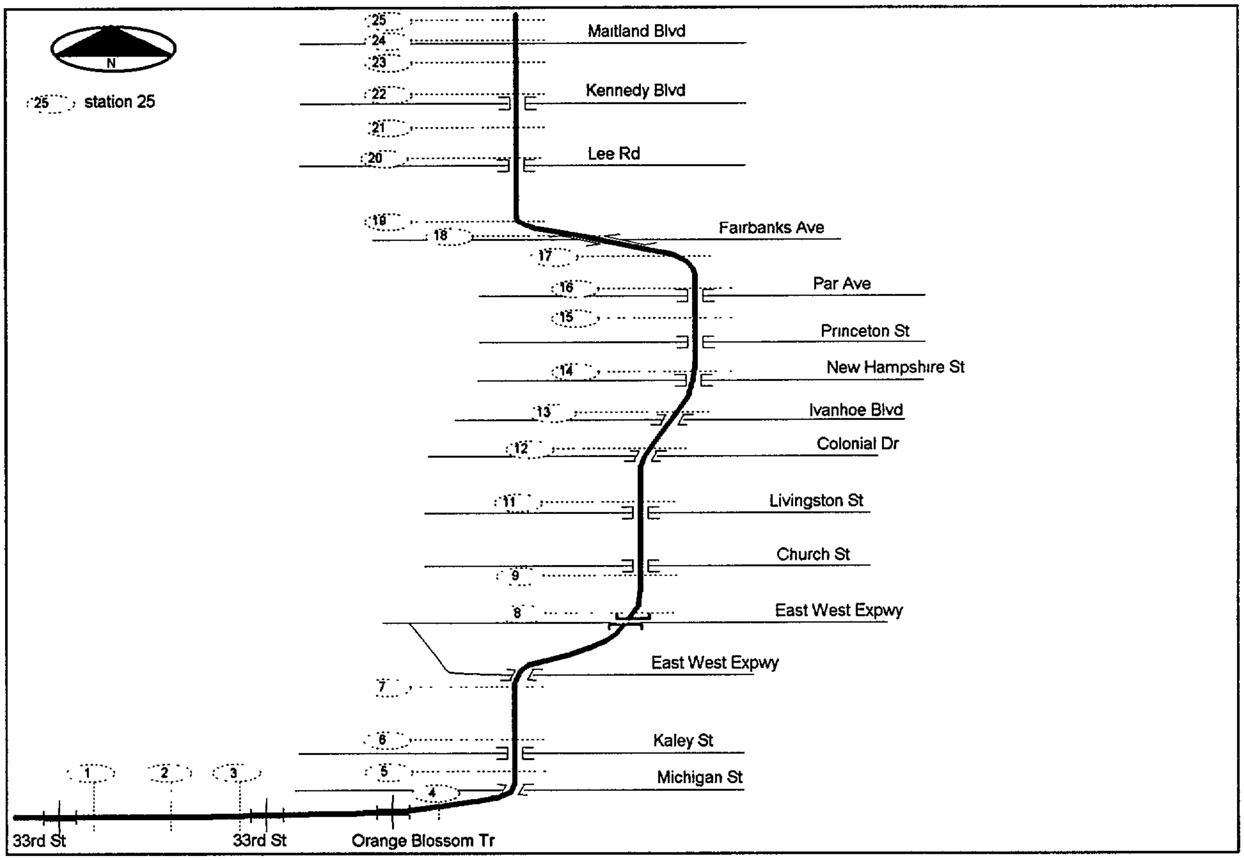

Figure 7: Location of FMC detector stations along the I-4 freeway in Orlando

Table 3: Days for which 30-s FMC data were analyzed for each station

Nov 92							Jan 93						
Sun	Mon	Tue	Wed	Thr	Fri	Sat	Sun	Mon	Tue	Wed	Thr	Fri	Sat
1	2	3	4	5	6	7	31					1	2
8	9	10	11	12	13	14	3	4	5	6	7	8	9
15	16	17	18	19	20	21	10	11	12	13	14	15	16
22	23	24	25	26	27	28	17	18	19	20	21	22	23
29	30	31					24	25	26	27	28	29	30
Feb 93							**Mar 93**						
Sun	Mon	Tue	Wed	Thr	Fri	Sat	Sun	Mon	Tue	Wed	Thr	Fri	Sat
	1	2	3	4	5	6		1	2	3	4	5	6
7	8	9	10	11	12	13	7	8	9	10	11	12	13
14	15	16	17	18	19	20	14	15	16	17	18	19	20
21	22	23	24	25	26	27	21	22	23	24	25	26	27
28							28	29	30	31			

Days in shaded boxes were analyzed

Table 4: Number of FMC data for each day of the week

Sun	Mon	Tue	Wed	Thu	Fri	Sat	
12	10	12	11	10	10	10	Total = 75

Derivation of Typical Traffic Conditions

Based on the FMC data available over the 4-month period it was possible to generate a surface that represented the average of all the speed, flow and occupancy measurements for all the days at a particular station and at a particular time of day. Equations 1 and 2 demonstrate how an estimate of each observation for the flow and occupancy was generated. In the case of the speed surface, a volume weighted average was estimated. Typical weekdays were considered to be Tuesday through Thursday, because Mondays and Fridays were found to differ at a statistically significant level from the typical traffic conditions, as discussed later in this section. There was a total of 33 core weekdays during the analysis period. These weekdays were checked for any abnormal traffic conditions such as major vehicle detector failures or incidents, as indicated in the incident data base. A detector failure or suspected failure was noted and any suspected days were removed from the estimated average.

The above selection process resulted in 22 weekdays being considered in developing the average eastbound weekday surfaces (*nd* = 22). In contrast, the entire 33 weekdays were utilized to generate the average westbound weekday surfaces (*nd* = 33). These latter surfaces represented the *best* estimate of the typical average weekday traffic conditions in Orlando during this time period. The graphical representation of the resulting average surfaces for the eastbound direction are only presented here, as the results for the westbound direction were very similar.

$$x^n_{i,j} = \sum_{k=1}^{10} x^n_{i,j,k} \quad \forall\, x^n_{i,j,k} \geq 0 \tag{1}$$

$$\bar{x}_{i,j} = \frac{\sum_{n=1}^{nd} x^n_{i,j}}{nday} \quad \forall\, x^n_{i,j} \geq 0 \tag{2}$$

Where:

nd = total number of non-incident weekdays.

nday = number of good observations ($x^n_{i,j} \geq 0$)

$x^n_{i,j,k}$ = 30-s observation on day *n* at station *i*, at 5-min time interval *j*, at 30-s period *k* during the 5-min interval.

$x^n_{i,j}$ = 5-min observation on day *n* at station *i* at time interval *j*.

$\bar{x}_{i,j}$ = average weekday 5-min observation at station *i* at time interval *j* (flow or occupancy; speed was generated as a volume weighted average).

The 30-min average flow surface, which is presented in figure 8, represents the average typical flow conditions in the eastbound direction along the I-4 section. The x-axis represents the time of day in hours since midnight that ranges from 0, at midnight at the start of the day, to 24 at midnight at the conclusion of the day. The y-axis represents the station numbers traversed, where the eastbound flow proceeds in the upward direction from station 1 to station 25. For each cell combination of time-of-day and station the z-axis represents the average hourly lane flow measured.

It can be noted from figure 8 that the flow gradually increased at 6 AM at all stations until it reached a flow of approximately 2000 vph/lane at 8 AM at most of the detector stations. The flow increased again during the PM peak at approximately 3:00 PM until 6:30 PM at stations 12 through 22. It appears from figure 8 that the flow from 5:00 to 7:00 PM at stations 7 through 12 was lower than at stations 12 to 22 (ranging from 1600-2000 vph/lane). However, figure 9 indicated that the speed in this area was also low (16 to 32 km/h). Thus, the lower flow measurements were most likely due to the presence of congestion, rather than a lower level of demand. Also, figure 10 demonstrates that for the same spatial and temporal combination the occupancy was high (25 to 30 percent).

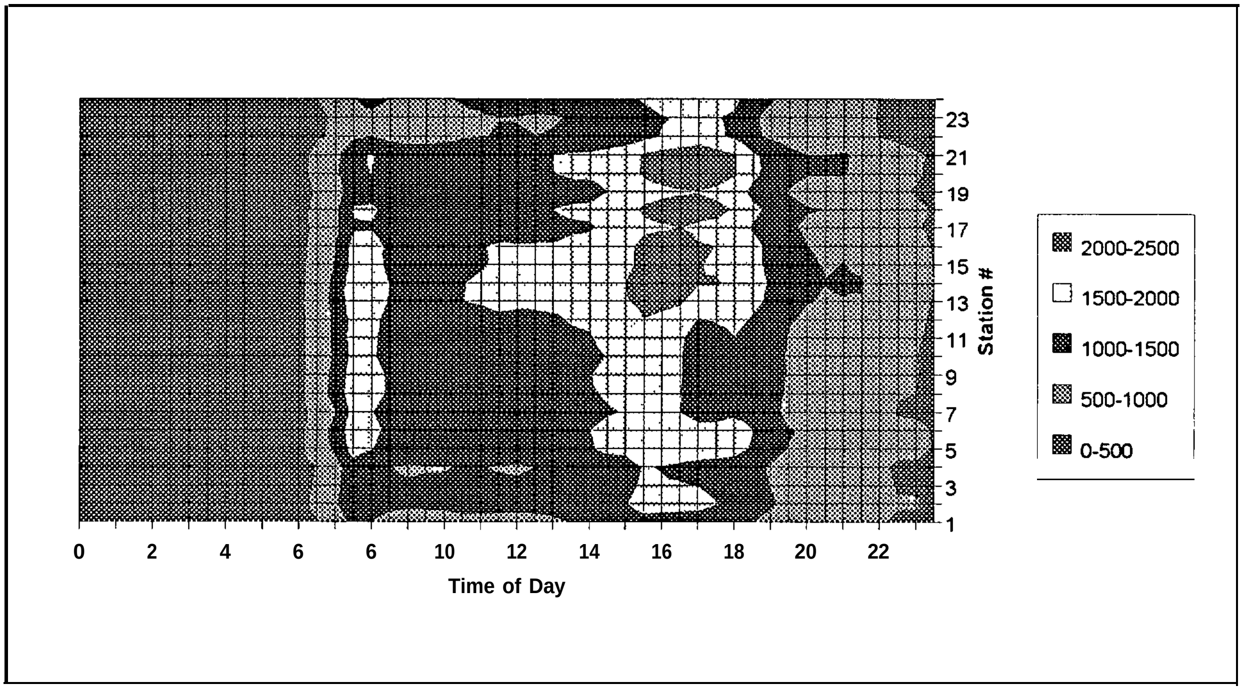

Figure 8: Temporal and spatial variation in 30-min EB average lane flow (vph/lane)

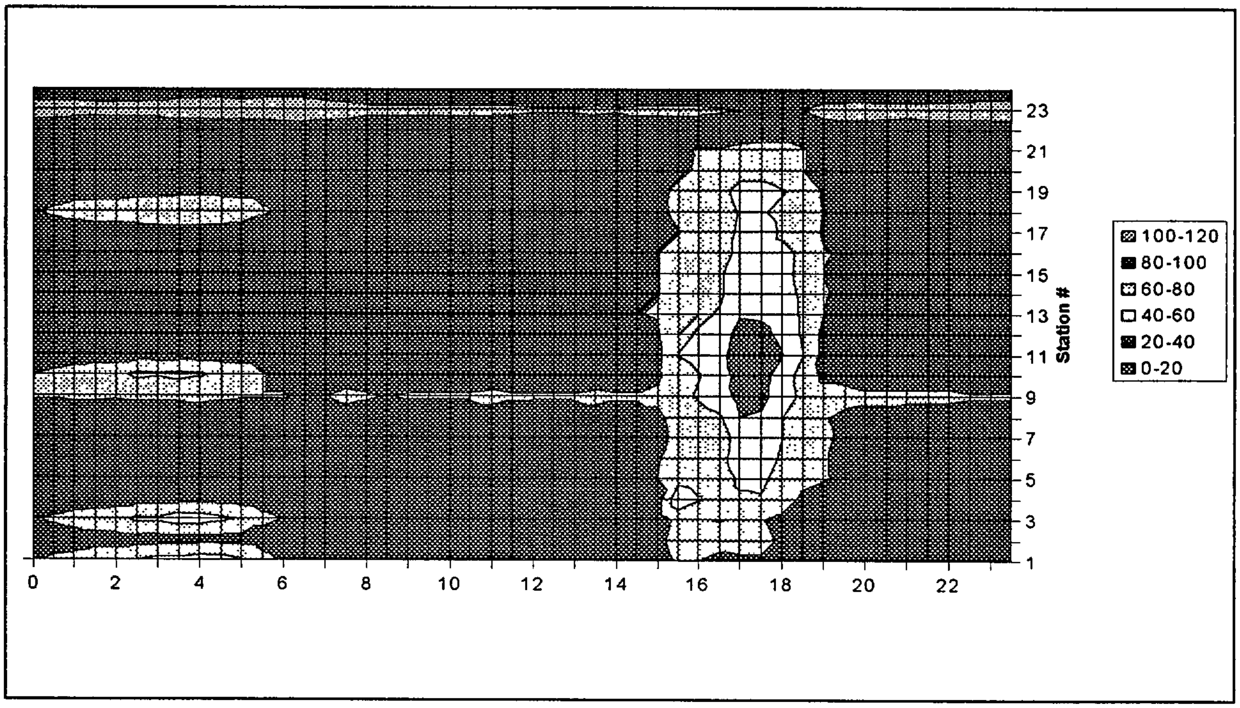

Figure 9: Temporal and spatial variation in 30-min EB average lane speed (km/h)

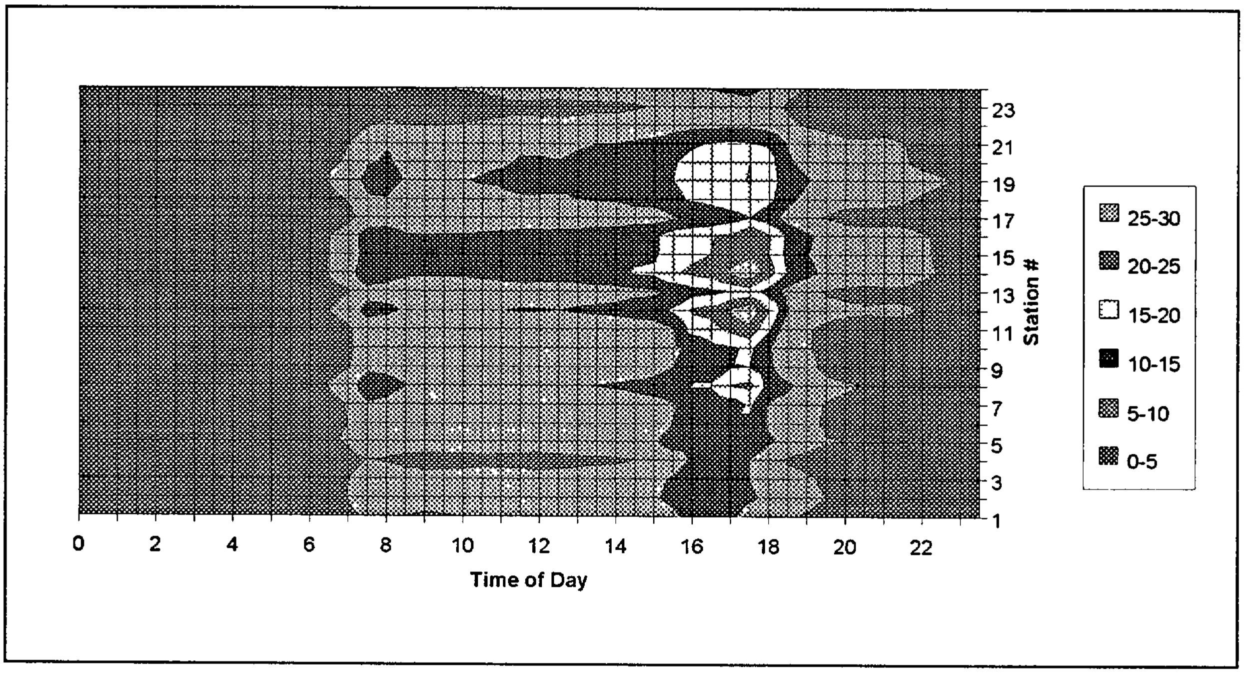

Figure 10: Temporal and spatial variation in 30-min EB average lane occupancy (percent)

Single-Factor ANOVA of Weekday Data

In order to investigate whether the variability in traffic conditions between the different days of the core of the week (Tuesday, Wednesday and Thursday) was statistically significant, a single-factor ANOVA was conducted using the SYSTAT model.[5] The ANOVA tested if the Root

Mean Square Error (RMSE) associated with the different day surfaces, about the typical average weekday surface, was greater than the variation within the samples for each specific day of the week using Equation 3.[6] Table 5 illustrates the ANOVA results for flow variations in the eastbound direction. These results, that are based on the 22 observations, indicate that the different days were not found to be statistically different at a level of significance of 95 percent. Similar results were obtained when comparing the speed in the eastbound direction, as demonstrated in table 6, and the occupancy in the eastbound direction, as demonstrated in table 7. Consequently, the observations in the eastbound direction for Tuesdays, Wednesdays and Thursdays were all grouped together as weekdays.

$$RMSE = \sqrt{\frac{\sum_{i}\sum_{j}(x_{i,j}^{n} - \overline{x}_{i,j})^2}{nobs}} \quad \forall x_{i,j}^{n}, \overline{x}_{i,j} \geq 0 \tag{3}$$

Where:

nobs = number of good observations $(x_{i,j}^{n}, \overline{x}_{i,j} \geq 0)$

A similar single-factor ANOVA on the different weekdays in the westbound direction was conducted, as presented in tables 8, 9, and 10. Again, the ANOVA results demonstrated that in the westbound direction there was no statistical difference between the observations for Tuesdays, Wednesdays and Thursdays at the 95-percent confidence level. Consequently, the data for these days were also grouped together as core weekdays.

In order to examine the ANOVA assumption of homogeneity of variance, the variation in residuals as a function of the estimated values (day mean) is plotted in figure 11. The *studentized* residuals were used because it is convenient to reference them against a *t* distribution. In figure 11 the residuals for the typical weekdays (Tuesdays, Wednesdays and Thursdays) were all within two standard deviations. It appears from figure 11 that the residuals are homogeneous as there appears to be no strong trend to the residuals. A similar absence of trends was found for the residual plots generated for the eastbound speed and occupancy surfaces. In addition, similar trends were also found for the westbound flow, speed and occupancy surfaces. However, due to the limited space in this report these are not presented here.

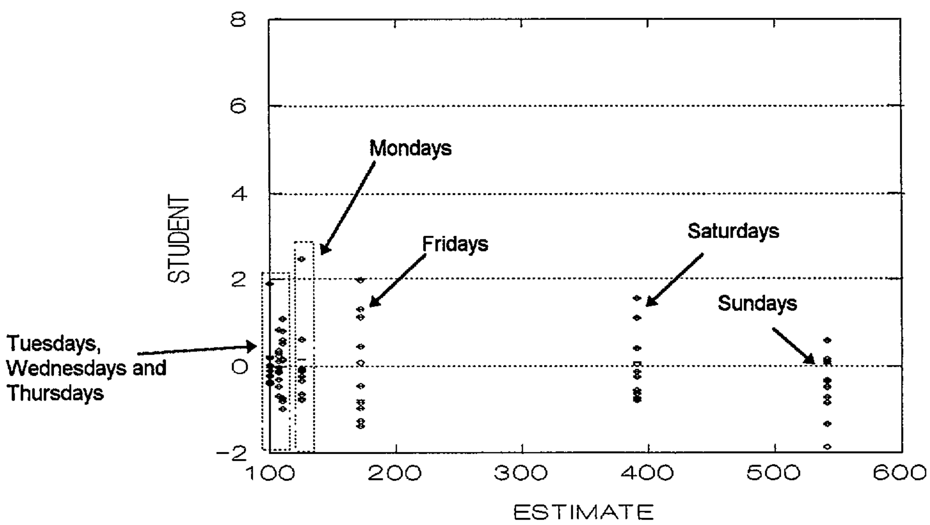

Figure 11: Variation in residual error as a function of the RMSE estimate for eastbound flows

Average Monday Surface

The average Monday flow, speed and occupancy surfaces for the eastbound and westbound directions were generated in a similar fashion to the average core weekday surfaces. The eastbound average Monday surfaces were estimated by averaging over nine Mondays, while the westbound average surfaces were estimated by averaging over 10 Mondays.

In order to quantitatively explore the similarity or variability between the Monday traffic conditions and the typical core weekday conditions, a single-factor ANOVA was conducted. The results of the ANOVA analysis for the eastbound direction, that are presented in table 5, demonstrate that the Monday flow conditions were statistically different from the typical weekday conditions at the 95-percent confidence level. However, the speed and occupancy measurements were not statistically different from the typical core weekday measurements (at the 95-percent confidence level), as illustrated in tables 6 and 7. The same trend in results was obtained in conducting an ANOVA analysis for the westbound direction, as indicated in tables 8, 9 and 10.

It appears that Mondays are different from core weekdays in terms of flow, but not in terms of speed or occupancy. Mondays were therefore not included in the data sample to create an average core weekday. These results were found to be consistent with the homogeneity assumption of ANOVA as illustrated by the residuals in figure 11.

Average Friday Surface

The ANOVA results for the eastbound direction indicated that the flows, speeds and occupancies on a typical Friday were statistically different from the traffic conditions of typical core weekdays at the 95-percent confidence level as demonstrated in tables 5, 6 and 7. The results for the westbound direction were similar, as illustrated in tables 8, 9 and 10. These results, again, were found to be consistent with the homogeneity assumption of ANOVA as illustrated by the residuals in figure 11.

Thus, in estimating the average typical link flows to be utilized in the synthetic O-D generation using QUEENSOD only Tuesdays, Wednesdays and Thursdays were considered.

Table 5: Single-Factor ANOVA of flow (EB)

ANOVA groups	df (within groups)	df (total)	F	Fcrit	Significance (95)
Tue. vs. Wed. vs. Thur.	19	21	1.16	3.52	No
weekday vs. Mon.	29	30	5.32	4.18	Yes
weekday vs. Fri.	30	31	101.87	4.17	Yes
weekday vs. Sat.	30	31	682.84	4.17	Yes
weekday vs. Sun.	32	33	384.79	4.15	Yes

Table 6: Single-Factor ANOVA of speed (EB)

ANOVA groups	df (within groups)	df (total)	F .	Fcrit	Significance (95)
Tue. vs. Wed. vs. Thur.	19	21	2.76	3.52	No
weekday vs. Mon.	29	30	2.40	4.18	No
weekday vs. Fri.	30	31	101.87	4.17	Yes
weekday vs. Sat.	30	31	682.84	4.17	Yes
weekday vs. Sun.	32	33	384.79	4.15	Yes

Table 7: Single-Factor ANOVA of Occupancy (EB)

ANOVA groups	df (within groups)	df (total)	F	Fcrit	Significance (95)
Tue. vs. Wed. vs. Thur.	19	21	1.88	3.52	No
weekday vs. Mon.	29	30	1.20	4.18	No
weekday vs. Fri.	30	31	17.13	4.17	Yes
weekday vs. Sat.	30	31	16.01	4.17	Yes
weekday vs. Sun.	32	33	47.25	4.15	Yes

Table 8: Single-Factor ANOVA of flow (WB)

ANOVA groups	df (within groups)	df (total)	F	Fcrit	Significance (95)
Tue. vs. Wed. vs. Thur.	30	32	0.85	3.32	No
weekday vs. Mon.	41	42	7.03	4.08	Yes
weekday vs. Fri.	41	42	66.39	4.07	Yes
weekday vs. Sat.	41	42	1678.67	4.08	Yes
weekday vs. Sun.	43	44	1668.55	4.07	Yes

Table 9: Single-Factor ANOVA of speed (WB)

ANOVA groups	df (within groups)	df (total)	F	Fcrit	Significance (95)
Tue. vs. Wed. vs. Thur.	30	32	0.55	3.32	No
weekday vs. Mon.	41	42	0.11	4.08	No
weekday vs. Fri.	41	42	12.15	4.07	Yes
weekday vs. Sat.	41	42	22.34	4.08	Yes
weekday vs. Sun.	43	44	23.54	4.07	Yes

Table 10: Single-Factor ANOVA of occupancy (WB)

ANOVA groups	df (within groups)	df (total)	F	F_{crit}	Significance (95%)
Tue. vs. Wed. vs. Thur.	30	32	0.62	3.32	No
weekday vs. Mon.	41	42	0.30	4.08	No
weekday vs. Fri.	41	42	15.98	4.07	Yes
weekday vs. Sat.	41	42	113.03	4.08	Yes
weekday vs. Sun.	43	44	208.02	4.07	Yes

Time Slice Aggregation Period

In order to investigate the effect of different time slice durations on the modeling accuracy, the 5-min loop detector data along the I-4 were aggregated and compared. Six time slice aggregation durations were evaluated using Equation 4, namely: 15, 20, 30, 60, 120 and 180 min. The 5-min flow, speed and occupancy surfaces served as the base case to which the other aggregation surfaces were compared.

$$\bar{x}'_{i,j} = \frac{\sum_{n5min} \bar{x}_{i,j}}{n5min} \quad \forall t \tag{4}$$

Where:

n5min = total number of 5-min intervals in aggregation period *t*.

$\bar{x}'_{i,j}$ = 5-min observation at station *i* at 5-min time interval *j* for aggregation period *t* (flow, speed, occupancy).

An estimate of the Coefficient of Determination (R^2) was utilized in the comparison. For each time slice aggregation period three matrices were generated, namely; flow, speed and occupancy observations. These matrices were 288 rows (number of 5-min intervals in the day) by 24 columns (number of loop detector stations). A separate overall mean for the average weekday flow, speed and occupancy measurements was also estimated, as demonstrated in Equation 5 (mean over all stations and all time periods $\bar{x}$).

For each of these surfaces, an estimate of the squared error about the 5-min surface was estimated as the difference for each station and time-of-day combination from the 5- min surface using Equation 6 (Sum of squared errors about the average surface S_1). The sum of squared errors for the flow, speed and occupancy measurements of each time slice aggregation duration about their respective overall mean was also estimated using Equation 7 (S_t). The sum of squared error explained by the base (5-min) flow, speed and occupancy (S_2) was estimated as the difference between S_t and S_1 based on Equation 8. The R^2 measure for each of the three surfaces, for each time slice aggregation duration, was calculated as the ratio of S_2 to S_t (S_2/S_t). Thus, R^2 was a measure of the amount of error captured by the corresponding aggregate surface. An R^2 of 1 indicates that the level of aggregation explains 100 percent of the squared error of the 5-min aggregation surface, while an R^2 of 0 indicates that the level of aggregation does not explain any of the error.

$$\bar{x} = \frac{\sum_{i=1}^{24}\sum_{j=1}^{288} \bar{x}_{i,j}}{nobs} \quad \forall \bar{x}_{i,j} \geq 0 \tag{5}$$

$$S_1 = \sum_{t=1}^{24}\sum_{j=1}^{288}(\overline{x}'_{i,j} - \overline{x}_{i,j})^2 \quad \forall\, \overline{x}'_{i,j}, \overline{x}_{i,j} \geq 0, t \tag{6}$$

$$S_t = \sum_{t=1}^{24}\sum_{j=1}^{288}(\overline{x}'_{i,j} - \overline{x})^2 \quad \forall\, \overline{x}'_{i,j} \geq 0, t \tag{7}$$

$$S_t = S_1 + S_2 \tag{8}$$

Where:

nd, $x^n_{i,j,k}$, $\overline{x}'_{i,j}$, and $\overline{x}_{i,j}$ are as defined earlier.

nobs = number of good observations ($\overline{x}_{i,j} \geq 0$; max.= 6912)

$\overline{x}$ = overall average observation (flow, speed, and occupancy).

S_t = total sum of squared errors about overall mean (flow, speed, and occupancy).

S_1 = sum of squared errors about 5-min surface (flow, speed, and occupancy).

S_2 = sum of squared errors explained by 5-min surface (flow, speed, and occupancy).

The variation in R^2, as a function of the duration of the time slice aggregation period, for the eastbound direction is presented in figure 12. It appears from figure 12 that flow and occupancy measurements are less sensitive to the time slice duration, and that the R^2 value for aggregation periods up to 60 min are relatively high (> 0.90). The R^2 tends to decrease steeply for time slice durations greater than 60 min. The same trend appeared to occur for measurements in the westbound direction as illustrated in figure 13. However, the reduction in R^2 for the westbound measurements for time slice durations greater than 60 min was more severe (0.30 vs. 0.64).

Consequently, in the modeling analysis a time slice of 60 min was selected in order to maintain the level of accuracy while reducing the computational time. This finding was generally consistent with the findings of a study conducted in Chicago as part of the Advanced Driver and Vehicle Advisory Navigation Concept (ADVANCE).[7]

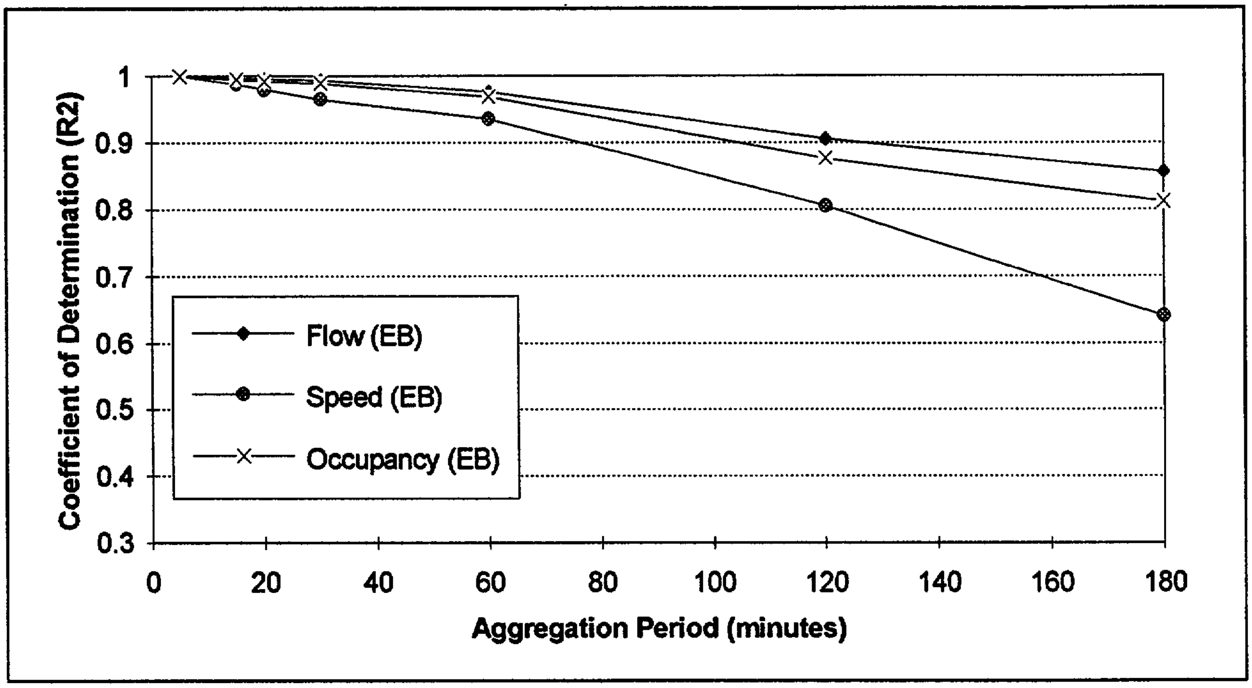

Figure 12: Effect of time slice duration on R^2 for eastbound direction

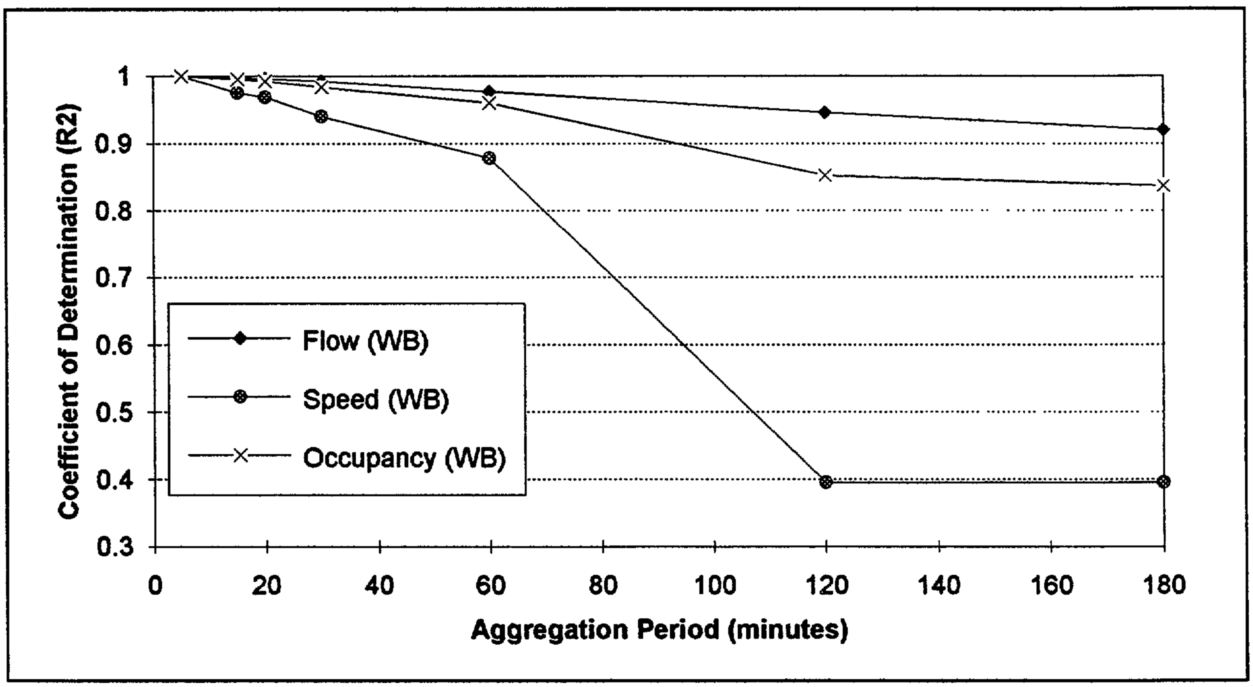

Figure 13: Effect of time slice duration on R^2 for westbound direction

Derivation of Synthetic O-D Patterns

The INTEGRATION model requires, as one of its input files, an Origin-Destination (O-D) demand file. In order to generate this O-D file for the Orlando network, the QUEENSOD model was utilized. QUEENSOD estimates O-D traffic demands based on observed link traffic flows, link travel times, an optional seed matrix and drivers' route choices using a maximum likelihood procedure. The QUEENSOD model is capable of estimating both static and dynamic traffic demands.

In this study two static hourly O-D demands were estimated for the first 2 h of the PM peak from 3 to 5 PM. A time slice of 1 h was selected based on the conclusions of the previous subsection. The link flows for the detectorized links along I-4 were generated from the typical weekday traffic conditions that were described earlier in this section for the PM peak. Flows for the remaining non detectorized links of the network were assumed to be 25 percent of the link saturation flow rate in the absence of any further information. The link flows on all links for the first hour were further reduced by 20 percent in order to model a demand buildup. The O-D demand was estimated for 40 iterations by minimizing the relative difference between observed and estimated link flows. Five equilibrium trees using the standard Frank-Wolfe algorithm were input to QUEENSOD for the entire 2-h time frame. The resulting O-D demand resulted in link flows that were highly correlated with the observed flows input (coefficient of correlation of 86 percent) to the model based on 12,955 observations.

LINK CAPACITY ESTIMATES AND SPEED-FLOW PARAMETERS

The general link characteristics of the INTEGRATION simulation model were derived primarily from the NavTech data base. In addition, some data were obtained from field observations that were made as part of the operational field test and from detector data for the Orlando Freeway Management Center (FMC). The use of FMC data, to produce link traffic flow parameters, is discussed next.

The INTEGRATION simulation model uses a simplified car-following model to track the movements of individual vehicles. This model considers that a vehicle's desired speed is primarily a function of the distance headway between that vehicle and the vehicle ahead of it, where the nature of the functional relationship is dependent on the geometry of the link. Due to the difficulty of calibrating this relationship at the individual vehicle level, the parameters for a macroscopic speed-flow relationship that corresponds to the above car-following model were fit instead using FMC loop detector data. For each station, four fitted parameters were computed from FMC loop detector data, namely: free-speed, speed-at-capacity, capacity, and jam density.

An integrated approach was developed specifically for generating the speed-flow relationship for implementation within the INTEGRATION model as discussed in this section.

Estimation of Speed-Flow Parameters

The car following logic in the INTEGRATION simulation model, that is illustrated in Equation 9. It considers that the minimum desired distance headway, between two consecutive vehicles, is the sum of a constant term plus a variable term which is dependent on the difference between the current speed and the free-speed, and a final term which is a linear function of speed. The macroscopic speed-flow relationship that corresponds to this car-following model is illustrated in Equation 10.(8) The speed-flow relationship is a single regime model which is an extension to Greenshields' model and which is prevalent throughout the Highway Capacity Manual and most traffic engineering books. (See references 9, 10, 11, 12, 13.) In order to generate the speed-flow relationship one needs to estimate three parameters, namely: c_1, c_2 and c_3, using Equations 11, 12, 13, and 14. In order to estimate these parameters one needs to identify four related parameters u_f, u_c, q_c, and k_j. These four variables are required as input for each link in the INTEGRATION model's link characteristic file.

$$h = c_1 + \frac{c_2}{u_f - u} + c_3 u \tag{9}$$

$$q = \frac{u}{c_1 + \frac{c_2}{u_f - u} + c_3 u} \tag{10}$$

$$k = \frac{c_1}{c_2} = \frac{(2u_c - u_f)}{(u_f - u_c)^2} \tag{11}$$

$$c_2 = \frac{1}{k_j (k + \frac{1}{u_f})} \tag{12}$$

$$c_1 = k c_2 \tag{13}$$

$$c_3 = \frac{-c_1 + \frac{u_c}{q_c} - \frac{c_2}{(u_f - u_c)}}{u_c} \tag{14}$$

Where:

h	= distance headway between vehicles (km)
c_1	= fixed distance headway constant (km)
c_2	= first variable distance headway constant (km^2/h)
u_f	= free-speed (km/h)
u_c	= speed at capacity (km/h)
u	= prevailing speed associated with headway h (km/h)
q	= flow rate of traffic traveling at speed u km/h (vph)
q_c	= flow at capacity (vph)
k_j	= jam density (veh/km)
k	= dimensionless constant to set the speed at capacity

A model was developed, as part of the evaluation process, that fits a curve to the observed data and generates the four parameters required by the INTEGRATION model based on speed-flow measurements from the field.[14] Figure 14 demonstrates a sample fit to data collected over an entire day at one of the I-4 detector stations. The discrete points represent the loop detector measurements while the continuous curve represents the fit estimated by a customized curve fitting model developed earlier at Queen's University. It is evident from figure 14 that the macroscopic relationship captures the variation in speed-flow quite efficiently.

The four parameters selected by the model for the data in figure 14 were as follows: u_f=87.2 km/h, u_c=70.6 km/h, q_c=1925 vph, k_j=92.2 veh/km. The free-speed is identified as the higher speed-intercept of the fit, the speed at capacity is the speed that corresponds to the maximum flow point (nose of curve), the capacity is the maximum flow, and the density is the inverse of the slope of the curve at the origin.

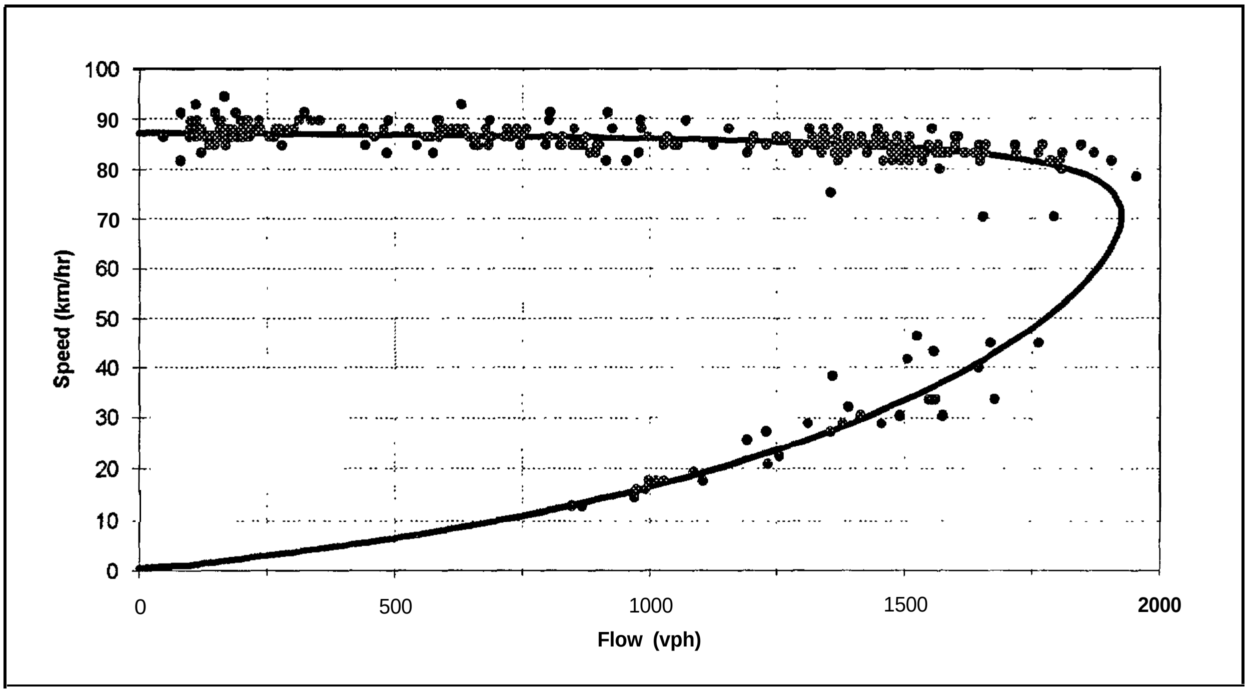

Figure 14: A typical speed-flow fit to I-4 data (ul -87.2 km/h, uc=70.6 km/h, qc=1925 vph, kj=92.2 veh/km)

Temporal and Spatial Variability of Speed-Flow Parameters

In order to investigate the temporal and spatial variability in the four speed flow parameters, ten weekdays of loop detector information were analyzed using the curve fitter program. The four parameters were estimated for each station for each of the 10 days.

Figure 15 demonstrates the temporal and spatial variation in the free-speed from station 9 to 22 over the 10 day analysis period. Because the other stations (1 to 8 and 23 to 25) did not have as many points in the congested region (or at the nose of the relationship), the curve fit was insufficiently constrained and therefore not performed. Thus, only the results for the stations located in the downtown area are presented here. One can observe from the surface plot that the free-speed ranged from 80 to 110 km/h. It appears that the free-speeds were relatively constant over the 10 day period as indicated by the minor variations in the y-axis direction. However, the speeds varied more along the different locations along the x-axis. The variation in free-speed was in the range of approximately $\pm$ 15 percent of the average free-speed.

The variability in the speed at capacity (u_c) was similar (approximately $\pm$15 percent) as illustrated in figure 16. However, in this case there appears to be no temporal nor spatial trend to the variability. The temporal and spatial variability in average lane capacity, which is illustrated in figure 17, demonstrates that the variability over space (between stations) exceeded the variability over the days. The capacity ranged between $\pm$20 percent of the average capacity. It also appears that the fourth day experienced a lower capacity than usual.

Finally, figure 18 demonstrates the temporal and spatial variation in jam density (k_j). It appears that the jam density ranged between approximately +60 percent of the average jam density. Also, there appears to be no temporal nor spatial trend to this variation. The reason for the extreme fluctuation in jam density is due to the small number of points in the congested region. This fact made the fitting of the curve more flexible at the origin.

Based on these results there did not appear to be any specific deterministic trend to the variation in the four parameters. Thus, their values were fixed for all the I-4 links at the following values: u_f=88 km/h, u_c=75 km/h, q_c=2200 vph, and k_j=100 veh/km.

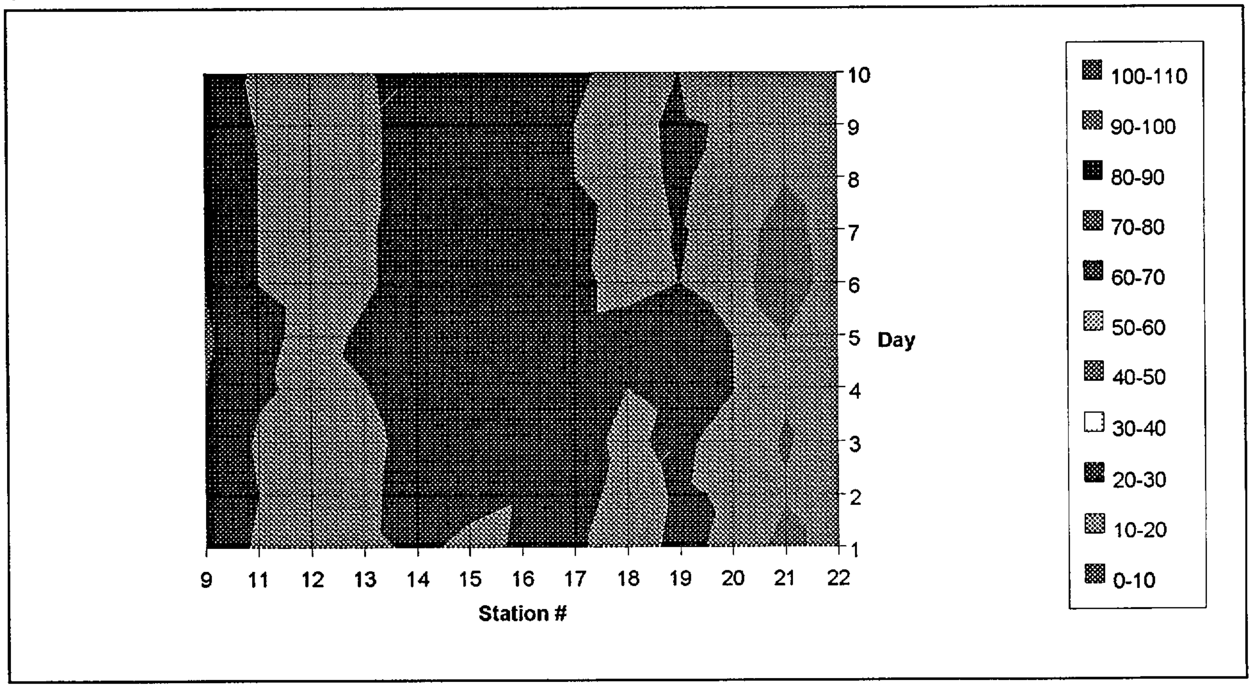

Figure 15: Temporal and spatial variation in free-speed along I-4

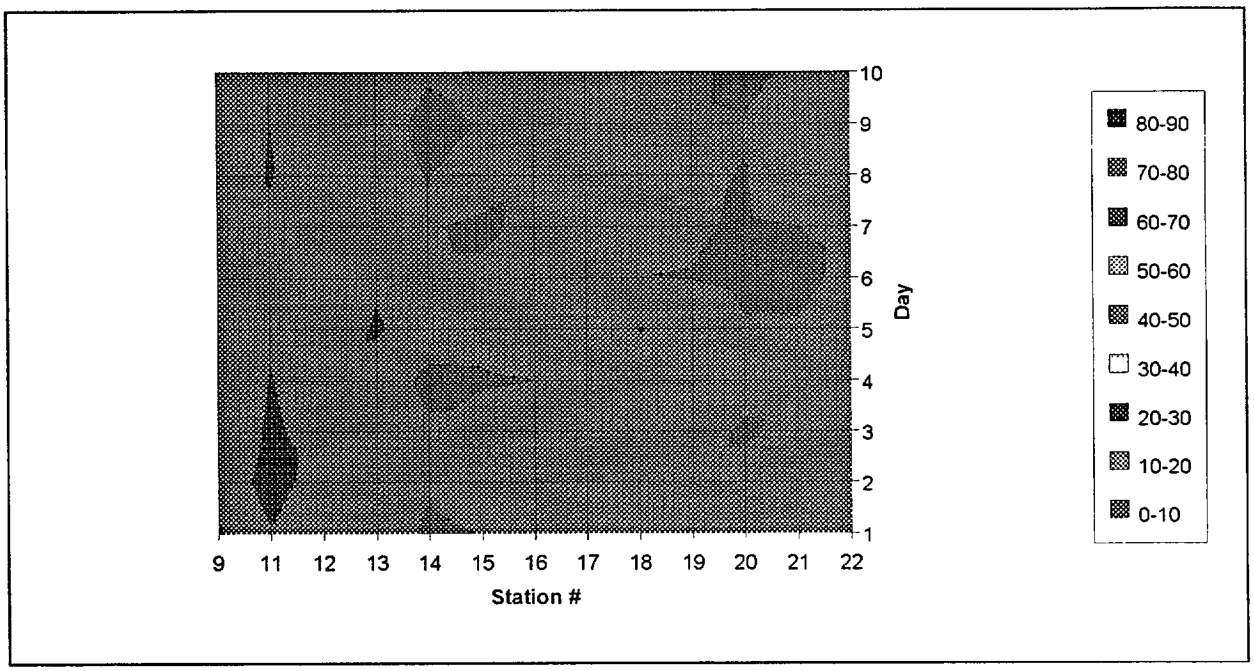

Figure 16: Temporal and spatial variation in speed at capacity along I-4

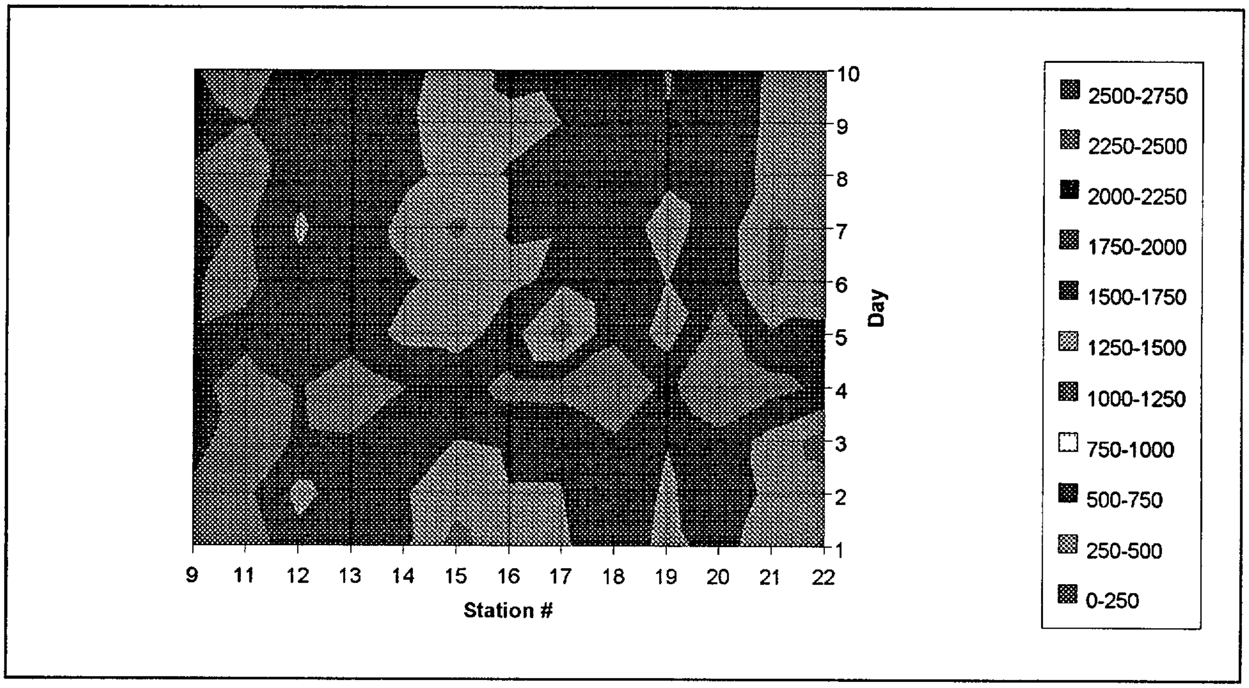

Figure 17: Temporal and spatial variation in capacity along I-4

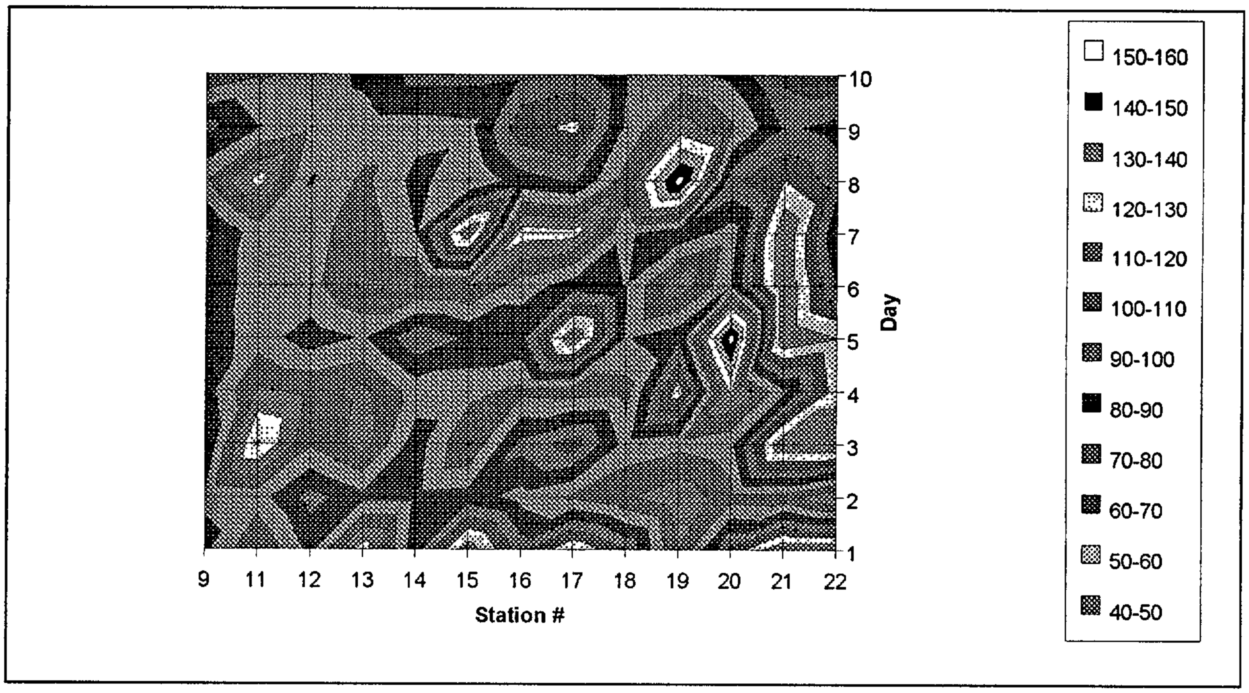

Figure 18: Temporal and spatial variation in jam density along I-4

Derivation of Link Parameters for Links not along I-4

For the links not under surveillance the following default parameters were used:

For I-4 off- and on-ramps:

u_f= 60 km/h, u_c = 50 km/h, q_c = 2050 vph/lane, and k_j = 100 veh/km

For highway & arterial links:

u_f= 56 km/h, u_c = 40 km/h, q_c = 2000 vph/lane, and k_j = 100 veh/km.

SUMMARY

This chapter described the general characteristics of the INTEGRATION simulation model. The objective of this description was to demonstrate how this model could be utilized in the evaluation study. This chapter also described the configuration of the Orlando downtown simulation network. It was illustrated how typical Origin-Destination demands were generated from FMC loop detector data, how a time slice duration was selected, and how the link specific parameters were selected.

The final simulation network encompassed all navigational links surrounding the downtown of the City of Orlando and all the detectorized portion of the I-4 freeway. This network resulted in a total of 2,670 links, 87 O-D zones, 1,295 nodes and 49 traffic signals. The traffic signals were modeled at a cycle length of 80 s with a 50:50 phase split due to lack of further specific information on the responsive nature of the signal settings. Two 1 h Origin-Destination demands (3:00 to 5:00 PM) were generated using real-time link flows along the I-4 freeway that were provided by the FMC and flows of 25 percent the saturation flow rate along the remaining links. The link flows for the initial hour (3:00 to 4:00 PM) were reduced by 20 percent to allow for a gradual increase in demands. The freeway links were set to have a free-speed of 88 km/h, a speed-at-capacity of 75 km/h, a saturation flow rate of 2200 vph/lane, and a jam density of 100 veh/km. Off- and on-ramps were set to have a free-speed of 60 km/h, a speed-at-capacity of 50 km/h, a saturation flow rate of 2050 vph/lane, and a jam density of 100 veh/km. Finally, the remaining links were coded using a free-speed of 56 km/h, a speed-at-capacity of 40 km/h, a saturation flow rate of 2000 vph/lane, and a jam density of 100 veh/km.

The setup and calibration of the base traffic flow model for the Orlando network was followed by the calibration of the generic features of the INTEGRATION model to those specific to the TravTek system routing logic. The next chapter will discuss in detail the derivation of these TravTek specific features.

CHAPTER 3: DERIVATION OF TRAVTEK SPECIFIC MODELING AND NETWORK FEATURES

INTRODUCTION

In the previous chapter the INTEGRATION model was described in detail together with the network configuration utilized in the modeling process. This chapter proceeds a step further by focusing on deriving the TravTek specific modeling and network features. Prior to discussing these specific features a brief overview of the real-time data transmission cycle is presented in the first section of the chapter.

Initially, the accuracy of probe information will be discussed based on some data collected from field studies conducted on the performance of vehicle probes in Orlando. Subsequently, the accuracy of the data fusion task is discussed. Finally, the extent of spatial and temporal availability of real-time information is presented in the following section. These three factors: probe accuracy, data fusion accuracy, and spatial and temporal availability of data impact the TravTek vehicle routing logic performance directly. Consequently, the following section discusses how the TravTek and background traffic routing were modeled in the INTEGRATION model and what assumptions were made in the modeling process representation.

A Yoked Driver Study was also conducted in Orlando using TravTek vehicles in order to estimate the navigational waste associated with background traffic and TravTek equipped vehicles. A description of how the results of this study were incorporated in the INTEGRATION model are also presented in this chapter. In addition, this chapter discusses how the modeling of fuel consumption was incorporated in the INTEGRATION model. Furthermore, the chapter demonstrates the emission and accident risk estimation procedure within the INTEGRATION model. Finally, the conclusion together with a summary of the major findings of the chapter are presented.

OVERVIEW OF REAL-TIME DATA TRANSMISSION CYCLE

The entire TravTek information processing cycle can be considered to consist of three main modules as illustrated in figure 19. The purpose of the first module is to fuse the traffic data and incident reports from the various input data sources, This module, therefore, estimates, based on these fused data, the prevailing travel times on each network link. All data inputs into the data fusion process are converted, extrapolated or translated into indirect estimates of link travel times. The estimated link travel times are not fully dynamic, in the sense that they do not consider anticipated traffic demands and traffic control policies. In addition, the travel time estimates do not consider any feedback effects that develop due to driver’s reactions to the travel time information that is disseminated to the TravTek vehicles.

The purpose of the second module is to translate these link travel time estimates into travel time multiplier factors relative to a reference travel time in order to reduce the amount of total data broadcast. These factors are broadcast every min by radio to all TravTek vehicles, if these factors are found to deviate from the default values by a pre-specified amount.

The logic of the first two modules are executed within the Traffic Management Center (TMC). The third data processing module is executed within each individual in-vehicle TravTek unit as the travel time factors are received and translated into a format that is suitable for the minimum route calculations. The calculation of the minimum routes is carried out in a distributed as opposed to centralized manner, as each vehicle performs its own optimum route calculation. This is in contrast to a centralized system in which the TMC would perform all such routing calculations and would only be broadcasting the resulting routes for each vehicle. This distributed logic may appear less suitable for mature systems, because the independent decisions in the route selection could result in the phenomena where the new routes become overloaded and therefore become non-optimum.

It should be noted that in figure 19 the boxes that represent processes are highlighted, while the single-boxed segments represent data items that are being generated.

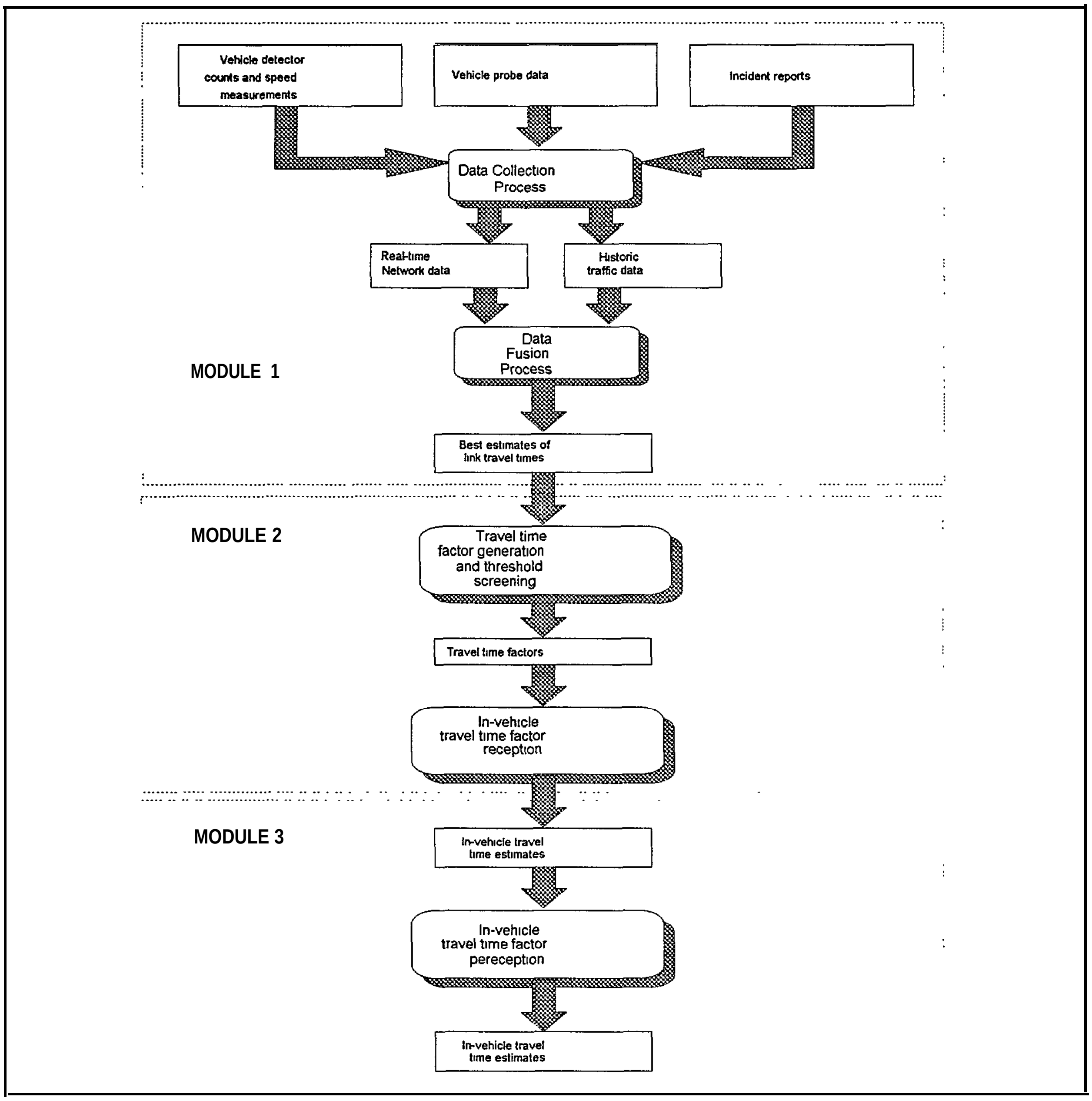

Figure 19: Conceptualization of the traffic features in the TravTek processing cycle

IN-VEHICLE LINK TRAVEL TIME ACCURACY ON ARTERIALS AND FREEWAYS

The TMC data base computer has access, on a min-by-min basis, to the I-4 freeway data from the FMC, the Urban Traffic Control System (UTCS) link delay data from the downtown Orlando traffic control system, the probe data, and the historical link travel times.

This section attempts to evaluate the quality of these three sources of dynamic travel time information in order to calibrate the modules within the INTEGRATION simulation model which represent these features.

Accuracy of Probe Link Travel Time Estimates

In order to evaluate the accuracy of the link and trip travel time estimates that are generated by the vehicle probes, the link travel times on a typical arterial corridor (Colonial Drive) and a downtown network were observed by human observer for travel which was also logged by the TravTek vehicle. The observed manual link travel time estimates were then compared to the automated vehicle probe estimates for the same trips. Initially, the characteristics of the networks analyzed in this analysis are presented prior to providing a description of the study.

Network description

The probe study was conducted on two networks. The first network was a typical four lane divided east/west arterial corridor (Colonial Drive). This network, which consisted of 36 TravTek links, extended from Alafaya Trail in the East of Orlando to Tampa Avenue in the West as illustrated in figure 20. The test corridor extended over approximately 19 km and was composed of a mixture of urban and suburban roadway segments which were all signalized.

The second network was located in downtown Orlando and consisted of a closed loop of 33 TravTek links. This loop extended over approximately 5 km, as illustrated in figure 21. These links were typically shorter than the links of the Colonial drive network. Thus, this study attempted to evaluate the differential quality of probe information on two typical networks.

Study description

In the study of the arterial the TravTek vehicle was driven along Colonial Drive twice in each direction. The first eastbound and westbound trip was conducted in the late morning/early afternoon (between 10:00 AM and 12:30 PM). The second trip was conducted in the early evening during the PM peak (between 4:00 and 6:30 PM). The TravTek vehicle was also driven five times along the entire downtown loop network. Three of these trips were conducted in the late morning (between 11:00 and 12:00 PM), while the remaining two were conducted in the evening during the latter part of the PM peak (between 5:00 and 6:00 PM).

The main objective of varying the trip start times was to capture the normal variations in demands during a typical day. Thus, the study attempted to capture both the spatial and temporal variations in network and traffic conditions. The spatial variations were captured by utilizing an arterial and downtown network while the temporal variations were captured by varying the study period.

The TMC probe data for the specified trips were compared to the observed manually measured link and trip travel times. The manually observed link travel times were measured as the time difference required in traveling from the centerline of the upstream cross street to the centerline of the downstream cross street. It was found that this link travel time measuring procedure did not always yield results which agreed with the method used by the vehicle probes, as will be demonstrated in this section.

Evaluation of link travel time estimates

The nine test trips indicated that the average link travel time discrepancy between the manual and automated methods was generally minor (not exceeding 4 s). It must also be noted that the percentage average error decreased as the average link travel time increased (average error/average travel time). Specifically, for the downtown network, the average error ranged from

2.5 to 3.5 s, the average absolute error ranged from 3 s to 4.4 s and the Root Mean Squared (RMS) error ranged from 3 to 6 s. It must be noted that the Least Significant Bit (LSB) of the vehicle travel time estimate provided a resolution to within 6 s. Thus, for the downtown network the level of discrepancy was within the accuracy of the probe estimates.

For Colonial Drive, the average discrepancy was also minor ranging from 2 to 3 s. However, the absolute and RMS errors were more significant, ranging from 4 to 15 and 5 to 27 s, respectively. In order to determine the reason for the high absolute and RMS errors, table 11 illustrates the automated probe estimated travel time, the manually observed travel times and the corresponding difference in the link travel time estimates. It can be noted from table 11 that the discrepancy was generally small, except for the highlighted cells. Furthermore, it is evident from the highlighted cells that for each large positive difference in link travel time estimates a corresponding nearly equal negative difference was present. This effect was caused due to the difference in including the delay at an intersection to the upstream versus downstream link for the probe estimated and observed link travel times. Thus, it can be concluded that although at first glance one may conclude that the probe link travel time estimates are not accurate, a further analysis indicates that the inconsistency in the link travel time estimates was caused due to the difference in the inclusion of the delay at an intersection, leading to errors of opposite sign that cancel. The mis-allocation of intersection delay resulted because of the linear layout of the network which did not provide an opportunity for the map matching logic to correct the Global Positioning System (GPS) estimate of vehicle location.

Averaged over the nine runs the average link travel time discrepancy was estimated to be 2.6 s, the average absolute error was estimated to be 6.3 s and the average RMS error was estimated to be 13.7 s. This error, apart from the RMS error, is consistent with the LSB of the link travel time estimate of 6 s.

In summary, the results of the runs indicated that the average link travel time error was minor (not exceeding 4 s). The average link error ranged from approximately 2 percent to 10 percent. In view of the above, a value of 5-percent error was used as the base case in the subsequent simulation results as shall be discussed in the forthcoming chapter.

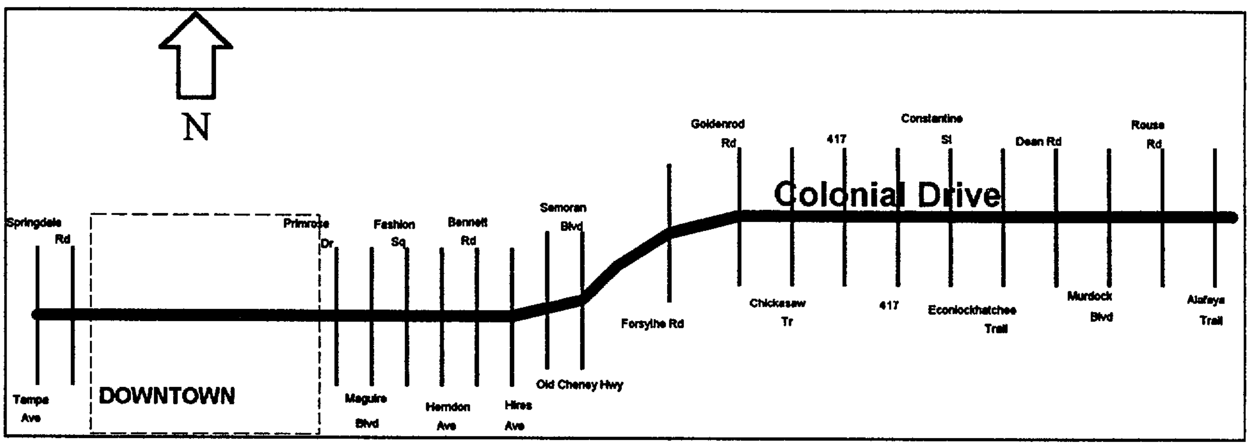

Figure 20: Colonial Drive test network

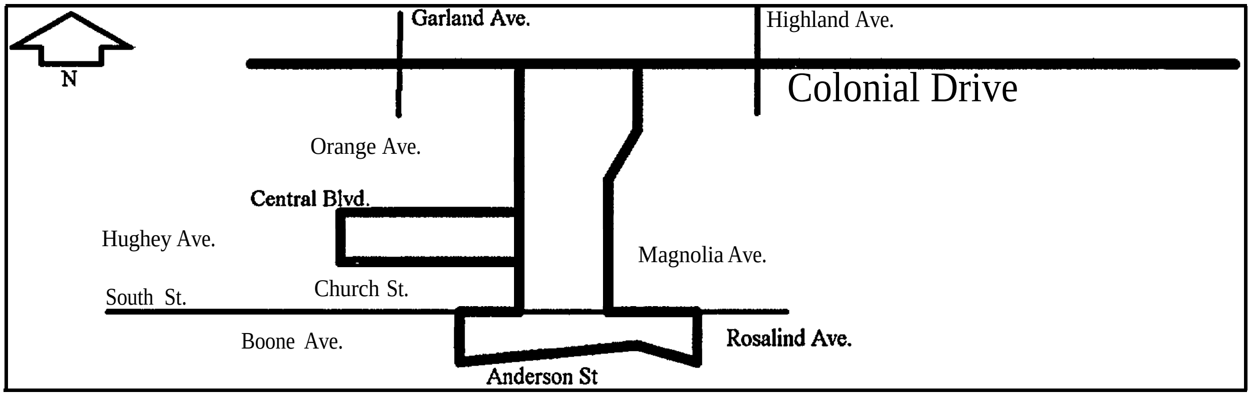

Figure 21: Downtown test network

Table 11: Observed and probe link travel time estimates along Colonial Drive

Link number	Probe link travel time (I)	Observed link travel time (2)	Obsewed-probe (2-l)
186	78	79	1
187	66	68	2
188	90	90	0
189	120	125	5
190	42	40	-2
191	6	15	9
193	12	13	1
19.5	42	44	2
196	66	71	5
197	72	73	1
198	186	188	2
199	60	61	1
200	60	65	5
201	36	40	4
202	30	35	5
203	6	85	79
204	108	27	-75
205	24	25	1
206	54	58	4
207	12	16	4
208	30	37	7
209	30	30	0
210	12	16	4
211	12	78	66
212	84	24	-60
213	30	54	24
214	42	22	-20
215	18	16	-2
216	36	82	46
217	72	26	-46
219	24	27	3
220	6	9	3
221	36	37	1
222	108	111	3
223	6	6	0
224	missing	50	50

Accuracy of FMC Link Travel Time Estimates

In order to attempt to quantify the consistency of vehicle probe and FMC loop detector based link travel time estimates, a regression analysis was conducted on the data for station 12 on I-4 over a 6 day period. Station 12 was selected as it experienced both congested and uncongested flow conditions when traversed by probes. Specifically, the analysis included a total of 34 probe observations over 6 different days. A listing of the various regressions that were fit to these data is presented in table 12.

Initially a regression was conducted on the entire range of observations allowing the regression analysis to select the appropriate y-axis intercept as illustrated in table 13. The regression analysis estimated the coefficient of determination (R2) to be 0.77. A perfect correlation of link travel time estimates would result in a line of unit slope that passes through the origin. The existence of an intercept would indicate a systematic error between the two sources of link travel time estimates, while a slope less or greater than unity would indicate an under or over estimation by the FMC of link travel times relative to probe based link travel times.

The regression line (REG 1) was estimated to have an intercept of 24 s with a standard error of 8.7 s. This resulted in 95-percent confidence limits that did not include the origin intercept. Thus based on the first regression results there appeared to be a statistically significant link travel time estimation bias. The slope of the first regression line was also estimated to be 0.8 with a standard error of 0.08. This resulted in 95-percent confidence limits that did not contain the unit slope. The existence of an extreme point was considered as one of the possible reasons that caused the regression line to have a statistically significant intercept, and not to have a unit slope.

A second regression was conducted on the data in which the intercept was forced to a setting of zero (REG 2). The results of the second regression are presented in table 14. In this regression the coefficient of determination was reduced from 0.77 to 0.72. The slope increased from 0.8, in the first regression, to 0.97 and the unit slope fell within the 95-percent confidence limit range of the estimated slope.

An extreme point was then removed from the analysis and the regression was re-fit to on the remaining 33 observations. In the initial regression (REG 3), the intercept was estimated to be -2.7 s with a standard error of 12 s as demonstrated in table 15. Thus the origin fell well within the 95-percent confidence limits. Because the intercept was again found to not be statistically insignificant at the 95-percent level, the regression was repeated by setting the intercept to zero, as demonstrated in table 16 (REG 4). The final regression analysis estimated a coefficient of determination of 0.68 while the slope was estimated to be 1.13. However, the lower bound 95-percent confidence limit was slightly greater than 1 (1 .O 1). Based on these regression results it was concluded that the FMC and probe link travel time estimates were highly correlated (correlation factor of 0.83).

As part of Task F (System Architecture Evaluation), the quality of the FMC data was also evaluated. In this comparison, it was found that the FMC overestimated the link travel times by 16 percent, 19 percent, and 27 percent in the AM, Off, and PM peaks, respectively. A ***t-test*** indicated that these results differed statistically from zero at the 95-percent confidence level. The study also estimated the Pearson Correlation Coefficient and found a high degree of correlation between

FMC and observed travel times (81 percent, 45 percent, and 78 percent for the AM, Off, and PM peaks, respectively). These results were generally consistent with the findings of the study conducted in this report.

Based on this analysis and the analysis in Task F, it was concluded that FMC consistently overestimated actual travel times. It was also concluded that speed measurements from standard loop detectors could provide a reasonably accurate estimate of link travel time (error of 20 percent).

Table 12: Regression analysis description

Regression #	Description
1	Regression on all 34 observations allowing the regression freedom of intercept calculation
2	Regression on all 34 observations with intercept fixed at zero
3	Regression on 33 observations after removing extreme point allowing the regression freedom of intercept calculation
4	Regression on 33 observations after removing extreme point with intercept fixed at zero

Table 13: Regression Analysis for Regression 1

Regression Statistics

Multiple R	0877034659
R Square	0.769189793
Adjusted R Squ	0.761976974
Standard Error	31.1736323
Observations	34

Analysis of Variance

	df	Sum of Squares	Mean Square	F	Significance F
Regression	1	103634.2472	103634.2472	1066420487	1 02631 E-l 1
Residual	32	31097.45123	9717953509		
Total	33	134731.6984			

	Ccefficients	Standard Error	t Statistic	P-value	Lower 95%	Upper 95%
intercept	2375004278	8668469836	2 73981951	0009839865	6092962482	41.40712307
Xl	0 801806853	0077643575	IO 32676371	7 19261E-12	0 6436522	0.959961506

Table 14: Regression analysis for regression 2

Regression Statistics

Multiple R	**0.845603907**
R Square	**0.715045967**
Adjusted R Squ	**0684742937**
Standard Error	**34.1087125**
Observations	**34**

Analysis of Variance

	df	*Sum of Squares*	*Mean Square*	*F*	*Significance F*
Regression	1	**9633935754**	**96339.35754**	**6280815206**	**2 16246E-10**
Residual	**33**	**38392.34085**	**1163.404268**		
Total	**34**	**134731.6984**			

	Coefficienls	*Standard Error*	*r Statistic*	**P-value**	*Lower 95%*	*Upper 95%*
Intercept	**0**	**#N/A**	**#N/A**	**#N/A**	**#N/A**	**#N/A**
Xl	**0969259584**	**0052394892**	**18 49912362**	**2 54134E-19**	**0 86266129**	**1 075857877**

Table 15: Regression analysis for regression 3

Regression Statistics

Multiple R	**0.826523412**
R Square	**0.683140951**
Adjusted R Squ	**0.672919692**
Standard Error	**28.08822267**
Observatlons	**33**

Analysis of **Variance**

	df **Sum** *of Squares*		*Mean Square*	*F*	*Significance F*
Regression	1	**5272959292**	**5272959292**	**6683529969**	**3 1118E-09**
Residual	**31**	**2445739584**	**7889482528**		
Total	**32**	**77186 98876**			

	Coefficients	*Standard Error*	*t* **Statistic**	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	**-2 785492684**	**12 0277539**	**-0 231588766**	**0 818331984**	**-27 31627218**	**21.74528662**
xl	**1159888941**	**0 141877477**	**8175285909**	**2 44797E-09**	**0.870527757**	**1449250126**

Table 16: Regression analysis for regression 4

Regression Statistics

Multiple R	**0.826191715**
R Square	**0.682592751**
Adjusted R Squ	**0.651342751**
Standard Error	**27.66976564**
Observations	*33*

Analysis of Variance

	df	**Sum** *of Squares*	*Mean Square*	**F**	*Significance F*
Regression	1	**52687.27098**	**52687.27898**	**68.81685303**	**2.27095E-09**
Residual	*32*	**24499.70978**	**765.6159306**		
Total	*33*	*77106.98876*			

	Coefficients	*Standard Error*	*t Statistic*	*P-value*	**Lower 95%**	*Upper 95%*
Intercept	**0**	**#N/A**	**#N/A**	**#N/A**	**#N/A**	**#N/A**
xl	**1 129869211**	**0.056816887**	**19 8861513**	**6.09178E-20**	**1.014137098**	**1** *245601325*

Accuracy of UTCS Link Travel Time Estimates

The UTCS travel time estimates were also evaluated as part of Task F (System Architecture Evaluation). It was found that UTCS overestimated the perceived actual travel times (as measured by vehicle probes) by 180 percent, 86 percent, and 71 percent in the AM , Off, and PM peak periods, respectively. A ***t-test*** indicated that these relative error was statistically different from zero at the 95-percent confidence level. Furthermore, a low correlation between travel time estimates using UTCS delay measurements and actual travel times in both the peak and off-peak periods was found (Pearson correlation coefficients of less than 36 percent for each respective period).

Based on this analysis it was concluded that the UTCS did not provide accurate estimates of actual travel time conditions on the arterial links, and any arterial links should be modeled as such.

TMC DATA FUSION ACCURACY

The objective of the data fusion process is to produce every min a new ***best*** estimate of the link travel times within the TravTek network. This activity is carried out within the TMC based on data received from a variety of subsystems and agencies, such as FMC data, UTCS data, police reports, media reports and/or vehicle probe data. The way in which these data fusion imperfections are modeled within the INTEGRATION is discussed below.

Lagging of Travel Time Information

The TMC broadcasts new link travel times every minute. However, the presence of noise requires that the data, that are broadcast, be filtered and averaged over several time periods. Furthermore, the finite amount of computer time involved in the processing cycle also ages the data. Consequently, the data that is broadcasted to each vehicle is usually 2 to 3 min old.

Reasonably accurate estimates of link travel times are, therefore, only possible if the data from the individual probes are averaged over several observations. The data available to vehicles during their routing calculations would therefore be subject to the time lag implicit in this exponential smoothing.

Within the INTEGRATION model the direct lagging effect of the receipt and re-transmission of the travel time estimates was implemented in the form of a lag matrix. The routing algorithm was only provided with data that was aged or lagged by up to l min, where l was a function of the speed of the TMC's data processing and dissemination capability of the communications system. The lag associated with the averaging of probe data was captured directly by means of incorporating a similar smoothing factor.

Quality of TMC Travel Time Estimates

The expected errors in the TMC estimates of dynamic link travel times were introduced within the INTEGRATION model by adding a normally distributed white noise error term to the rather accurate initial link travel time estimates, The Coefficient of Variation (COV) of these link travel time error terms was varied between 1 to 10 percent in order to perform a sensitivity test on its impact.

SPATIAL AND TEMPORAL AVAILABILITY OF LINK TIME DATA

Continuous updates of travel time information were available only on a small portion of the TravTek network as only those links covered by the FMC and Urban Traffic Control System (UTCS) were capable of providing continuous real-time information automatically. These links comprised only 12 percent of the links in the TravTek traffic network. The TravTek System Architecture Evaluation study reported that approximately 55 percent of the broadcast travel time estimates were based on the historical information, whereas only 3 percent of the broadcast data were from FMC data. The architecture study also reported that the TMC to vehicle communication error rate (i.e. transmission not received) for the total test period was 14.8 percent while the vehicle to TMC communication error was 14.1 percent.

As a result of reducing the network size from 18000 links to 2670 links-all of which were located in the downtown area-the network link coverage was increased to exceed 80 percent. As a result of this abstraction, all links within the INTEGRATION model were assumed to provide real-time information. The impact of transmission errors was merged with the earlier white noise factor.

MODELING OF TRAVTEK VEHICLES AND BACKGROUND TRAFFIC

This section describes the logic that was utilized within the INTEGRATION model (version 1.5e) in modeling both the TravTek Route Guidance System (RGS) and the non-TravTek background traffic.

The TravTek Routing Logic within INTEGRATION

As mentioned in the previous section, the TravTek vehicles were assigned a normalized error to modify the initial accurate link travel times in such a way as to capture the error within the data fusion process.

Module 2: Data dissemination

The function of module 2 of figure 19, within the TravTek data processing cycle, is to process the minute-by-minute *best* estimates of dynamic link travel times and to determine the magnitude of any travel time factors or multipliers that may need to be broadcast. The TravTek system examines which links have travel times that differ, during the given minute, from the system's default link time by more than a certain threshold amount. Only the travel time factors for the links which differ from the default by a set threshold amount are broadcasted as a discrete travel time factor or multiplier, as discussed below.

The intent of the use of a minimum travel time threshold is to limit the number of link travel time factors that must be broadcast. Similarly, the use of travel time factors reduce the length of each data item that must be broadcast. Both these options, however, degrade the resolution (and therefore accuracy) of the travel time estimates that are provided to the minimum path algorithm within each vehicle.

Routines were incorporated within the INTEGRATION model to permit the emulation of a factor transformation function with up to ***n*** steps. These discrete factor values are within the simulation, as in the actual TravTek system, held constant throughout the entire duration of the simulation and for all links in the network.

The impact of each of these inaccuracies was examined, first by modeling the performance of an ideal system, and sly by modeling the performance of a system with an emulation of the actual TravTek attributes. Most of the sensitivity analysis results presented in this report describe the system performance for an ideal system.

Module 3: Route selection

The TravTek routing algorithm considers not only the individual link travel times, but it also employs different static penalties for turning movements of different severities at traffic signals. The minimum path algorithm within each vehicle is also hierarchical in nature, in that it first examines possible routes to the destination along strictly highways and major arterials, before considering the use of residential streets. This is done for both computational efficiency and for public policy considerations. Finally, the TravTek vehicles utilized a modified *"one-to-one"* *"label-setting"* minimum path algorithm approach that considered penalty constraints.

The INTEGRATION model replicates the above routing mechanism in a slightly different manner. First, it uses a much smaller network data base of only the major routes and considered signal timings explicitly. Therefore it did not assign further turning movement penalties. Secondly, the INTEGRATION model calculates the shortest routes in a *many-to-one* fashion using a *label-correcting* minimum path algorithm. These trees are updated frequently so as to permit the partitioning of a specific *one-to-one* tree from recently *many-to-one* tree. Most of the sensitivity analyses did not include the proprietary NavTech routing algorithms, but a small number of runs with freeway versus arterial bias factors were performed.

Background Routing Logic Within INTEGRATION

The background traffic was modeled using the standard static and stochastic user-equilibrium assignment using the method of successive averages approach. The multipath routes were updated every hour in order to capture any changes in the demand traffic conditions. This update pattern was considered reflective of the assumption that users maintain a user equilibrium.

The actual link travel times were also allocated a randomized normal error in order to capture the perception error that users would be expected to have in estimating link travel times. This error was set at 10 percent based on a previous study that found that drivers, who were familiar with a trip, chose routes which incurred excess travel distance and time totaling approximately 7 percent on average.(15) However it can be expected that the drivers such as those in Orlando who are not familiar with the network, would have excess travel times much greater than these values, as will be discussed in the forthcoming chapter. A sensitivity analysis of this factor was, therefore, also performed.

MODELING WRONG TURNS

In order to measure the absolute and relative effects of alternative configurations on the TravTek system, a collection of drivers were required to make approximately 600 trips between three O-D pairs within Orlando during the fall and winter of 1992 and 1993.

Some of these drivers were provided with Turn-by-Turn (T-b-T) instructions to travel to their destination. These instructions were provided in terms of simple graphical arrow displays, which indicated the recommended turn movement at each intersection. Other vehicles were provided with a detailed electronic map (Map) on which the recommended route was identified by means of a different color. Finally, other vehicles were not provided with any electronic visual aids (NoVisual), and needed to find the optimum route towards their destination by means of either a series of voice commands or a paper map. For each of these three display configurations, a subvariation was introduced in which some drivers were assisted by means of an electronic voice (Voice) while others were not (No Voice). Furthermore, for the configurations in which an electronic display was provided, this electronic display was sometimes driven based on a static link travel time data base (Nav) or a dynamic link travel time data base (Nav+).

An analysis of the wrong turns indicated that the number of wrong turns per trip ranged from 0.60 to 0.90, depending on the configuration of the display/voice. The probabilities of making 0, 1, 2, 3,4, or 5 wrong turns were found to be, approximately, 0.60, 0.26, 0.06, 0.03, 0.02, and 0.00. In a Chi Squared type of analysis these values were not found to be statistically different from the Poisson distribution predictions at the 95-percent confidence level. It was therefore concluded that, if the people who never completed the trip were removed from the analysis, the remaining drivers could be considered to follow a wrong turn distribution which is independently distributed. In other words, the fact that a driver may have made an earlier wrong turn during a trip was not indicative of the fact that this specific driver was more likely to make another wrong turn later on during the trip. This logic was incorporated as such within the INTEGRATION model.

The study also indicated that the average number of wrong turns on a typical trip for a T-b-T display was 0.62 versus 0.74 wrong turns when no display was present during the PM peak. In addition, during the off-peak the number of wrong turns for Nav vehicles was 0.66 versus 0.81 wrong turns for vehicles with no display. Based on these results a weighted scaling factor was estimated to be 0.68 (0.62/0.74*0.66/0.81), which when multiplied by the “no display” input data wrong turn rate of 0.8 1 resulted in an average wrong turn rate of 0.55 wrong turns for the TravTek vehicles. A node wrong turn probability for background and TravTek traffic was estimated for a typical 30 node trip utilizing Equations 15 and 16. A copy of the INTEGRATION wrong turn default file is demonstrated in appendix A.

$$\text{Node wrong turn probability for background vehicles} = 1 - \sqrt[30]{1 - 0.81} = 0.054 \quad (15)$$

$$\text{Node wrong turn probability for TravTek vehicles} = 1 - \sqrt[30]{1 - 0.55} = 0.036 \quad (16)$$

FUEL CONSUMPTION MODEL CALIBRATION AND VALIDATION

This section describes the development of the fuel consumption model that was incorporated within the INTEGRATION simulation model for the evaluation of the fuel implications of the TravTek system. For further detail refer to Baker.[16] A copy of the INTEGRATION fuel consumption input data file that was utilized in the study is presented in appendix A.

Introduction

A drive mode elemental fuel consumption model was selected as the approach to be incorporated in the INTEGRATION model for estimation of the fuel consumption of TravTek. An elemental model can capture all of the different main types of operating conditions a vehicle would typically encounter on a trip and is sensitive to speed profile rather than average speed. The first of these modes is travel at constant speed. The second mode is the making of either a full or a partial stop from a constant speed reference. The third possible mode is idling, which in effect is an extreme case of the cruise mode. The basic underlying assumption for this form of model is that the driving mode elements are all independent of each other and the sum of their fuel use equals the total fuel consumed.

The fuel consumption model discussed in this section is concerned only with modeling the behavior of the TravTek vehicle in Orlando. Consequently, most issues concerning the differential impact of various climatic test environments were not relevant at this stage of the analysis. However, as the test results were conducted at various times over a 5- month period, the tests were completed with and without the air conditioning operative in an effort to reflect Florida's summer and winter driving conditions. The runs conducted in August and September of 1992 were completed with the air conditioning operational. Conditions representing a typical Orlando winter were captured during those runs completed in December 1992, when the air conditioning unit was not activated. All test runs were conducted in Orlando, Florida with a hot stabilized engine.

Data Collection Methodology and Model Calibration

For each of the three driving modes fundamental to the drive mode elemental fuel consumption model, test runs were conducted using a 1992 Oldsmobile Toronado fully equipped with the TravTek route guidance system.[2,17] This particular vehicle is capable of displaying vital fuel consumption data on screen. The system, which can be reset to zero at any time, monitors average fuel consumption, instantaneous fuel consumption, and total fuel consumed during a trip.

Constant Speed

In order to establish the fuel consumption while traveling at a constant speed, a number of short 4.8 km (3 mi) trips were taken on level terrain in Orlando on an isolated section of the road. The trip cycle was initiated by accelerating up to the desired speed and then invoking the vehicle's cruise control feature. Once the desired constant speed was attained, the vehicle's fuel consumption meter and odometer were reset. At the conclusion of the 4.8 km trip, the average fuel consumption rate was recorded. This process was repeated for each desired speed level at various times during the 5 month test period. In addition to the systematic variations in speed, it should be noted that the air conditioning unit was operational only during the warmer summer months.

The raw data collected during the Orlando test runs at constant speed were organized to provide: a series of observations at constant speed (km/h); a binary variable indicating the activity of the air conditioner (0 off, 1 on); and the observed fuel consumption (L/l00 km) for each condition. The speed and air conditioning terms were used as the independent predictor variables for estimating the dependent variable, namely the fuel consumption at each constant speed. Since the air conditioning term is binary in nature, it may be interpreted that the influence of air conditioning on fuel consumption is modeled as being dependent on the amount of time for which it is active, rather than the distance for which it is driven.

Figure 22 illustrates constant speed fuel consumption rates observed, and the rates predicted by the resulting model, for the TravTek vehicle at an ambient temperature of about 32 ^{0}C. It can be noted that fuel consumption rates increased monotonically as cruise speed increased, with the minimum rate represented by idle conditions. The constant speed fuel consumption model had an R2 value of 0.96.

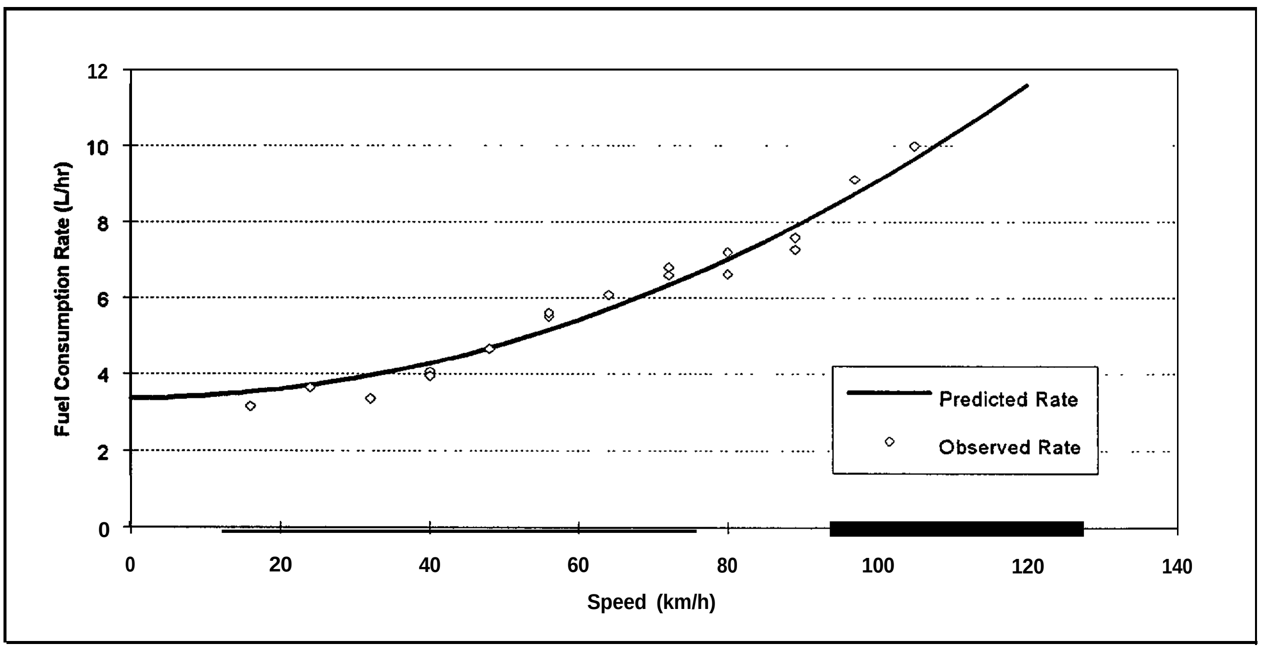

Figure 22: Observed and predicted constant speed fuel consumption rates for Orlando Florida **conditions (32 "C)**

Stop/Go Conditions

The next stage of the model development was to measure the additional fuel and time consumed when the TravTek vehicle was decelerated from a known cruise speed to a complete stop, and then returned back to the original cruise speed. Utilizing the same 4.8 km test site, that was described earlier, the *average* fuel consumption gauge was invoked on the TravTek vehicle prior to commencing the trip. The vehicle was accelerated in a *comfortable* manner up to the desired speed and then the vehicle was maintained at that speed until the deceleration phase back to zero speed was required. The vehicle was then *comfortably* brought to a complete stop. This acceleration/deceleration cycle was repeated a total of seven times within the 4.8 km section of road for each cruise speed. Figure 23 illustrates the speed, braking and longitudinal acceleration status as a function of time for one such test cycle condition.

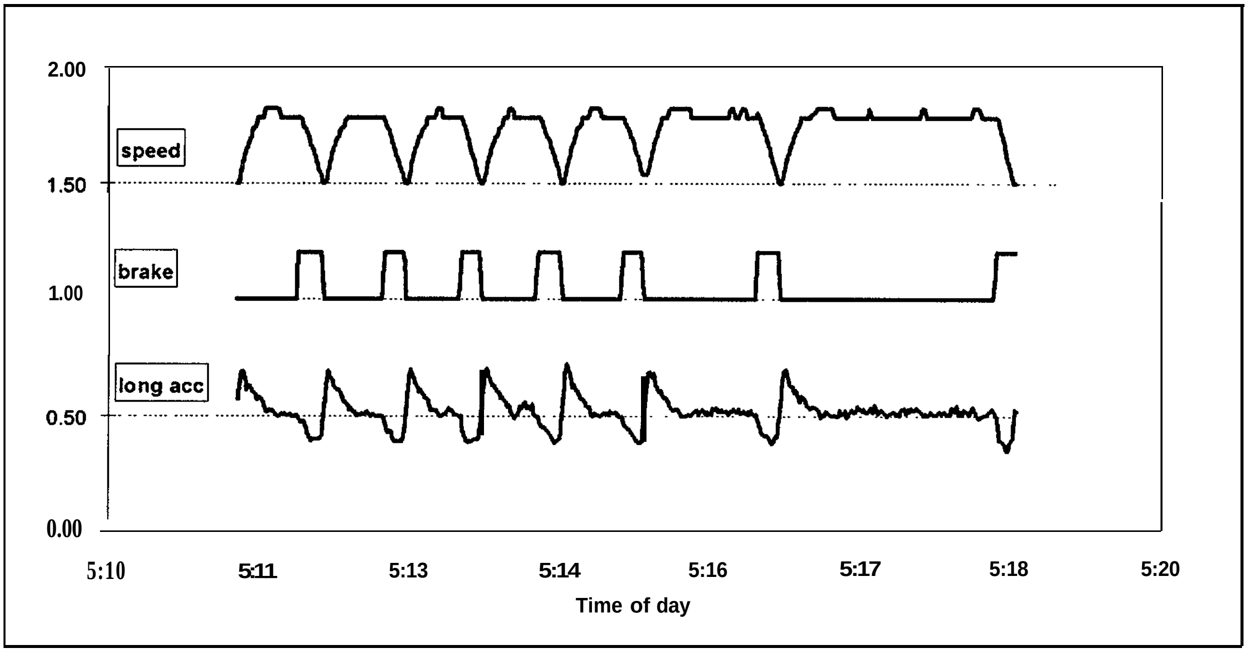

Figure 23: Typical speed, braking and acceleration profile of a TravTek vehicle completing the stop/go fuel consumption test cycle

By subtracting the amount of fuel used at constant speed, from the total fuel used to complete all seven stop and go cycles, and then dividing this value by the number of stops (seven), the additional fuel per stop was calculated for each of the desired cruise speeds. By assuming consistent driving patterns, the fuel consumed per partial stop was computed by subtracting the relevant fuel penalties for full stops from the fuel consumption for the appropriate constant speed runs. It should be noted that the predicted value represented the additional fuel used to drop from one speed, to another speed, then return back to the original speed, as compared to traveling the same distance at a constant speed.

In order to account for either complete vehicle stops and/or partial slow downs, a curve was fitted to the stop and go data collected in Orlando during the months of September and December 1992. A total of 10 data points were used to develop the model for stop and go driving, where 5 points were taken from summer conditions in September and an additional 5 points were taken from the data for December when no air conditioning unit was operating. The raw data collected included the average fuel consumption rate (L/100 km) required to complete the 4.8 km stretch, driven in a manner to include seven stop and go cycles from a specified cruise speed, and a value indicating the activity of the air conditioner (0 off, 1 on). By subtracting the amount of fuel consumed to complete the identical 4.8-km route, while driving at a constant speed and then by dividing by the number of stops completed, the net amount of fuel lost per stop (for each initial speed recorded) could be computed. It should be noted that for those runs completed with the air conditioning unit operational, the contribution of the air conditioning to the total volume of fuel consumed was removed prior to computing the fuel penalty per stop.

As illustrated in figure 24 the fuel penalty for completing a full stop, and the subsequent return to the original reference speed, increases monotonically. The line produced by the regression on the observed data also passes through the origin indicating that the extra fuel per stop tends to go to 0.0 when stops are made from a minimal initial speed. The stop/go model had an R^2 value of 0.89.

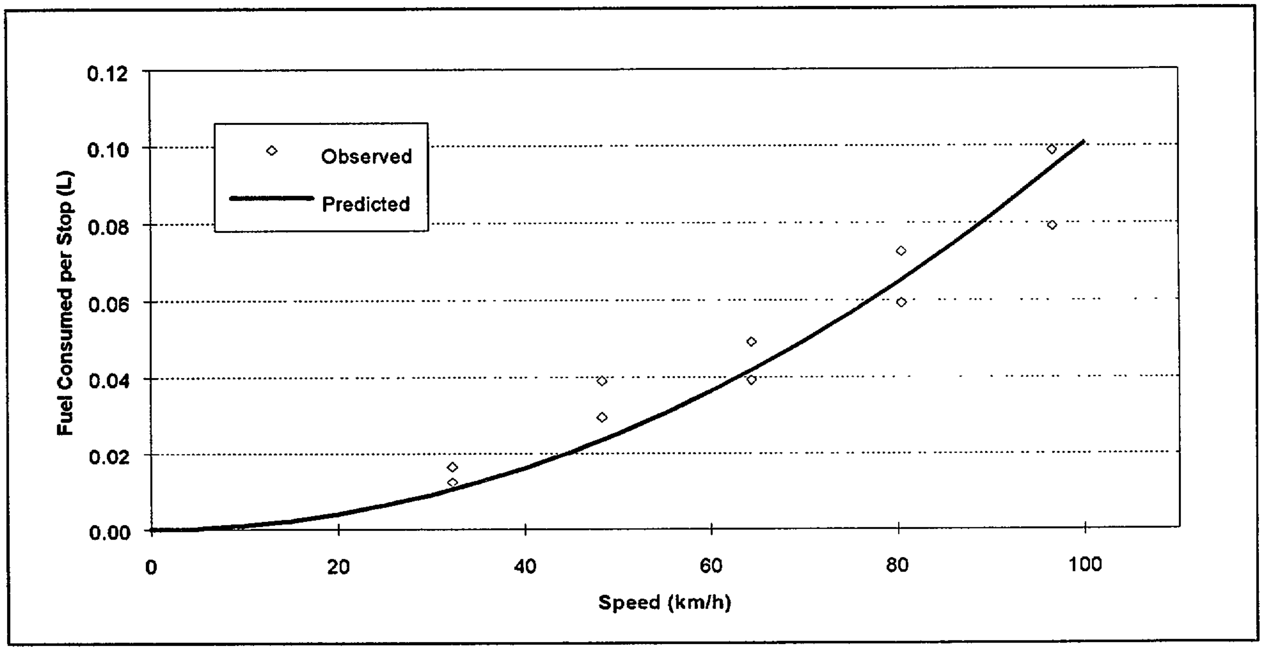

Figure 24: Observed and predicted stop/go fuel consumption rates for Orlando Florida conditions (32 °C)

Model Validation

Four sample road networks, all located in Orlando, Florida, were driven using the TravTek vehicle. During these runs the necessary network characteristics and fuel consumption measurements were recorded. The networks were chosen to represent a wide range of the possible driving conditions a vehicle may experience while driving the TravTek vehicle within the Orlando test network.

Specifically, a major east-west arterial complete with traffic signals and various levels of congestion; a small urban network in downtown Orlando; a simple suburban residential network with stop signs regulating very low daily traffic flows; and two stretches of freeway, served as the four test networks. The validation test networks were driven at the same time of year as the runs completed to calibrate the elemental fuel consumption model. The modeled fuel consumption for these cycles was then compared to the fuel consumption that was directly measured in the vehicle, as indicated next.

a. Major *Arterial*

The first fuel consumption network validation run involved the traversal of Colonial Drive as illustrated in figure 20. Colonial Drive is a major, four-lane, signalized arterial oriented in an east-west direction and having a posted speed limit of 80 km/h. A TravTek vehicle traversed a 21.2 km section of this roadway from Woodbury Road in the east to Tampa Avenue in the west. Two runs were completed in each of the eastbound and westbound directions. The trials were performed at various times during the day on Friday, December 5, 1992 in order to observe the model performance both during peak and off-peak conditions. The air conditioning unit was not in use during any of these runs.

On average, the absolute error between the measured fuel consumption and that calculated based on the speed profile was less than 6 percent.

b. Downtown Network

In an effort to reflect urban rather than suburban driving conditions, a small network was driven in downtown Orlando as illustrated in figure 2 1. This signalized network traversed a loop of approximately 5 km. The trip commenced by driving south on Orange Avenue, completing a loop through a portion of the downtown core, and returning northward to Colonial Drive on Magnolia Avenue. A total of five test runs were completed for this network on Friday, December 4, 1992. The air conditioning unit was turned off during these runs. The data were collected in a similar manner as described for the Colonial Drive network.

Averaging the absolute percentage error across all the trips yielded a relative prediction error of slightly over 14 percent.

c. Residential Network

A residential network was also traversed as part of the validation runs in order to provide an opportunity to test the fuel consumption model on a series of streets with low volumes of traffic. Consequently, the majority of the variation in fuel consumption rates between runs could be explained by the unique driving characteristics of the individual drivers who drove the test circuit. The entire network measured 12.2 km in length. Six stop signs, in addition to four yield signs, served as the primary means of traffic control. Of the six test runs, two were completed on Monday September 7, 1992, with the air conditioning operative, and the remaining four runs were completed on Saturday December 5, 1992 without the air conditioning unit functioning.

The average absolute percentage error between the measured fuel consumption and that calculated based on the speed profile for this network was less than 3 percent.

d. Freeway Network

Test runs were conducted on sections of two freeway facilities on Saturday December 5, 1992, namely: a 16 km portion of the East-West Expressway that contains two toll plazas; and a 16 km and 9 km stretch of Interstate 4 (I-4) within Orlando.

The complete series of tests on the freeways resulted in an average absolute error of nearly 10 percent for the predicted versus observed fuel consumption.

e. Summary of All Orlando Fuel Consumption Test Networks

A plot of all observed and predicted fuel consumption rates for the four test networks combined is presented in figure 25. The 0.95 correlation coefficient for these data indicated that a very high correlation across all facilities existed even though within a facility group the relative error was significant. It can also be noted that the model predicted fuel consumption rates quite well for those facilities that had relatively low rates, but appeared to overestimate the fuel consumed in the urban environment where numerous micro speed change cycles occurred and therefore were not captured by the more macro methodology of the validation process. For example, the validation process assumed that one cruise speed was applicable to the entire test run, which generally was not the case. Thus the basic model was unable to replicate the cycle in the same fidelity as the other networks, where the cruise speed was more consistent within the run and where the speed changes were more easily defined.

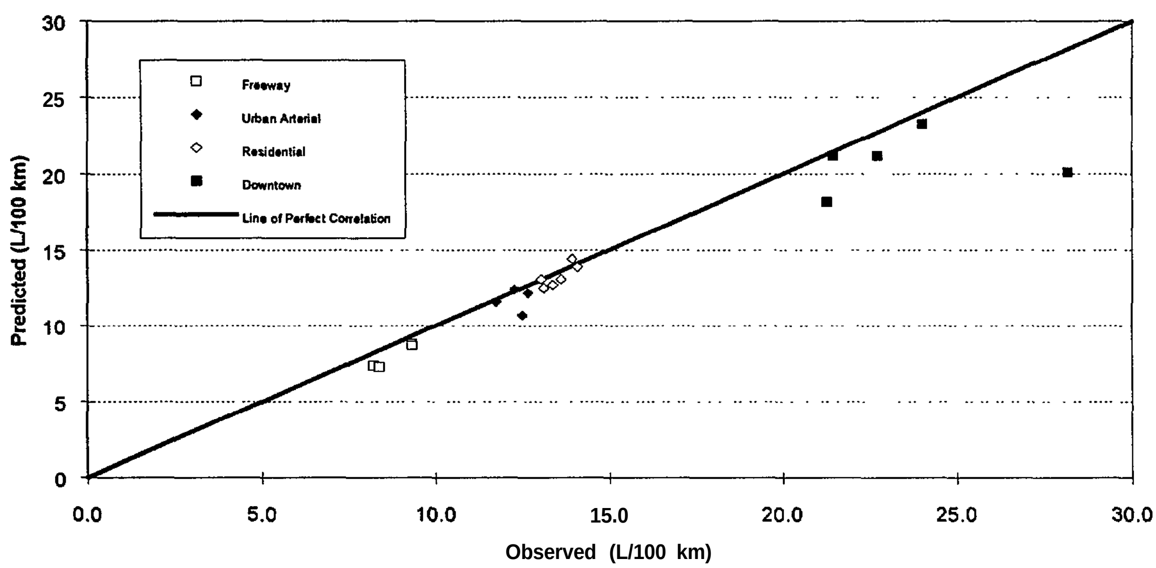

Figure 25: Observed and predicted fuel consumption rates for all Orlando fuel consumption test networks

Other Operating Conditions and Non-TravTek Vehicles

The climatic conditions experienced in Orlando, Florida would not be considered by most to be typical for most major urban centers in North America. The fuel consumption model described thus far was developed exclusively in the warm climatic conditions experienced in Florida. However, this type of test environment, although desirable because of its consistency for developing the base model, did not enable the fuel consumption model calibration to consider the effects of extreme changes in ambient temperature. In addition, the detrimental effects of cold starts on fuel consumption are known to be magnified as ambient temperatures decrease. This element is not captured in the basic set of equations representing the field calibrated fuel consumption model. In order to address this limitation, literature was referenced in an effort to obtain correction factors for ambient temperature and cold start effects that could be applied to the Florida-based fuel consumption model.

A method of transforming the existing model to reflect a wider variety of vehicle types was also developed using the data provided in the widely available (EPA) fuel consumption guides. The addition of modifications to account for vehicle characteristics, ambient temperature and operating mode transformed the fuel consumption model into a more versatile analysis tool that would be suitable for application to non-TravTek vehicles and/or outside of Orlando.

Influence of Ambient Temperature on Hot Stabilized Engine Fuel Consumption

The presence of greater heat losses and, in some cases, the much greater viscosity of the oil in the transmission system, leads to an increase in fuel consumption as the ambient temperature lowers. A hot engine is defined as having an engine oil temperature in excess of +80 °C. The Organisation for Economic Co-operation and Development (OECD) recommends correction coefficients that piece-wise adjust the fuel consumption rate between two operating temperatures.[18] The first adjustment is one of 0.2 percent per °C for ambient temperatures of 0 °C to +30 °C, while a second includes corrections of 0.5 percent per °C for ambient temperatures below 0 °C. These effects are as illustrated in figure 25. The effect of changes in ambient temperature on fuel consumption will vary to some extent between vehicles, but for the purpose of this study are considered to be constant.

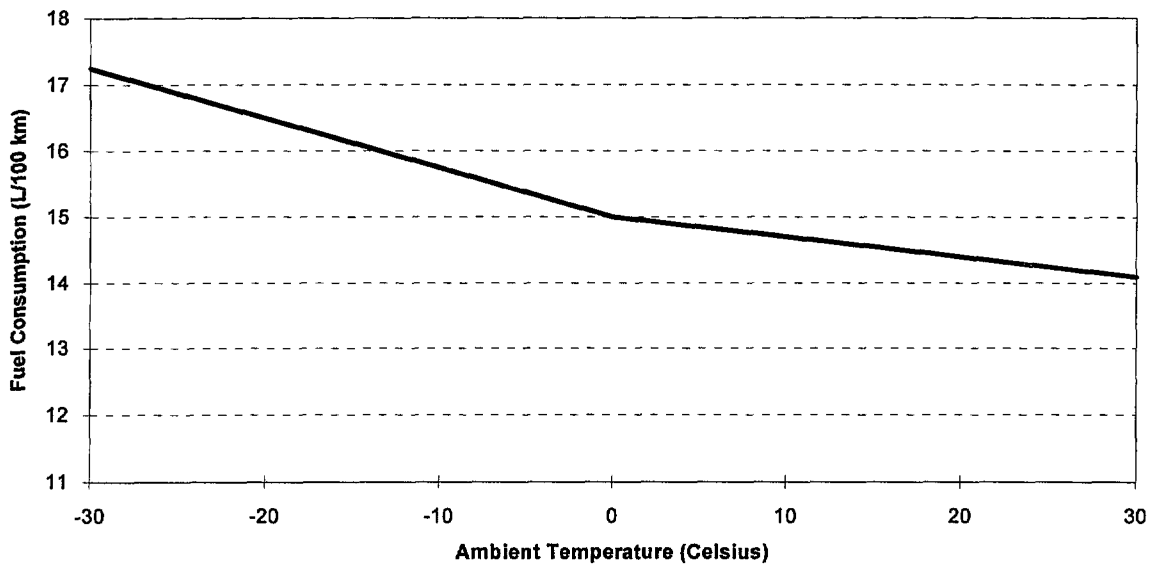

Figure 25: Consumption rates as a function of ambient temperature

Derivation of a Fuel Consumption Correction Factor for Cold Starts

Short trips initiated from cold start engine conditions involve a very pronounced impact on fuel consumption. The literature indicates that vehicles typically require approximately 5.8 km to reach optimal operating conditions. It was found that by representing the cold start penalty as a fraction of the ideal or hot stabilized base, that the severity of the cold start penalty increases as the ambient temperatures decreases. This is illustrated in figure 26. For conditions typical of Orlando, the correction factor for cold start conditions was determined to be only slightly higher than unity.

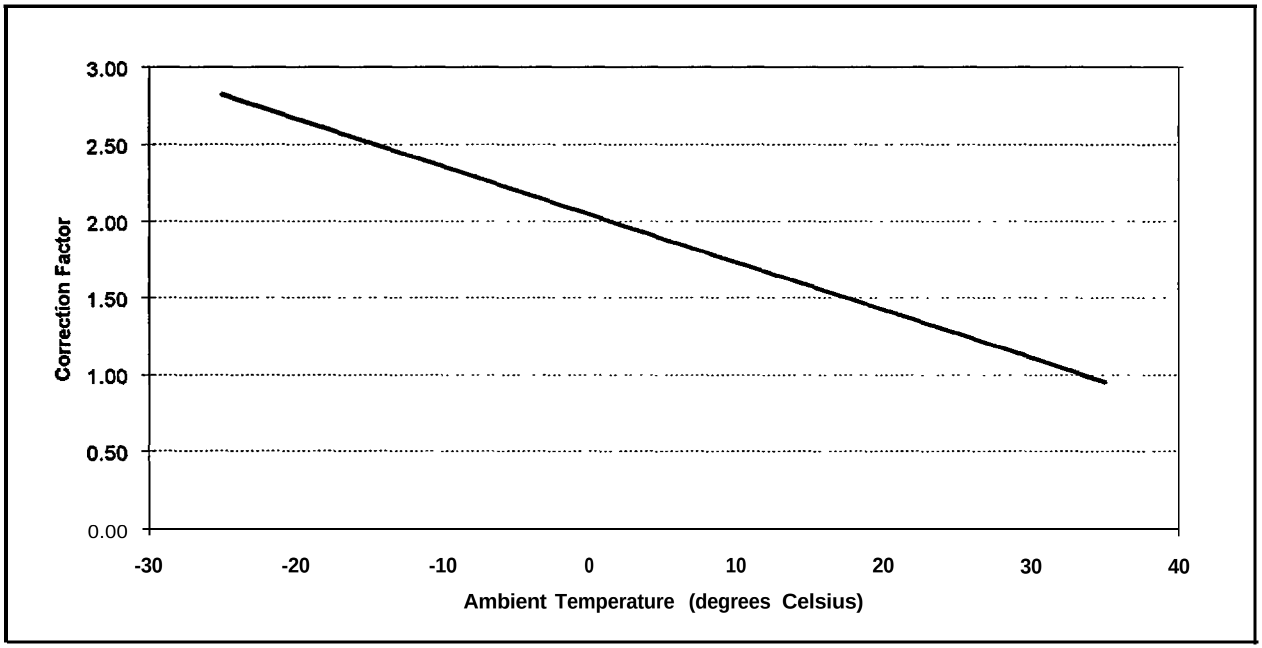

Figure 27: Cold start correction factor as a function of ambient temperature

Extension of the TravTek Model to Other Vehicles

The previous sections illustrated how the fuel consumption pattern of the TravTek vehicle was represented using two non-linear drive mode relationships. The first relationship estimated the amount of fuel that was utilized per unit of time for travel at constant speed, while the second estimated the additional amount of fuel that was utilized per complete or partial stop from a given reference speed. These two relationships were quantified using three parameters each, resulting in a total of six parameters for each vehicle. These calibrated parameters are unique to the TravTek vehicle and ideally should be calibrated using field experiments on other vehicles.

This section provides an approximate procedure which may permit these six parameters to be derived from more commonly available EPA highway and urban fuel economy ratings for a particular vehicle.(19) Such ratings are published annually for virtually all new vehicles, but provide only two input points from which one needs to derive the required six parameters.

The total fuel consumed for completing the highway and city cycles are first parsed into the three potential components - cruise, stop and go, and idle. These cruise and idle fuel rates for each cycle are first computed by assuming a cruise speed equivalent to the average speed. Subsequently, the total volume of fuel consumed in these two modes is computed based on the time spent traveling during each mode. By subtracting these values from the total fuel, as estimated from the rates listed in the EPA Guide and adjusted for temperature and/or operating mode, one obtains the fuel consumed during their respective stop and go cycles. Furthermore, by predicting the additional fuel consumed during a single stop/go maneuver from the defined cruise speed, the volume of fuel per stop can be obtained. The number of stops for each cycle is then determined by dividing total fuel consumed for stops by the fuel per stop. This procedure derives equivalent highway and city cycles in terms of fuel consumption, but does replicate the actual movements a vehicle would experience if driven the defined driving cycles.

The assumption that all vehicles perform in a manner similar to the Toronado, in terms of the fact that a constant fraction of the total fuel is consumed by each drive mode during city and highway driving, enables a method of deriving fuel consumption model coefficients for other vehicles to evolve. Some sample derived constant speed fuel consumption rates are illustrated in figure 28. It should be noted that the original fuel consumption model developed for the Oldsmobile Toronado was able to capture the EPA City and Highway Cycles within 12 percent and 6 percent, respectively.

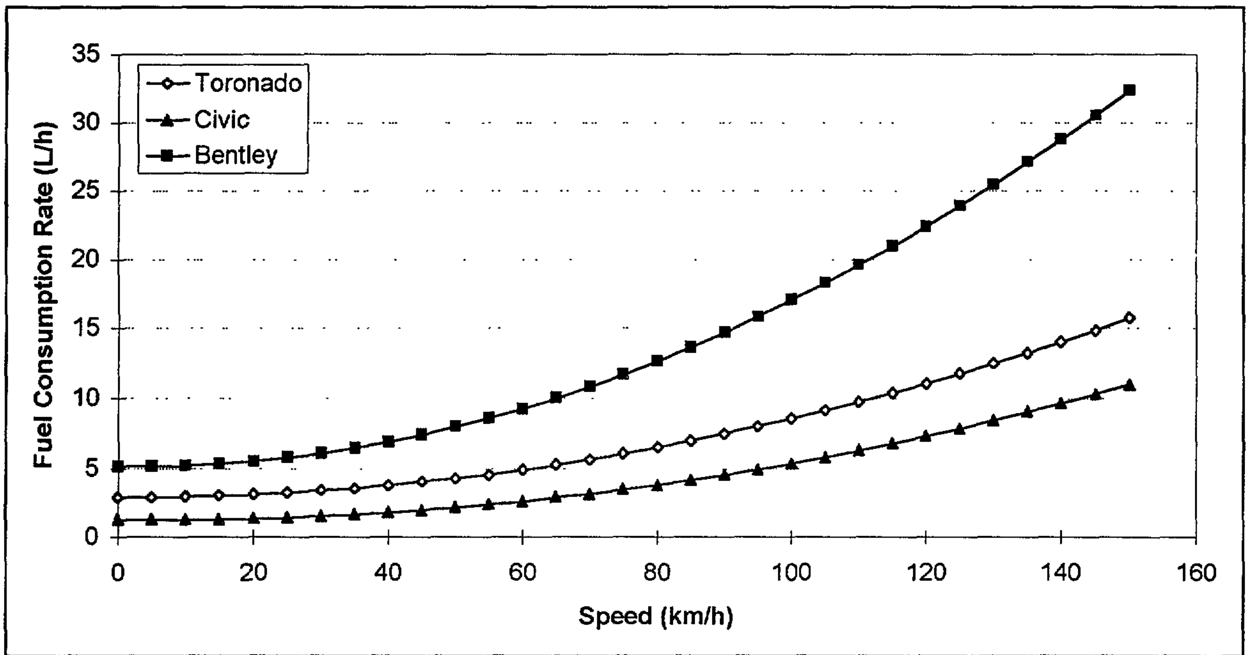

Figure 28: Derived constant speed fuel consumption rates for a range of passenger cars

VEHICLE EMISSION MODEL CALIBRATION AND VALIDATION

This section describes the development of an emission model that was incorporated in the INTEGRATION simulation model as part of the TravTek evaluation study. A copy of the emission input file utilized in this study is presented in appendix A.

Introduction

The primary source of North American data for assessing the emission impacts of transportation planning or traffic engineering proposals is the MOBILE program. This program is a source emission model developed by the EPA.[20] Although very detailed in terms of vehicle characteristics and operating conditions, the MOBILE model is less able to respond to the detailed manner in which traffic management measures may influence the precise driving cycles that a particular vehicle experiences in completing its trip. However, even considering this limitation, source emission models such as MOBILE remain virtually the only means by which significant amounts of emission data can be readily obtained.

In order to better capture the relationship between vehicle emissions and traffic flow/control characteristics, an appropriate emissions model was developed by linking strategically selected

MOBILE output to corresponding fuel consumption output. Using these emission and fuel consumption data for similar driving cycles, operating environments, and vehicle types, a series of regression equations was calibrated which predict the quantity of HC, CO and NOx that would be emitted per unit of fuel consumed. The new model therefore estimates the emissions of a specific vehicle in a manner which is responsive to the traffic conditions it experiences along a specified route. This route may be influenced by the network characteristics and any traffic management strategies associated with the driven network.

Modeling Approach

The emission factors generated directly by MOBILE5A are presented in units of grams of pollutant per kilomter driven. Traditionally, these emission factors are then multiplied by a corresponding measure of vehicle kilometers traveled (VMT) to estimate an absolute mass of pollutant produced by a given region. However, since the objective of this study is to model the emission impacts of specific vehicle speed profiles, a method for converting the distance based emission factors to time based equivalents was required. Furthermore, it was considered to be advantageous to link these time based emission factors to the fuel consumption rates presented in the previous section as these rates are more responsive the speed profiles of a vehicle. The procedures for achieving this are described next.

Conversion to a Time Based Scale

The first step involved the conversion of the MOBILE5A imperial output into its metric equivalent. This was accomplished by dividing each gram per mile (g/mi) entry in the emission factor matrix by 1.6 to yield entries in grams per kilometer (g/km). In addition, the ambient temperatures were converted from degrees Fahrenheit (“F) to degrees Celsius (“C), and average speed from mi/h to km/h. The next critical, but very simple step, involved multiplying each emission factor entry by the associated average speed to provide emission values in g/h of travel.

Linking to the Fuel Consumption Mode/

MOBILE5 A has a total of eight vehicle classes capable of being modeled. Only three of these are of interest to this study, namely light duty gasoline vehicles and two classes of gasoline trucks. In order to link the fuel consumption model to the emission data, appropriate fuel consumption model coefficients needed to be selected for each of these three vehicle classes.

A series of representative vehicles were classified into the three MOBILE defined vehicle classes and an average EPA fuel consumption rate was calculated for each based on the standard city and highway driving cycles. The average fuel consumption values were then parsed to derive three sets of constant speed fuel consumption model coefficients, one set for each vehicle class. These coefficients were only valid at an ambient temperature of +32 ^{O}C. For a series of cruise speeds, ranging from 8 to 105 km/h, the fuel consumption was then computed and subsequently converted to reflect conditions at the range of ambient temperatures for which the MOBILE runs were conducted (-18 to +38 ^{O}C). The resulting fuel consumption matrices would then consist of fuel consumption entries which were classified as a function of cruise speed and ambient temperature.

Conversion from Cruise Speed to Average Speed Fuel Consumption Rates

The analysis of the field data indicated that the amount of fuel that is consumed at a certain average speed, when considerable fluctuations about this average are present, is higher than if a vehicle travels at this same average speed in the absence of speed fluctuations. Consequently, travel within a network at any average speed should have a higher fuel consumption rate than the curves in figure 22, for example, would suggest. This difference at speeds of 77.1 km/h and 3 1.5 km/h, as noted from the analysis of the EPA Highway and City ratings, is found to be approximately 5 percent and 9 percent, respectively. In order to account for these discrepancies at any other potential speed, an interpolation was possible if the following two further assumptions are considered: (i) both fuel consumption rates were considered to be identical at an average speed of 0 km/h; and (ii) both fuel consumption rates were considered to be identical at an average speed equal to the highest prevailing speed limit (100 km/h).

The objective then was to fit a curve through these four points such that a conversion between constant speed fuel consumption and fuel consumption rates for variable speed cycles could be made at any intermediate speed. In order to pass through all four points exactly, the required equation needed to have a constant term (equal to unity) and three additional coefficients for the terms v, v^2, and v^3, The magnitude of these coefficients could be obtained by solving a system of four equations. Figure 29 represents the correction factors to convert fuel consumption rates for driving a constant speed to a rate for driving a typical variable speed cycle with an equivalent average speed.

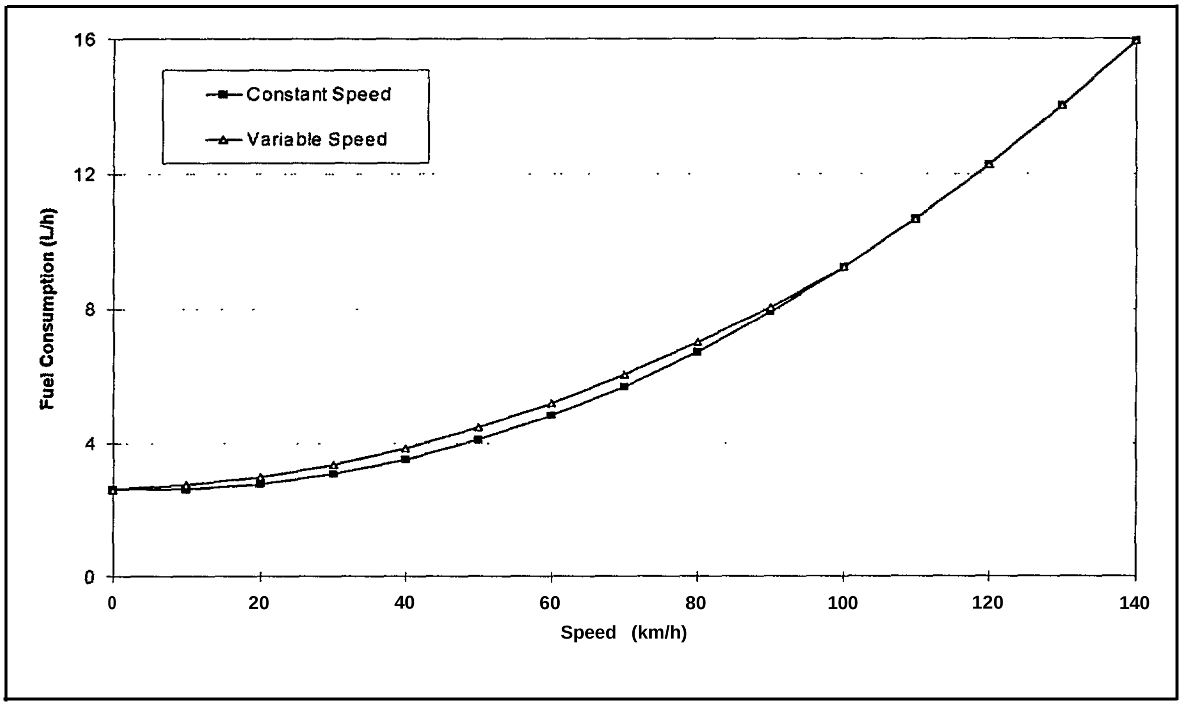

Figure 29: Conversion from constant speed to average speed fuel consumption rates

Merging the Fuel and Emission Models

Step c was required to link the fuel consumption model to the emission output generated by MOBILE5A. This step divided the fuel consumption matrix for each vehicle class by the corresponding emission rates that classified average speed and ambient temperature. The overall process for deriving emission rates in g/L of fuel is summarized below in figure 30.

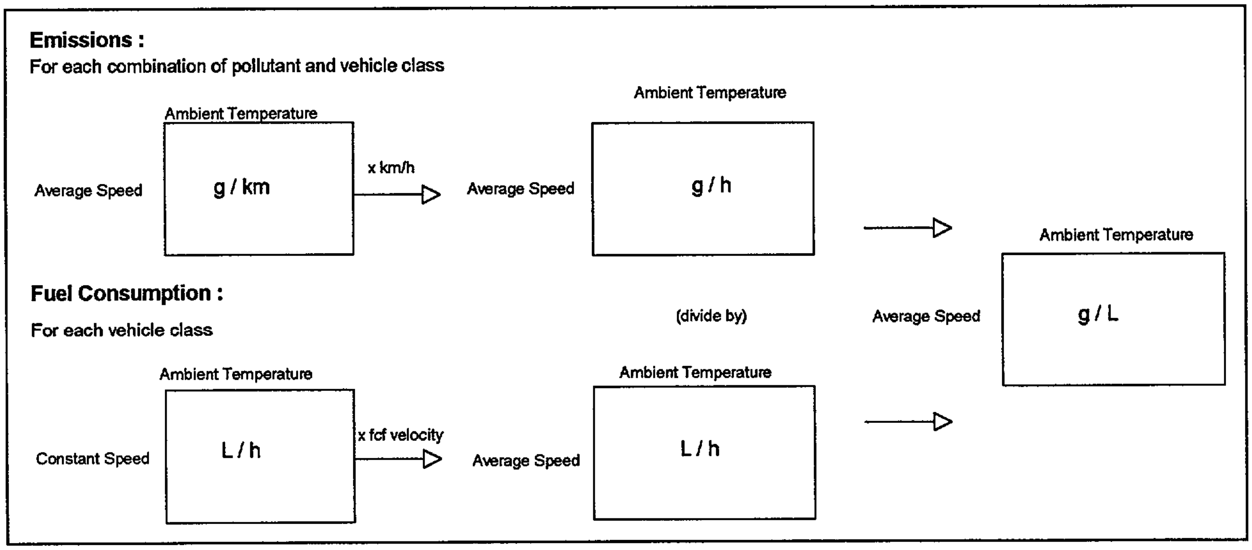

Figure 30: Representation of emission modeling procedure

Emission Model Calibration

For every vehicle class and pollutant combination pair, a surface estimating the mass of pollutant per liter of fuel consumed was generated as a function of speed and temperature using the MOBILE5A output data. A regression analysis was subsequently performed on the data defining each surface in order to develop an analytical model. The independent variables consisted primarily of statistically significant combinations of first and second order speed and temperature terms. Third order terms of speed only were also considered. The statistical significance of any term was defined by the *t* distribution at the 95-percent confidence level. All nine of the final regression models had R^2 values in excess of 95 percent. However, the specific variables contained within the model changed for each vehicle class and pollutant. Figure 31 illustrates the impact of speed on HC, CO, and NO emission rates for a typical light duty gasoline vehicle at only one temperature, namely 32 °C. It can be noted that HC emissions typically decrease as speed increases, while the opposite can be said for NO emissions. The MOBILE5A data also show that CO emissions tend to fluctuate with speed in a less consistent manner.

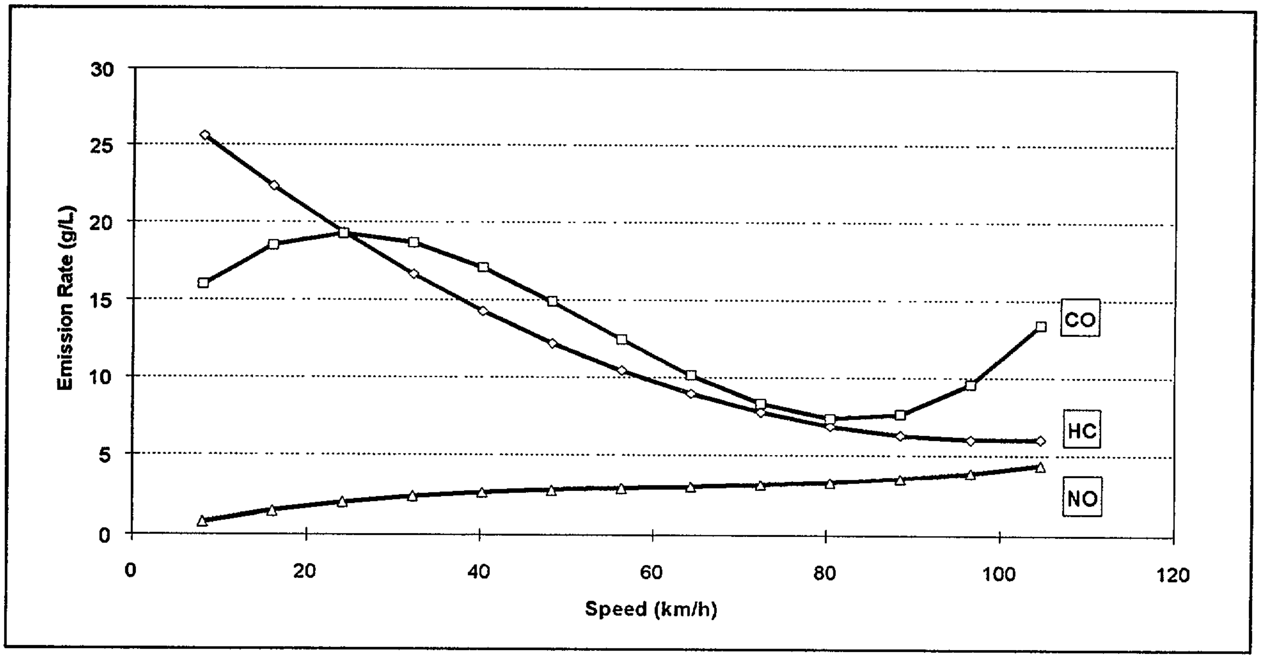

Figure 31: Emission rates as a function of speed for a light duty gasoline vehicle at 32 °C

Emission Model Verification

Since there was no opportunity to directly calibrate the emission models to actual field data from the TravTek vehicle in Orlando, an overall comparison of the predicted emissions (obtained using the regression models described above) and the MOBILE5A outputs, was conducted as illustrated in figure 32. It was anticipated that the extent to which simulated emissions for the standard EPA City and Highway Driving Cycles correlated with the MOBILE5A outputs would perhaps best achieve this goal. Therefore, a typical light duty gasoline vehicle, operating at an ambient temperature of +32 °C (90 °F), was used the compare the results predicted by the two models for hot stabilized conditions.

It can be noted that for hot stabilized conditions, the simulation model appears to overestimate the amount of HC and NO emissions produced as a result of driving the city cycle by 12 percent and by 6 percent on the highway cycle. In terms of total CO emissions for the hot stabilized condition, the model underestimated the amount of pollutant for the city cycle by 11 percent when compared to the MOBILE5A output data, but overestimated the MOBILE5A results by 3 percent for the simpler and more well defined highway cycle.

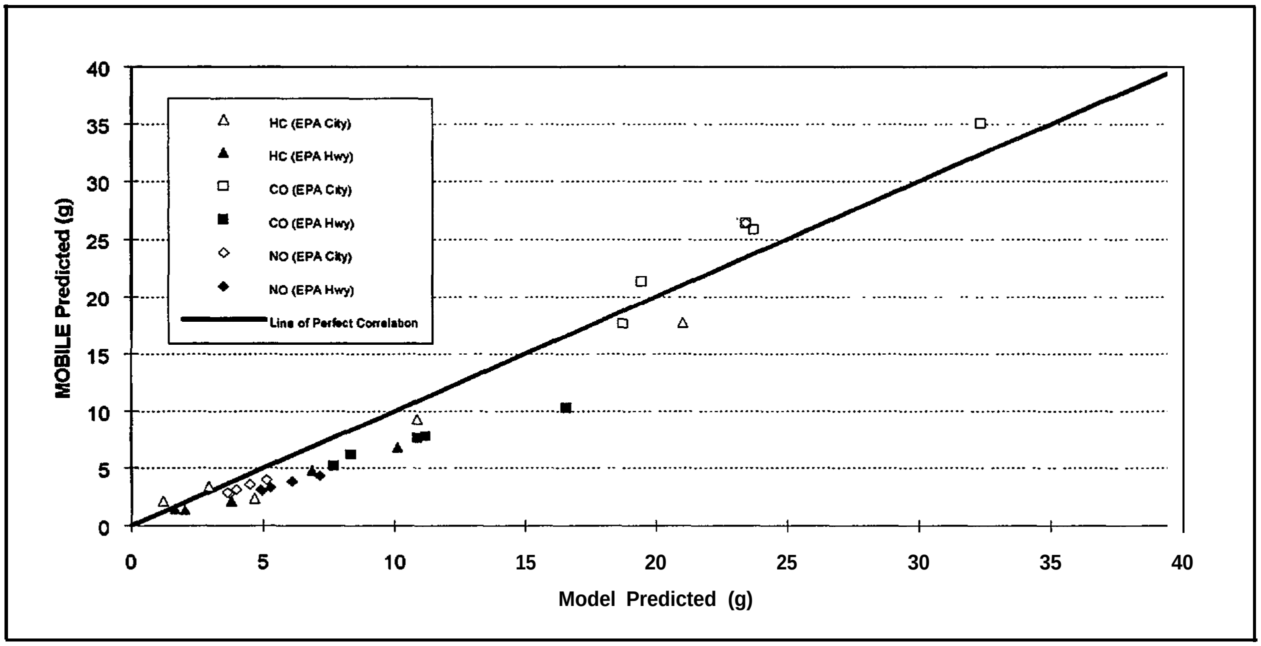

Figure 32: Comparison of MOBILE5A and model predicted emission estimates for a light duty gasoline vehicle operating under hot stabilized conditions.

SAFETY MODEL CALIBRATION

The most direct measure of safety is often considered to be the frequency or probability of the occurrence of an accident. This would require that the accident risk be directly measured during any operational tests for both the subjects participating in a prototype deployment and for a comparable base case group that are equal in all respects except for the use of the IVHS technology. Unfortunately, the limited resources that is usually available for performing an IVHS field test preclude setting aside a subpopulation of drivers that are put under surveillance yet is not utilizing the IVHS technology. Alternatively, the main factors that influence the accident risk can be utilized to estimate the accident risk. The second approach was utilized in the TravTek evaluation study. The derivation of this approach is discussed in this section in some detail, however, a more comprehensive presentation can be found in the TravTek Safety Study.

Facility Accident Risk Component

It is known that accident risk is correlated to exposure. Consequently, any IVHS measure which reduces exposure, while keeping all other factors equal, will likely reduce accident risk. However, some debate exists as to whether exposure should be measured in terms of distance, i.e. vehicle kilometers, or in terms of time, i.e. vehicle hours, or some combination of both. The distinction between distance and time exposure becomes quite critical when some congestion avoidance measures may reduce travel time through diversions which increase travel distance.

A second major factor influencing accident risk is facility type and facility environment. On a lane kilometer basis, rural roads are much less safe than urban roads. However, on a vehicle kilometer basis, the trend is reversed. This ratio (based on statewide statistics in the United States) of urban to rural rates for comparable facility types is about 1:3. Superimposed on this relationship is the fact that within a given setting accident risks vary by facility type by a factor of 1:3 or 1:5. For example, access control freeways are much safer than either arterials, collectors, or local streets.

A further complication arises from the fact that accident rates on a given facility are traffic volume dependent. In other words, the level of accident risk varies depending on the degree of facility utilization and or the level of congestion. The final complications associated with determining accident risk arise from the fact that on arterials the factors influencing accident frequency are quite different mid-block than they are at intersections. Similarly, accident causes are different within basic freeway segments versus those segments that are considered ramp or weaving areas. It is likely that navigational tools will have the most pronounced impacts at intersections and weaving or ramp areas as in these areas routing decisions need to be acted upon. Unfortunately, little is known about how accident risk will vary as a function of the type of turning movement that is performed, as a function of the type of turning movement control that is being applied and or the level of prevailing traffic congestion.

Within the TravTek analysis of accident risk, safety was modeled within the INTEGRATION model as being a variable that is environment specific (rural versus urban), facility specific, (i.e. freeway or arterial/collector/local), and dependent on the presence or absence of traffic congestion. This analysis permitted consideration of IVHS impacts on distance exposure such that diversion to a longer route was penalized while the reduction of navigational waste was considered to be a benefit. However, the above analysis needed to further consider to what extent the links on the diversion route and the links on the route diverted to were experiencing congestion.

Gadget Factor Accident Risk Component

The above analysis considers the impact on safety of the influence that TVHS technology has on guiding vehicles on different facilities under different circumstances and with different levels of exposure. However, it precludes an analysis of the intrinsic benefit or risk associated with the technology which suggests and confirms the routes that are to be taken. This latter impact, that during the course of the TravTek experiment, became known as the gadget factor, can only be determined from direct observation of test subjects.

The differential impact of an IVHS technology on accident risk should ideally be measured directly as a difference between the accident risk experienced by a subject group with the IVHS technology and a comparable control group utilizing a placebo. Unfortunately, it is somewhat difficult to contrive of a placebo which would not reveal the absence of IVHS functionality. The second difficulty is the fact that accident frequencies are still fairly rare occurrences. For example, vehicles are expected to only experience one accident per 1.6 to 2.4 million vehicle km. Consequently, the number of accident observations during an experiment as extensive as TravTek, which involved 100 vehicles that traveled just over 1.6 million vehicle kilometers during a 12-month period is, therefore, only sufficient to prove that the TravTek accident risk is significantly worse than the base accident risk, and could never demonstrate that TravTek was significantly safer even though one reportable accident occurred.

In view of the limitations and complications of utilizing direct accident rates as a measure of relative accident risk for situations which an IVHS technology is present, the TravTek experiment considered the reliance on various safety surrogates instead, as discussed in the TravTek Safety Study.

With this in mind, a variety of safety surrogates was collected as part of the TravTek experiments in order to complement and or to replace a direct accident rate comparison. The most common of these accident rate surrogates were measurements taken using either a human observer in a subject's vehicle or through the use of a camera car. Typical measurements included the frequency of lane deviations, number of steering wheel reversals, number of hazardous movements, number of excessive lateral or vertical accelerations and or the duration and frequency of eye movements. The real challenge was in determining the nature of the functional relationship between the safety surrogates and the variable of interest, namely accident risk. Little data exists and/or has been analyzed to quantitatively link any of these variables to accident risk and/or to suggest whether the potential relationship is either linear or non-linear in nature.

The second complication arises from the fact that no quantitative data exist to indicate which one of these multiplicity of data sources should be given greater credence or weight when conflicts in terms of the magnitude and/or the sign of the impact arise.

Within the TravTek analysis, the above two difficulties were addressed by a data fusion analysis. This data fusion analysis served two functions. In the first instance, the data fusion scaled the diverse safety surrogates and their corresponding incompatible units of measure into a common dimensionless safety index with common units. Part of this scaling was the conversion to different safety measurements to a single relative risk measure, while concurrently this computation addressed the issues associated with the absence or presence of non-linearities. The second function of this conversion was the selection of weights to be placed on the various data sources. Both of these two steps were, in the absence of an analytical procedure, performed through consultation with a panel of subject matter experts.

The net result of the above analysis was a derivation of what became known as the TravTek gadget factor. This factor captured the impact of the medium which provided the route guidance and navigational information to the driver independently of the message that was conveyed through this medium. In other words the gadget factor considered the safety impact of how routing instructions were being conveyed whereas the earlier analysis of facility, congestion and exposure effects considered what the implications were on accident risk when the message that was conveyed was acted upon. The gadget factor focuses predominately on issues which are related to the ergonomics of the vehicle display. In contrast, the non-gadget factors relate primarily to the impact of the route guidance algorithm within the network in which TravTek system was deployed. The gadget factor input file that was used in the INTEGRATION runs is presented in appendix A.

In conducting the TravTek runs, all drivers were assumed to be local drivers in the 35 to 45 year age group. The TravTek vehicles were considered to be operating with a T-b-T Nav+ configuration. A copy of the overall accident rate file that was considered during the model runs is presented in appendix A.

SUMMARY

This section has indicated how the various features of the TravTek vehicle and driver were represented within the INTEGRATION model. Specifically, based on some limited field tests on two networks. In the City of Orlando, it was found that the error in the probe vehicle travel time estimate ranged from 2 percent to 10 percent. In addition, the Yoked Field Study conducted in Orlando had shown that the background traffic experienced an increase in travel time of approximately 20 percent over equipped vehicles. Therefore it could be inferred that the travel time error of background vehicles would range from approximately 3 percent to 12 percent,

The TMC received data from the various sources, and filtered and fused these data every minute. The fusing of data consumed some finite amount of time, which resulted in a lag in broadcasting the accumulated data back to each vehicle. This time lag usually exceeded 1 minute. In addition, real-time information was available on approximately 80 percent of the links in the simulated network. However, in most of the simulation studies discussed in this report, a more ideal TravTek system was modeled that had its routes optimized every minute. This optimization assumed that there was no lag in the data processing cycle and assumed that full real-time coverage existed. The background traffic was routed along a combination of five concurrent minimum path trees that were selected using the method of successive averages assignment technique. These trees were updated every hour.

Based on findings of the Yoked Field Study the background vehicles were found to experience a wrong turn probability of 5.4 percent, while TravTek vehicles experienced only a 3.6 percent probability of making a wrong turn at each node.

A drive mode elemental fuel consumption model was incorporated in the INTEGRATION model in order to capture all of the major types of operating conditions a vehicle would encounter on a typical trip. The second-by-second fuel consumption module estimates the steady-state fuel consumption of a vehicle plus the additional fuel consumed by any acceleration/deceleration maneuvers. In addition, the fuel consumption module is sensitive to the prevailing ambient temperature and to the extent to which the car’s engine has reached its hot stabilized temperature. Similarly, speed , ambient temperature and the extent to which the catalytic converter has already warmed up are also utilized to estimate the vehicle’s emissions of hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NOx).

The road class a vehicle travels on coupled with the congestion level on that road permits an appropriate accident risk factor to be computed for each vehicle at any instant in time. This base risk is adjusted based on the characteristics of the driver and of the TravTek system that is utilized. The accident risk is accumulated for each vehicle for the entire length of the link, and is further aggregated either for all the vehicles that traverse a particular link, or for all the links that are traversed by a particular vehicle.

In chapter 2 the configuration of the general network utilized in the simulation study was presented. In this chapter, the derivation of the TravTek specific features of the model were discussed. Based on the settings of chapters 2 and 3, a base INTEGRATION run was conducted to replicate the existing conditions in the City of Orlando. Chapter 4, describes the general calibration of this base run.

CHAPTER 4: ASSUMPTIONS OF SIMULATION STUDY AND CALIBRATION OF INTEGRATION TO ORLANDO

INTRODUCTION

In order to predict the potential benefits of alternative TravTek route guidance logic, it was essential that the existing traffic behavior be modeled accurately. Consequently, the INTEGRATION model, in the absence of TravTek, needed to be calibrated to the existing traffic network conditions. It was anticipated that inadequate model calibration could produce model biases that could exceed the potential benefits of the TravTek route guidance system. It was, therefore, important that the calibration of the INTEGRATION model be conducted in a systematic and unbiased fashion.

The previous two chapters discussed the coding of the Orlando network together with the derivation of the TravTek modeling and network specific features. Consequently, this chapter discusses the assumptions made in the evaluation study described in this report in addition to the calibration of the overall network characteristics and the I-4 traffic counts.

ASSUMPTIONS OF SIMULATION STUDY

This section of the report summarizes the major assumptions that were implied during the overall simulation study that is presented in this and the forthcoming chapters. These assumptions will allow the reader to interpret the results in a more appropriate context:

- The random number seed was kept constant for all simulation runs, unless specifically noted, and thus all runs were directly comparable in terms of their outputs.
- All vehicles equipped with the TravTek system were assumed to utilize the system during their entire trip.
- All vehicles equipped with the TravTek system were assumed to comply to the route guidance system, except when they made wrong turns during their trip, as discussed earlier.
- All guided vehicles were assumed to utilize a Turn-by-Turn configuration of the TravTek system in the Nav+ mode with the voice active (T-b-T, Nav+ and voice).
- An ideal TravTek system was modeled as the default. In this ideal system no account was made for the fact that travel time data were broadcast as discrete travel time factors (rather than actual continuous values), and that the typical data transmission lagged for 3 to 5 min.
- Guided vehicles were assumed to have real-time travel time information on every link in the network for their entire trip.
- Background traffic was considered to follow five minimum path trees that were computed using the method of successive averages traffic assignment. These minimum path trees were updated every hour.

- Background and TravTek vehicles were assigned wrong turn probabilities per turning movement of 0.054 and 0.036, respectively.
- Link travel times were assigned a normal error for both the background and TravTek vehicles. The Coefficient of Variation (COV) of this link travel time error was varied from 5 percent to 20 percent for the background traffic and from 1 percent to 10 percent for the TravTek vehicles.

BASE CASE STATISTICS

The simulated Orlando TravTek network consisted of 2670 links, 87 zones, 49 signals and 782.3 lane-km. During a typical modeling run 62,899 individual vehicles were traced, during the PM peak, through a total of 679,111 veh-km or 11,882.4 veh-h. For the base scenario a link travel time error of 10 percent was incorporated in the link travel time estimates based on the findings of chapter 3. In addition, a link travel time error of 5 percent was assigned to the link travel time estimates of the TravTek vehicles based, on the findings of chapter 3. Furthermore, wrong turn probabilities of 5.4 percent and 3.6 percent per turning movement were assigned to the background and TravTek equipped vehicles, respectively. In the base run, all vehicles were assigned to five multipath trees that were derived using the method of successive averages traffic assignment. These trees were updated each hour in order to capture any variations in the traffic demand, where this interval duration was selected based on the conclusions of chapter 2.

The network configuration required a version of INTEGRATION that utilized approximately 60 Megabytes of memory. The base run execution time was approximately 10 h on a 486DX 66 Megahertz machine with 32 Megabytes of RAM and would be expected to be faster if virtual memory had not been required.

The overall results of the base case study, that are presented in table 17, indicate that the average simulation trip duration was 11.3 min, while the average trip length was 10.8 km. Table 17, also indicates that the average number of stops experienced on a 10.8 km trip was 5.3, and on average 0.744 wrong turns were made per trip. Finally, the average vehicle fuel consumption rate was 1.7 L, the average HC, CO and NOx emissions were 18.4 g, 60.3 g and 10.9 g, respectively, these vehicles were estimated to experience an accident risk of 10.4 accidents per million trips.

Table 17: Summary results of base case

Average Trip Time (min)	11.3
Average Trip Length (km)	10.8
Average Number of Stops	5.3
Average Number of Wrong Turns	0.744
Average Fuel Consumed (L)	1.7
Average HC Emissions (g)	18.4
Average CO Emissions (g)	60.3
Average NOx Emissions(g)	10.9
Average Accident Rate (accidents/million trips)	10.4

CALIBRATION OF I-4 EASTBOUND DIRECTION

Actual real-time information from detectors was only available along the I-4 freeway in Orlando. This FMC data included 30-s flow, speed and occupancy measurements for 24 stations in both directions along the I-4, as discussed in detail in chapter 2.

In order to verify that the base case simulation run replicated the existing traffic characteristics, the 15-min flow and speed measurements estimated by the simulation model were compared to the measured 15-min flow and speed measurements obtained from the loop detectors, as discussed next.

Spatial and Temporal Flow Comparison

Figure 33 illustrates the spatial and temporal variation in the average 15-min flow rate per lane along the eastbound direction of the I-4 freeway. The x-axis represents the station number from 1 to 25 not including station 10, where flow proceeds from station 1 to 25 from left to right. The y-axis identifies the 15-min time interval for which the flow rate was estimated, while the z-axis represents the average 15-min flow rate per lane for that station/time. Figure 33 indicates that during the PM peak the flow rate varied from 1200 to 2400 vph/lane based on the three shaded areas. There appears to be lower flows at both the east and west ends of the freeway at stations 1 to 4 and 23 to 25, respectively. There also appears to be an increase in flow rate at stations 14 through 19 and stations 21 and 22 (2000 to 2400 vph/lane range).

Figure 34 illustrates, for the same spatial and temporal section of the eastbound I-4, the simulated flow rate variations. The spatial and temporal variation in flow presented in figure 34 is for a single simulation run, while that of figure 33 is the average typical measured variation. It appears from figure 34 that the simulated flow variation was larger than that for the actual measured flows (400 to 2400 versus 1200 to 2400 vph/lane). The low flow rates during the first 15-min interval at the downstream stations (stations 17 to 25) resulted from a build up of flow from an empty network. There appears to be a consistent build up of flow from stations 8 to 22. However, there also appears to be a reduction in flow at stations 1 through 5 at 16:45 (800 to 1200 vph/lane range).

Figure 35 demonstrates at the end of the 2-h demand (5:OO PM) the spatial variation in flow along the detectorized section of I-4. The dashed line represents the average typical flow variation for 22 core non-incident weekdays. Based on a Chi squared type goodness of fit test it was found that the measured 5-min flows were not statistically different from the expected outcome of a normal distribution at the 95-percent confidence level. Based on the assumption of normality, the 95-percent confidence limits for the average typical measured flows were estimated and plotted in figure 35. Figure 35 demonstrates how the simulated flow estimates compared to the average measured conditions at the conclusion of the 2-h demand. It appears from this figure that most of the simulated results were within the 95-percent confidence limits, and that simulated flows that were outside the bounds were only marginally so. Figure 35 also demonstrates a reduction in flow upstream of station 7.

Spatial and Temporal Speed Comparison

Figure 36 illustrates the corresponding spatial and temporal variation in the actually measured speed along the eastbound detectorized section of I-4. This average speed ranged from 50 to 110 km/h. It appears from figure 36 that there is a reduction in speed at stations 8 through 16 from 4:00 PM to 5:00 PM (speed below speed-at-capacity = 75 km/h). This reduction in speed did not spill back farther than station 8. Figure 36 also demonstrates that there was an increase in speed at station 24 in the 100 to 110 km/h range.

Figure 37 illustrates the spatial and temporal variation in the simulated speeds for the base simulation run. Again, as in the case of the flow variation, the simulated speeds experienced more variation than the typical loop detector measurements when averaged over many days. Specifically, the simulated speed varied from 10 to 90 km/h. Comparing figures 36 and 37 demonstrates a similar reduction in speed between stations 8 and 16. However, this simulated reduction in speed in figure 37 spills back to station 1 at 4:30 PM, as indicated by the low speeds in the range of 10 to 30 km/h.

Figure 38 demonstrates the spatial variation in simulated and measured speed estimates at the conclusion of the 2-h demand (5:00 PM). It appears that the simulated speed estimates were within the estimated confidence limits at stations 8 through 25. However, the simulated speed estimates were outside the bounds at stations 1 through 7, indicating queue spill back conditions from station 7. This queue spill back resulted because the non-TravTek vehicles were routed along the I-4 and did not receive any real-time information of the traffic conditions to divert.

Figure 39 illustrates the speed variation at 5:00 PM along the eastbound detectorized section of the I-4 when 10 percent of the vehicles were provided with real-time information (TravTek vehicles). It appears from this figure that the queue spill back ended at station 5 because vehicles diverted from the freeway. It can be concluded, from the spatial variation in the average measured speed, that the non-equipped vehicles do have limited real-time knowledge of traffic conditions and thus divert from the freeway, however, this was not captured in the base simulation run.

Summary

In summary, it appears that although the simulated flows replicated the measured flow estimates reasonably well, the simulated versus measured speeds at station 7 and upstream differed considerably for the base case. The simulated results indicated a queue spill back from station 7 to station 1 after 1.5 h of the demand. However, the measured flows did not indicate a spill back to the same extent. The lesser queue spill back in the field indicates that drivers do have limited real-time information and thus can react to congestion.

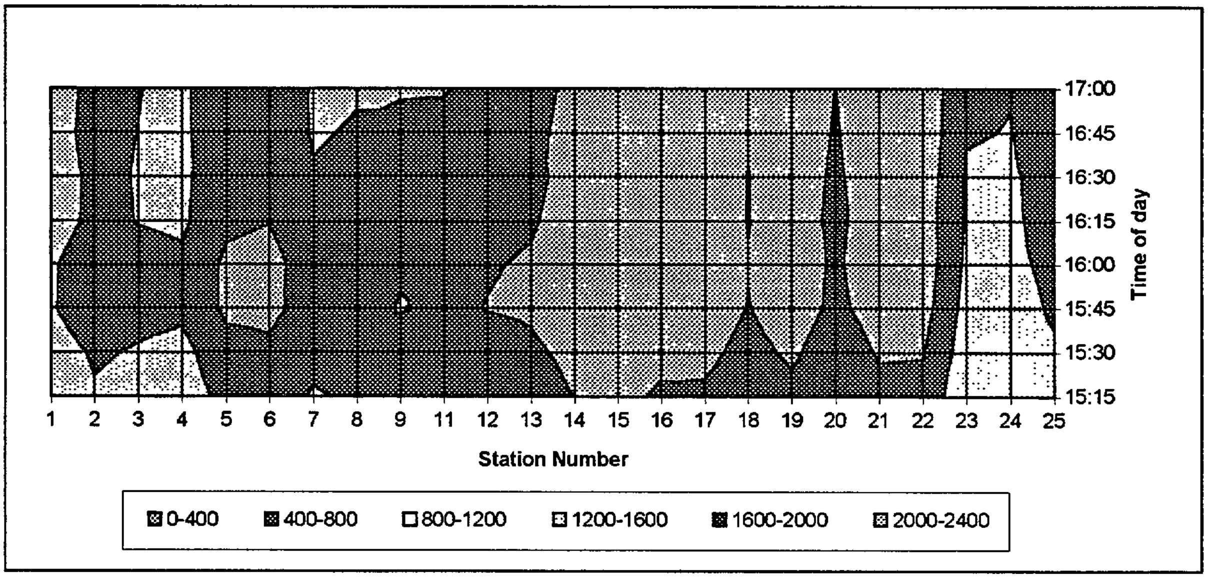

Figure 33: Spatial and temporal average loop detector flow rate measurements along the eastbound direction of I-4 (vph/lane)

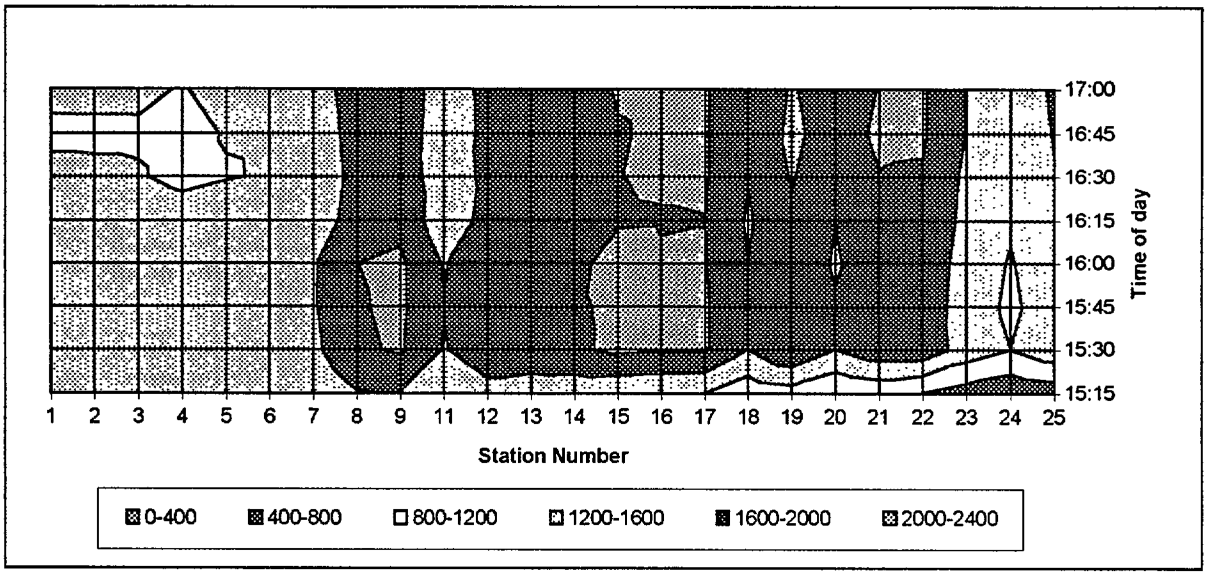

Figure 34: Spatial and temporal simulated flow rate estimates along the eastbound direction of I-4 (vph/lane)

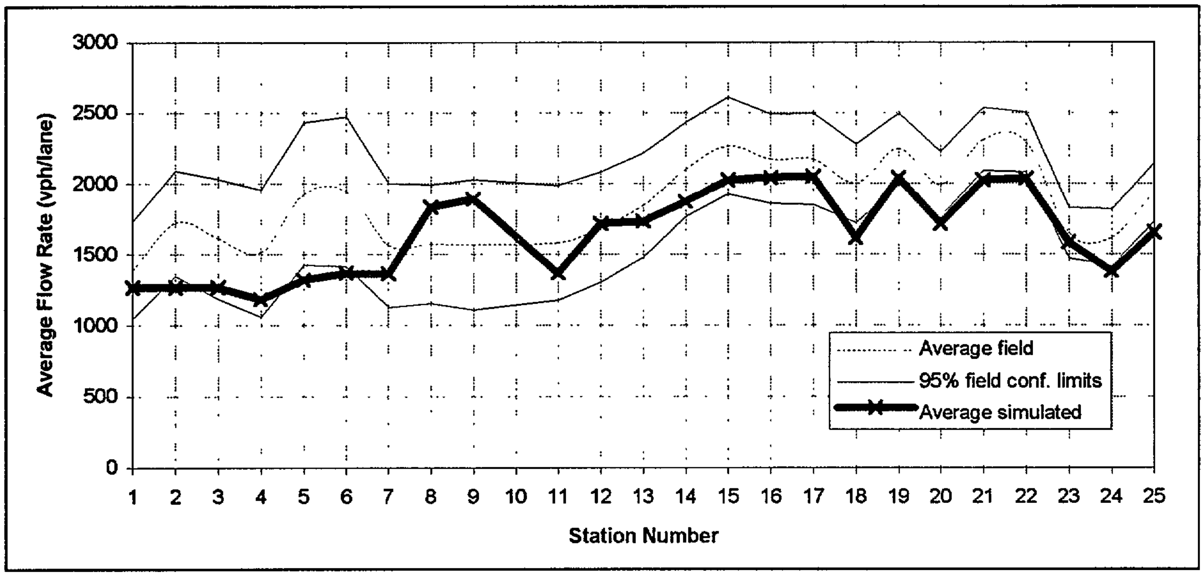

Figure 35: Spatial variation in simulated and average flow rate estimates at 5:00 PM along the eastbound direction of I-4

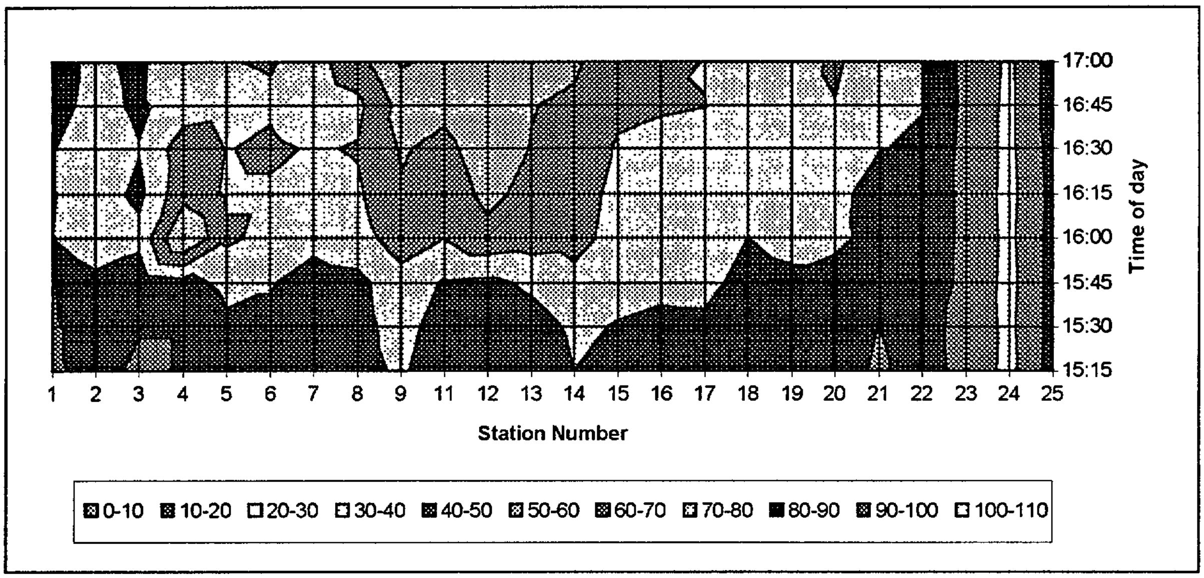

Figure 36: Spatial and temporal average loop detector speed measurements along the eastbound direction of I-4 (km/h)

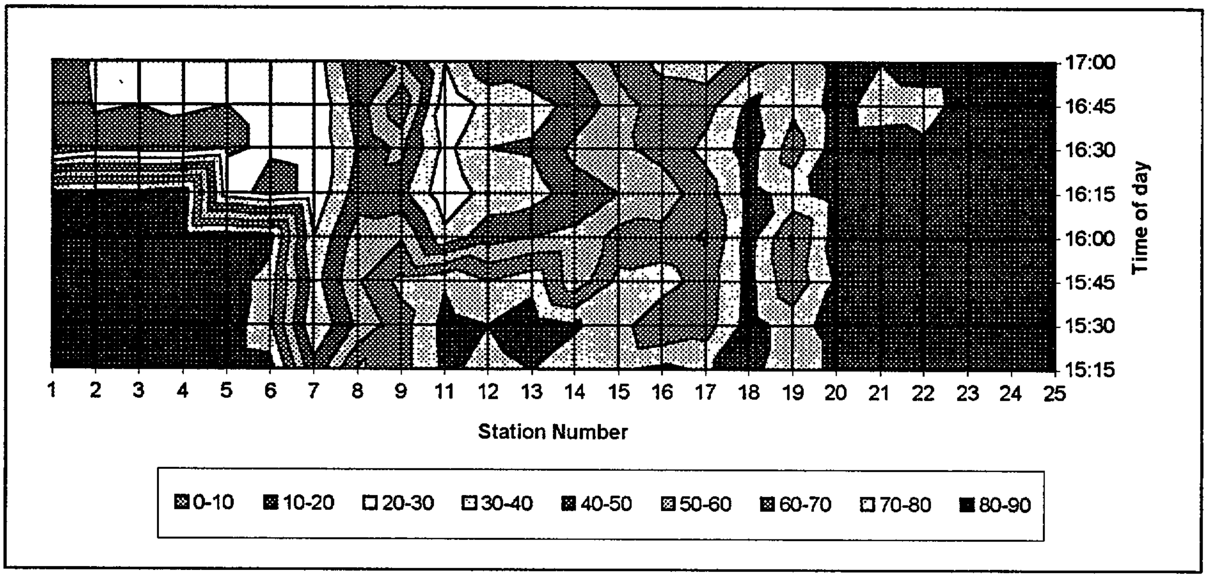

Figure 37: Spatial and temporal simulated speed estimates along the eastbound direction of I-4 (km/h)

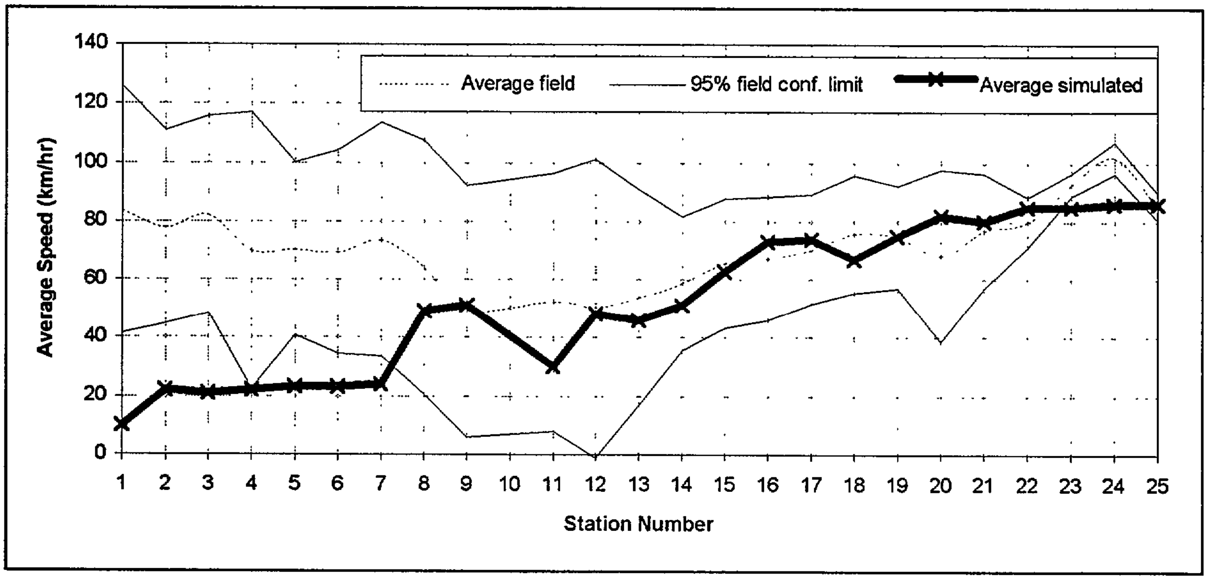

Figure 38: Spatial variation in simulated and average speed estimates at 5:00 PM along the eastbound direction of I-4

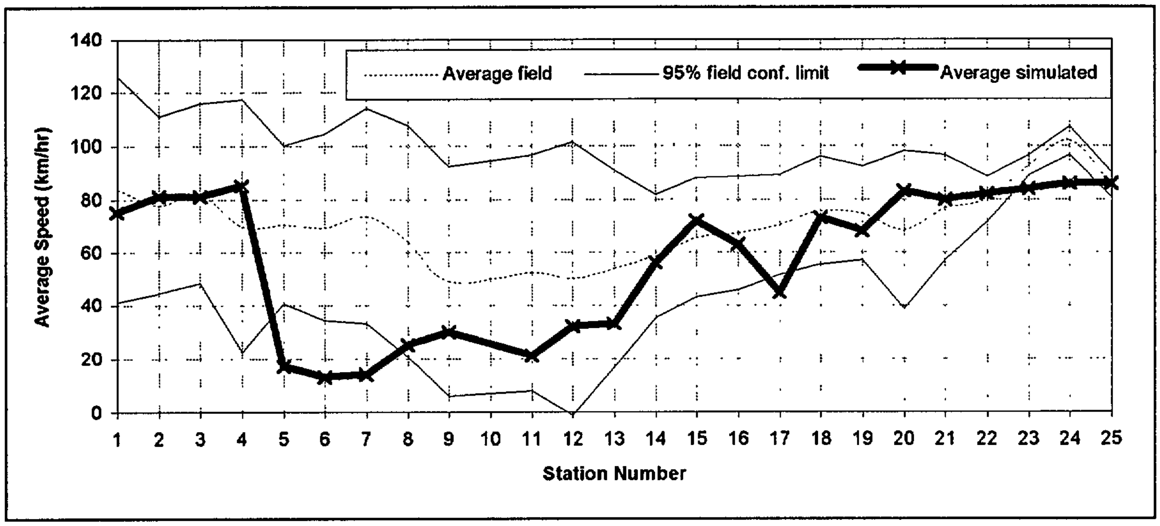

Figure 39: Spatial variation in simulated and average speed estimates at 5:00 PM along the eastbound direction of I-4 for 10 percent LMP

CALIBRATION OF I-4 WESTBOUND DIRECTION

In order to quantify the extent to which the base case run replicated the existing traffic characteristics in the westbound direction of I-4, the 15-min flow and speed estimates by the simulation model were also compared to the actual flow and speed measurements along the westbound direction of the I-4 freeway.

Spatial and Temporal Flow Comparison

Figure 40 illustrates the spatial and temporal variation in the average 15-min lane flow rate along the westbound direction of I-4. The x-axis represents the station number from 1 to 25, again not including station 10, where flow proceeds from station 25 to station 1 from right to left. The y-axis represents the 15-min time interval for which the flow rate was estimated, while the z-axis represents the average 15-min flow rate per lane. It appears from figure 40 that the flow rate varied from 800 to 2000 vph/lane based on the three shaded areas. Within this variation, there appear to be lower flows at both the east and west ends of the freeway at stations 1 to 4 and 20 to 25, respectively. There also appears to be an increase in flow rate at stations 5, 6, 8 through 11, and 14 through 17 into 1600 to 2000 vph/lane range.

Figure 41 demonstrates the simulated spatial and temporal variation in flow along the same westbound section of I-4. Again, as in the case of the eastbound direction, the range of simulated flows is larger, ranging from 0 to 2000 vph/lane, as opposed to 800 to 2000 vph/lane for the typical measured conditions. One can also observe again the low flow observations along the entire section of the freeway for the first 15-min interval, where these lower values arise from loading the network from the initial empty conditions. The spatial and temporal variation in simulated flow along the westbound direction replicates the same trend in increase and decrease in flow for the typical measured estimates. Specifically, there is a decrease in flow at both ends of the freeway, in addition to an increase in the flow along stations 7 through 9 and 13 through 17.

Figure 42 demonstrates the spatial variation in flow along the I-4 detectorized westbound section at the end of the 2-h demand (5:00 PM). As was the case for the eastbound direction, the dashed line represents the typical average flow variation for 33 core non-incident weekdays. Based on the assumption of normality, the 95-percent confidence limits for the average typical flows were estimated and provided in figure 42. Figure 42 demonstrates how the simulated flows compare to the measured conditions at the conclusion of the 2-h demand. It appears from the figure that the simulated results were generally within the 95-percent confidence limits. Furthermore, simulated flows outside the bounds were only marginally outside. It can also be noted from figure 42 that the confidence limits appear to be relatively constant over all the observed stations.

Spatial and Temporal Speed Comparison

Figure 43 illustrates the typical spatial and temporal variations in loop detector speed estimates, It ‘appears that the speeds do not vary considerably along the westbound direction as speeds only ranged from 70 to 100 km/h. There also appeared to be very little congestion along the westbound direction, unlike the eastbound direction, as indicated by the relatively small amount of travel in the 70 to 80 km/h range.

The simulated westbound speeds, as depicted in figure 44, also demonstrate minor variations in the speed from 50 to 90 km/h. These speeds also appear to be mostly in the 80 to 90 km/h range with a few drops in speeds at some spatial and temporal locations.

Figure 45 demonstrates the spatial variation in speed along the I-4 detectorized westbound section at the conclusion of the 2-h demand (5:00 PM). As was the case for the eastbound direction, the dashed line represents the average typical speed variation for 33 core non-incident weekdays. Based on the assumption of normality, the 95-percent confidence limits for the average typical speeds were estimated and plotted in figure 45. Figure 45 demonstrates how the simulated speed estimates compared to the average measured speeds at the conclusion of the 2-h demand. It appears from figure 45 that the simulated results were mostly within the calculated 95-percent confidence limits. Furthermore, simulated speeds outside the bounds were only marginally outside. It can also be noted from figure 45 that the confidence bounds appear to increase at stations 7 through 13 due to the presence of shock waves in the downtown area.

Summary

Based on the analysis of the speed/flow data in the westbound direction, it appears that the simulated base run replicated the existing typical spatial and temporal flow and speed variations reasonably well.

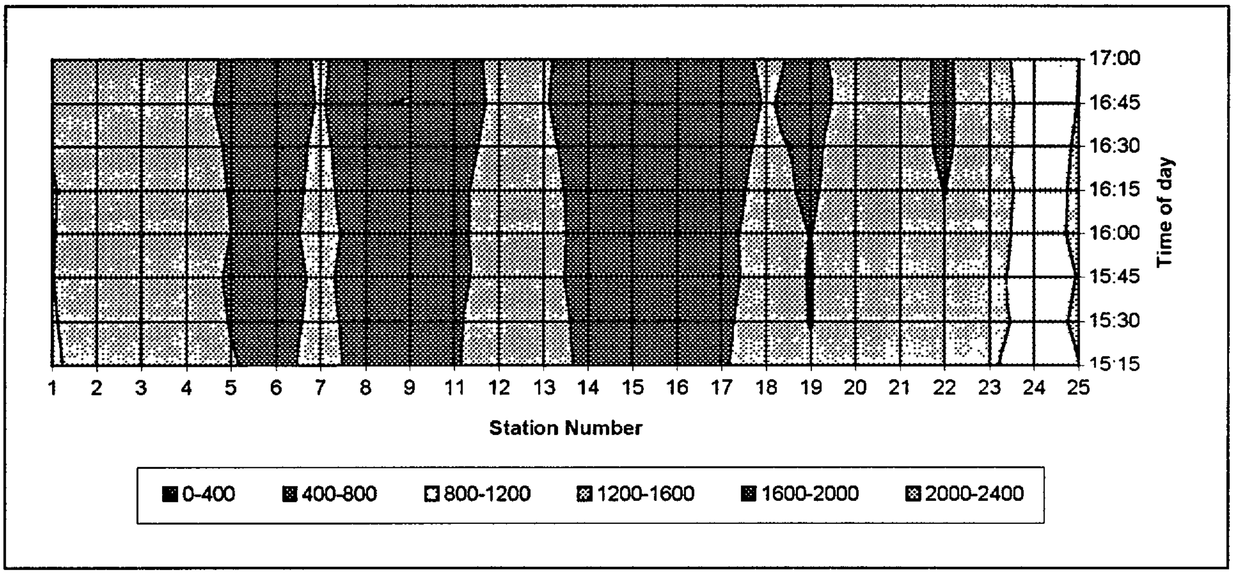

Figure 40: Spatial and temporal average loop detector flow rate measurements along the westbound direction of I-4 (vph/lane)

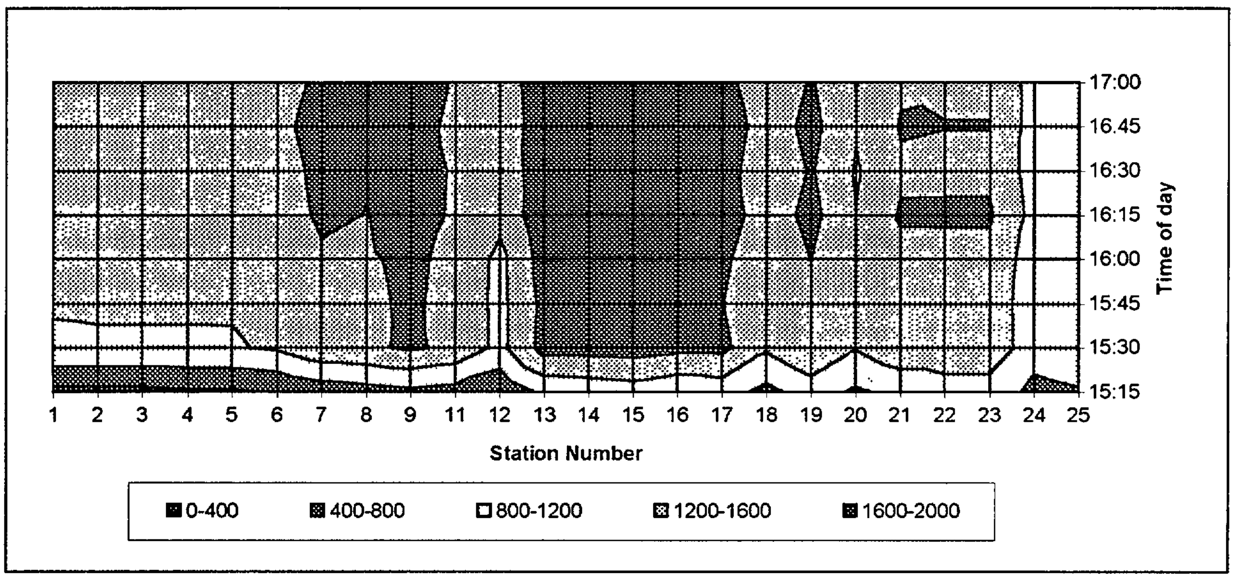

Figure 41: Spatial and temporal simulated flow rate estimates along the westbound direction of I-4 (vph/lane)

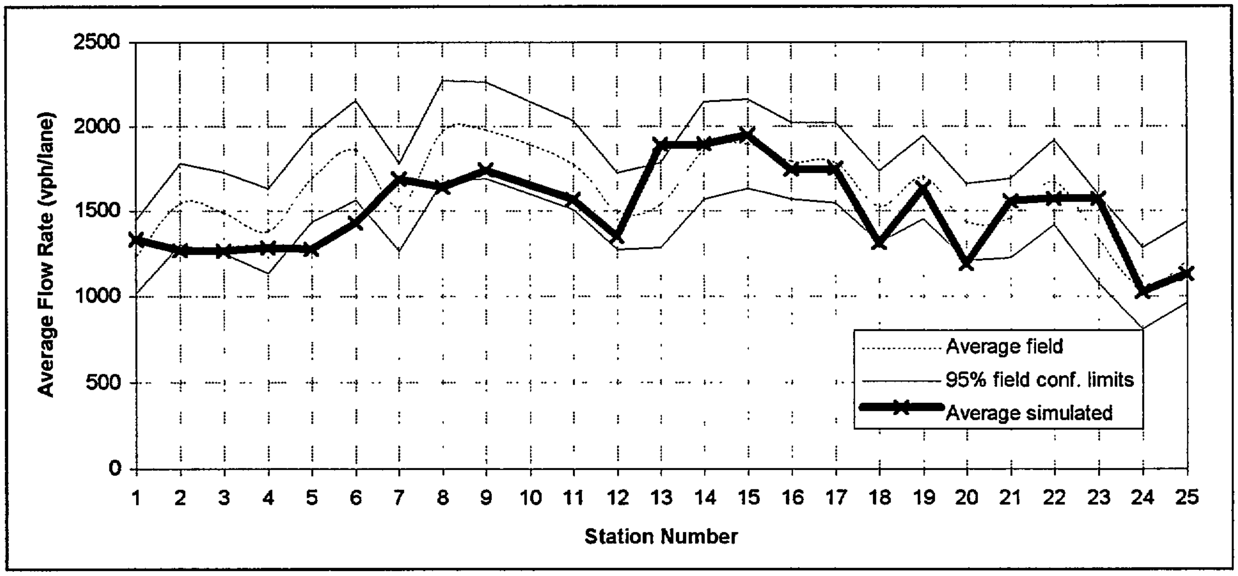

Figure 42: Spatial variation in simulated and average flow rate estimates at 5:00 PM along the westbound direction of I-4

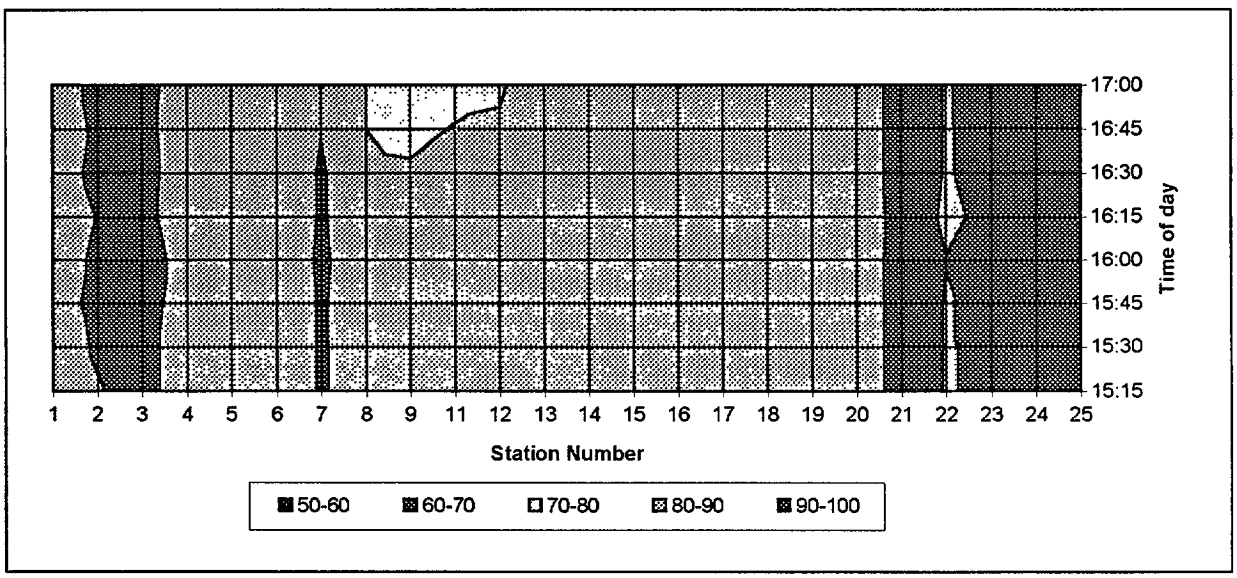

Figure 43: Spatial and temporal average loop detector speed measurements along the westbound direction of I-4 (km/h)

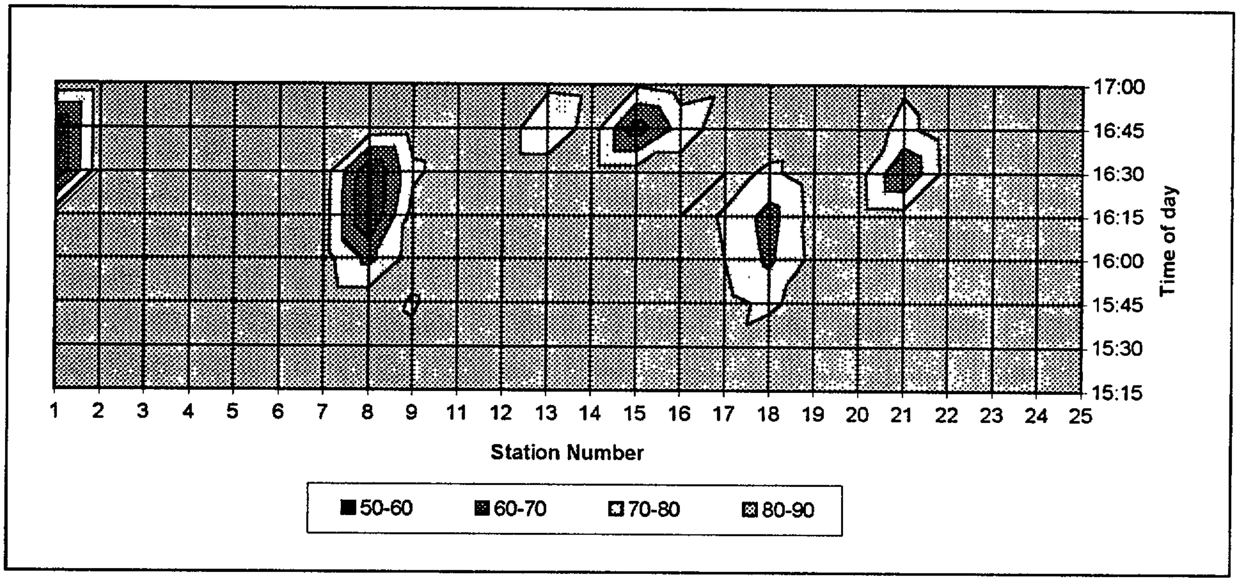

Figure 44: Spatial and temporal simulated speed estimates along the westbound direction of I-4 (km/h)

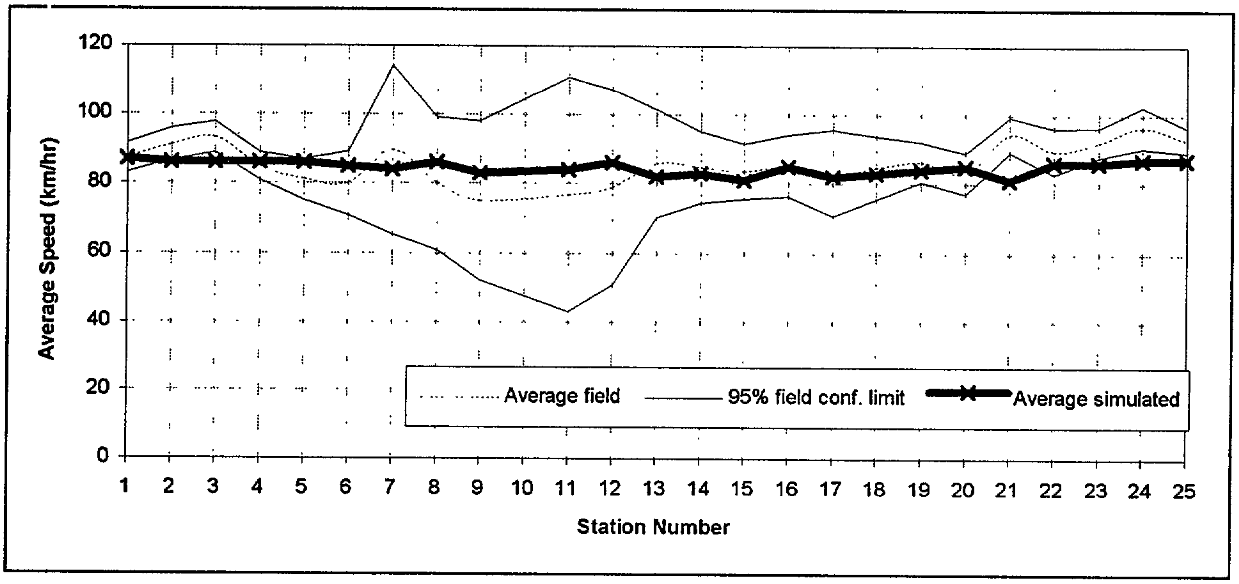

Figure 45: Spatial variation in simulated and average speed estimates at 5:00 PM along the westbound direction of I-4

SUMMARY

Prior to presenting the results of the various sensitivity analyses in the forthcoming chapters, this chapter presented the general assumptions that were made within the study presented in this report. In addition, this chapter attempted to quantify the extent to which the base simulation run replicated the existing traffic conditions on I-4 in the downtown area of the City of Orlando. Real-time traffic flow and speed measurements were only compared to the simulated results along the I-4 freeway as real-time flow and speed data were not available for the surface streets. In order to address the impact of surface street flows, sensitivity analysis of these flows is later conducted.

The validation of the model based on the available data indicated that the base simulation run routed a higher than expected demand along the eastbound direction of 1-4 which resulted in a queue spill back from station 7 to station 1. The remaining stations experienced similar temporal variations within the base simulation run as compared to the real data, as did typical weekday traffic conditions. The simulated westbound direction experienced similar spatial and temporal variations as the typical weekday conditions.

Based on this verification, the forthcoming chapters will present several sensitivity analyses of the various assumptions/configurations in order to evaluate the potential impact of these assumptions/configurations.

CHAPTER 5: IMPACT OF LEVEL OF MARKET PENETRATION ON NETWORK MEASURES OF PERFORMANCE

INTRODUCTION

The previous chapter illustrated the extent to which the base case run replicated the actual traffic conditions experienced in the downtown area of the City of Orlando. In this base run, no vehicles were provided with real-time information on traffic conditions. This chapter attempts to examine one of the fundamental questions about the TravTek system, namely; what is the impact of increasing the market penetration of these vehicles on the network MOP's. During this examination, the base runs were modeled with proportions of TravTek equipped vehicles of 1, 10, 30 and 50 percent. Nine performance measures for the TravTek system users and the background traffic were derived from the INTEGRATION model, namely: the total trip travel time; the total distance traveled; the number of stops incurred; and the number of missed turns experienced; as well as the estimated fuel consumption; vehicle emissions of hydrocarbon (HC), carbon monoxide (CO) and oxides of nitrogen (NOx) and the expected accident risk.

This chapter presents the impact of the different levels of market penetration on the nine network MOP's for the base scenario. The impact of different LMP's on the background and guided vehicles is also discussed. The following section of the chapter provides a more detailed analysis of the effect of LMP on the nine network MOP's for a background link travel time error of 5 percent and a TravTek link travel time error of 5 percent. This more detailed analysis involved LMP's of 1, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 percent. In these sections, the same set of random number seeds was utilized for each of the simulation runs that was conducted. Consequently, the following section investigates the effect of changing the seed on the overall simulation results. Finally, the conclusion together with a brief summary of the main findings of this chapter are presented.

IMPACT OF LMP FOR BASE CASE SCENARIO

Run 21 in the previous chapter modeled background traffic using five minimum path trees that were derived based on the method of successive averages traffic assignment technique. In this section different LMP's of TravTek vehicles are introduced to the base case run in order to investigate their impact on the network MOP's, A summary of the run coding convention for this study is presented in table 18. Further information on the input tiles are provided in appendix A.

It should be noted that the same set of random number seeds was utilized for each of the simulation runs conducted. This seed controls all stochastic elements within the model and thus, any runs completed using identical input files should generate identical results if the seed is the same. A brief discussion of the impact of changing these seeds is provided later in this chapter.

Aggregate Effects

Figure 46 illustrates a series of sample results for increasing Levels of Market Penetration (IMP's) of TravTek vehicles from 1 percent to 50 percent. In order to plot all of the MOP's on a common scale, each of the nine measures of performance were normalized to be at 100 percent for an LMP of 0 percent (i.e. base run 21).

It can be noted that in this set of scenarios, the total trip time experienced by all vehicles decreased by about 3.5 percent when the LMP of TravTek vehicles was 10 percent. At an LMP of 30 percent the travel time was reduced by about 9.5 percent, and at an LMP of 50 percent the reduction in travel time was found to be about 11 percent. These results indicate that there was a diminishing rate of return associated with further increases in the LMP, but that for all levels of market penetration (up to and including 50 percent) there continued to be a net travel time benefit associated with TravTek. The rather substantial decrease in total travel time indicates that the TravTek system appears to perform its basic function, namely the avoidance of traffic congestion and the associated delays. The savings in travel time were also partially due to the reduced number of wrong turns experienced by TravTek vehicles and the associated reduction in navigational waste, as indicated next.

Specifically, trip distance decreased by approximately 1,2 and 3 percent for LMP's of 10, 30 and 50 percent, respectively. The reason for the decrease in trip distance is that TravTek vehicles make fewer wrong turns and that they therefore experience reduced navigational waste. However, the decrease in trip length was not as large as the decrease in travel time, as the avoidance of traffic congestion typically involves an increase in the distance that is traveled.

The number of vehicle stops decreased by the largest amount of any of the Measures of Performances (MOP's). Specifically, it decreased to a value of approximately 78 percent of the number of stops associated with the base case (run 21). This number decreased in part because of the decrease in navigational waste and the decrease in the number of wrong turns. It also decreased because of the avoidance of congested conditions, as the stop-and-go cycles associated with travel during congested conditions are likely the main reason for the large initial value of this number. The simulated reduction in the number of wrong turns to a level of about 82 percent of the base case value, for a LMP of 50 percent, is primarily due to the fact that the TravTek unit has been shown in the field experiments to significantly reduce the number of wrong turns. This wrong turn reduction is also due, in part, to reducing the total trip distance. However, this latter reduction was only about 3 percent, as noted above.

The total fuel consumption dropped by up to 8 percent for an LMP of 50 percent. This drop was due in part to the avoidance of traffic congestion and hence the reduced time duration of the trip. The relative fuel consumption was less than the corresponding travel time reduction, as some of the travel time reduction arose from travel at a higher speed over a longer distance.

The reduction in HC emissions for an LMP of 50 percent was estimated to be about 12 percent. This value is greater than the relative reduction in the fuel consumption, as engines bum cleaner (in terms of HC) when traveling at higher speeds, as noted in chapter 3. Therefore congestion avoidance not only results in less fuel being consumed per km of travel, but also in less HC being emitted per liter of fuel consumed. The emissions of CO exhibit a less consistent pattern, as the emissions increased slightly by about 0.5 percent for an LMP of 10 percent, but then decreased by about 5 percent for an LMP of 50 percent. The lack of consistency in the response of CO is largely due to the rather complex response surface of CO relative to fuel consumption, as indicated earlier in chapter 3.

Finally, emissions of NOx increased for allLMP's, even though they may have peaked at an LMP of about 30 percent. The maximum increase of NOx emission of about 2.5 percent is less, however, than the reductions in HC and CO emissions of 12 percent and 5 percent, respectively. The main reason for this increase is that NOx emissions per liter of fuel consumed increases emissions at a constant and rapid rate as travel speed increases, as indicated in earlier in chapter 3. This increase in emission, per unit of fuel, is greater than the decrease in fuel consumption per unit distance. Hence the interaction of these two factors results in an overall net increase in emissions. The fact that NOx emissions increase by about 1 percent to 5 percent, as traffic flow conditions improve, is consistent with the findings of other traffic system evaluations.

The ninth and last MOP is one which illustrates the reduction in total accident risk of about 1 percent for an LMP of 50 percent. This decrease follows a brief increase in accident risk for a level of market penetration of 10 percent. The main reason, for the decrease in the accident risk measure, is that the reduction in number of wrong turns and in navigational waste reduce the risk exposure, while the presence of the TravTek unit in the vehicle was shown during the field tests to also decrease accident risk relative to the paper map base case. The lack of a much greater reduction in accident risk is likely due to the fact that congestion avoidance often results in extra distance traveled along arterials. This diversion from a freeway to an arterial increases accident risk, all other things being equal. A more detailed analysis of the impact of the level of congestion on the freeway and arterial roads on the potential accident risk will be conducted in chapter 6.

Disaggregate Effects

Figure 47 illustrates that the reduction in total travel time, for both TravTek equipped vehicles and non-TravTek vehicles, follow a consistent pattern. Specifically, at an LMP of 1 percent, TravTek equipped vehicles have a 1-min advantage over non-equipped vehicles, where this advantage continues to increase, but at a decreasing rate, with increases in LMP. Specifically, at a 50 percent LMP, equipped vehicles gain an additional half minute travel time saving over the l-percent LMP condition. However, as the LMP increases, the background traffic also benefits considerably as they now encounter considerably less residual congestion. This effect takes place to such a great extent, that at an LMP of 50 percent, the background traffic experiences a travel time equivalent to that of TravTek equipped vehicles at an LMP of 1 percent. Furthermore, while it would appear that the relative benefit of equipped vehicles over non-equipped vehicles is less at higher LMP's, from a societal point of view it is clear that significant benefits continue to be accrued to all drivers.

Figure 48 provides a similar illustration of LMP impacts on trip distance. Specifically, due to their greater avoidance of wrong turns and navigational waste, equipped vehicles make trips that are shorter than those by non-equipped vehicles for virtually all levels of market penetration from 0 to 50 percent. Despite the relatively constant trip distances for each trip maker subpopulation, the overall combined performance clearly continues to improve, as the weighted average of the top and bottom curves places an increasingly higher proportional weight on the performance of the equipped vehicles.

Figure 49 illustrates how the average number of vehicle stops of TravTek equipped and non-equipped background vehicles varies as a function of the LMP on a typical trip. One can observe from this figure that the number of vehicle stops for the equipped vehicles is always less than that for the non-equipped vehicles, primarily because the equipped vehicles are diverted from the congested routes. The difference in the number of vehicle stops, however, decreases as the LMP increases. It is also interesting to note from figure 49 that the number of stops for the equipped vehicles increases initially at an LMP of 10 percent relative to an LMP of 1 percent. This initial increase could have resulted from a diversion of TravTek vehicles from freeway to arterial routes. However, as the number of equipped vehicles increases, more TravTek equipped vehicles can remain on the freeway and thus the total number of vehicle stops begins to decrease. The number of stops being experienced by the non-equipped background vehicles also decreases. Although they remain on their original routes, the diversion of the equipped vehicles reduces the residual congestion on the routes chosen by the non-equipped vehicles.

Figure 50 illustrates how the number of wrong turns for equipped and non-equipped vehicles varies for different LMP’s along a typical trip. Because the non-equipped vehicles remain on their routes, the number of wrong turns, which is primarily a function of the trip distance, remains constant. Alternatively, because the equipped vehicles are diverted to shorter lower class routes, the number of wrong turns reduces initially and then appears to be constant. Despite the relatively constant number of wrong turns for each trip maker subpopulation, the overall combined performance continues to improve. This effect is due to the fact that the weighted average of the top and bottom curves places an increasingly higher proportional weight on the equipped vehicle performances at higher LMP’s.

Figure 5 1 illustrates how the fuel consumption of equipped and non-equipped vehicles changes for different LMP’s. It can be noted that the performance of the equipped vehicles is more or less constant for all levels of market penetration, but that the performance of the non-equipped vehicles improves steadily. This latter reduction is primarily due to the fact that the non-equipped background vehicles continue to drive routes of constant length, but that these routes are decreasingly less congested as they are being avoided by larger numbers of TravTek vehicles.

Figure 52 illustrates how the HC emissions for equipped and non-equipped vehicles vary as a function of the LMP. One can note lower HC emissions for TravTek equipped versus non-equipped background vehicles. However, the absolute difference in emissions decreases as the LMP increases. One can also note that the emissions for equipped vehicles remains constant up to a LMP of 10 percent, and then decreases as the LMP increases. This effect could also be explained by logic which suggests that, for lower LMP’s, a higher percentage of the equipped vehicles are diverted from the already congested freeways.

Figure 53 illustrates how the CO emissions for equipped and non-equipped vehicles vary as a function of the LMP. These emissions demonstrate that a rather peculiar trend arises as a result of the rather complicated CO saddle shaped response surface that was demonstrated in chapter 3. Specifically, it can be noted from figure 53 that the CO emissions for equipped and non-equipped vehicles increased up to an LMP of 10 percent, but that the CO emissions decreased as the LMP increased further. The CO emissions of equipped vehicles at an LMP of 50 percent eventually equaled the emissions at an LMP of 1 percent.

Figure 54 illustrates how NOx emissions for equipped and non-equipped vehicles varied as a function of the LMP. It appears that this effect is due to the fact that the NOx emissions increased as the LMP increased. As earlier demonstrated in chapter 3, initially NOx emissions increase as the speed increases. Thus, although the non-equipped vehicles remain on their routes, the diversion of equipped vehicles from these routes allows these non-equipped vehicles to travel at higher speeds and therefore produce more NOx.

Finally, figure 55 illustrates the components of the simulated safety relationship for different LMP's. It is interesting to note that, in order to avoid traffic congestion, the simulated TravTek vehicles leave the freeways to drive on the arterials which increases their risk exposure at a 1-percent LMP from 10.4 to 11.3 accidents per million vehicle trips. While from a travel time point of view it is more efficient for some vehicles to avoid the freeway, from a safety point of view, the use of arterials is less safe on a per kilometer basis as it results in a 250 percent higher accident risk (Safety Study). However, while the TravTek vehicles are actually increasing their risk (up to an LMP of 30 percent) by traveling further distance on arterials to avoid traffic congestion, the non-equipped background traffic indirectly benefits from these diversions for three reasons. First, by not diverting, their trip distance does not increase. Secondly, by remaining on the freeway, the background vehicles avoid using higher risk arterials. Finally, as the diverted TravTek vehicles leave behind less residual traffic congestion, the accident risk due to congestion on the freeway also drops for the non-equipped vehicles. The impact of varying the level of congestion along the freeway and arterial routes on the potential accident risk is conducted in chapter 6.

The simulated higher risk index for TravTek vehicles at LMP's less than 10 percent is a result of the traffic diversion from the freeways to the less safe arterials. However, as the percentage of TravTek vehicles increases more equipped vehicles remain on the freeway but experience less residual congestion, as does the background traffic, and thus the safety index of the TravTek vehicles is simulated to improve.

Table 18: Run numbering convention of base LMP sensitivity analysis (background error-10 percent, guided error-5 percent)

Level of Market Penetration (LMP)				
0 percent	1 percent	10 percent	30 percent	50 percent
21	22	23	24	25

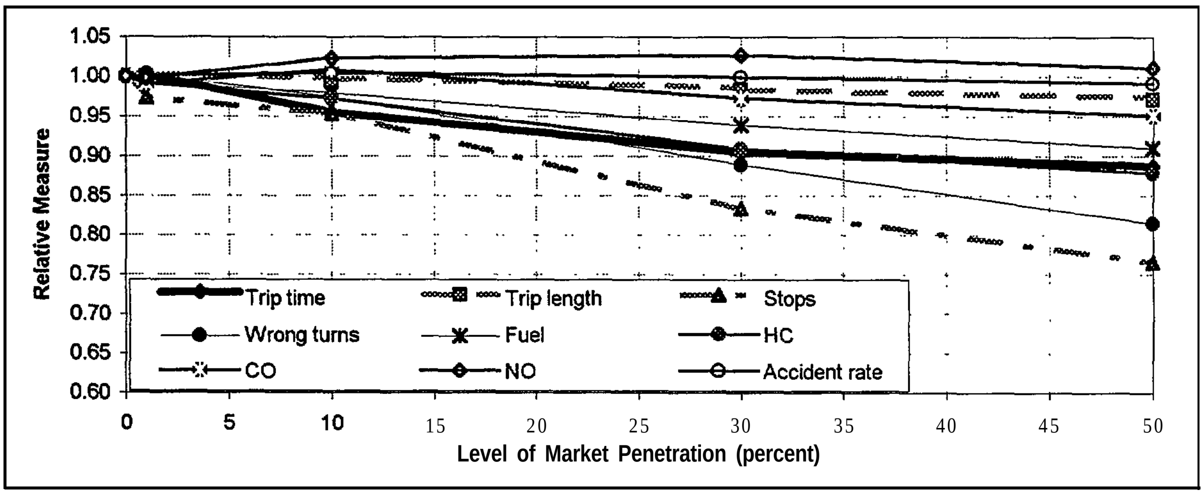

Figure 46: Impact of LMP for base case on network MOP's (background vehicle error=10 percent, guided vehicle error=5 percent)

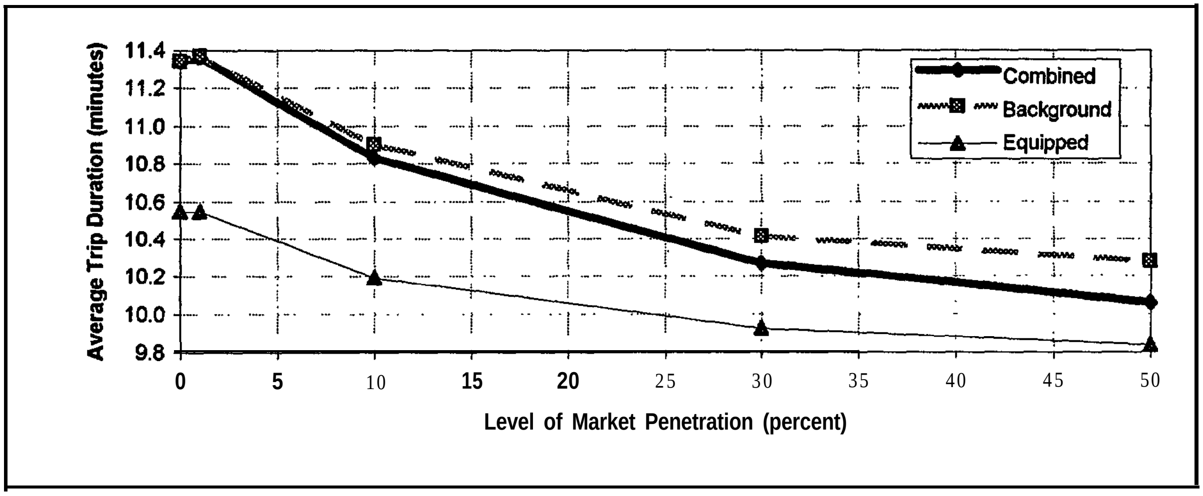

Figure 47: Impact of LMP on trip travel time for guided and unguided vehicles (background vehicle error=10 percent, guided vehicle error=5 percent)

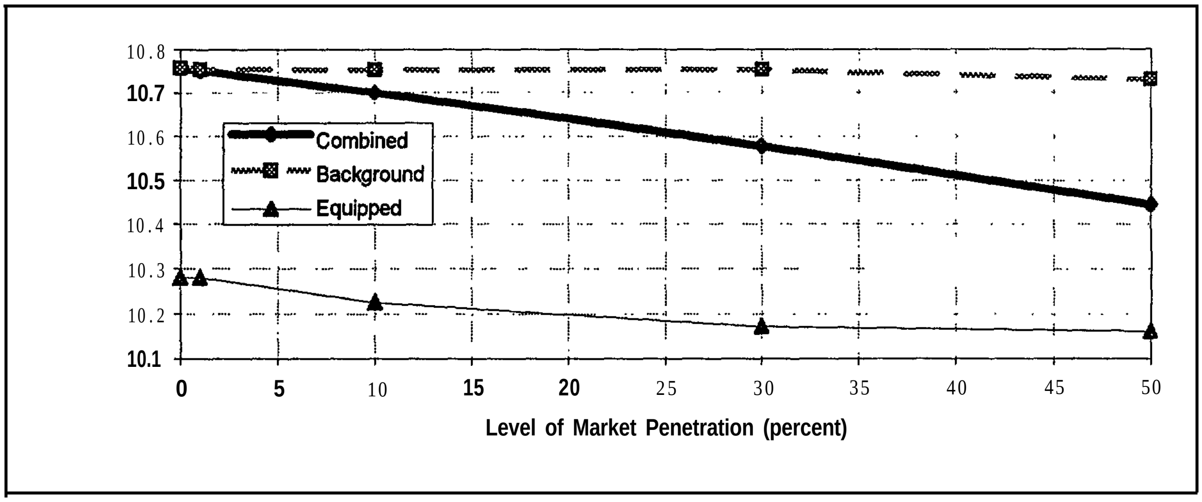

Figure 48: impact of LMP on trip length for guided and unguided vehicles (background vehicle error=10 percent, guided vehicle error=5 percent)

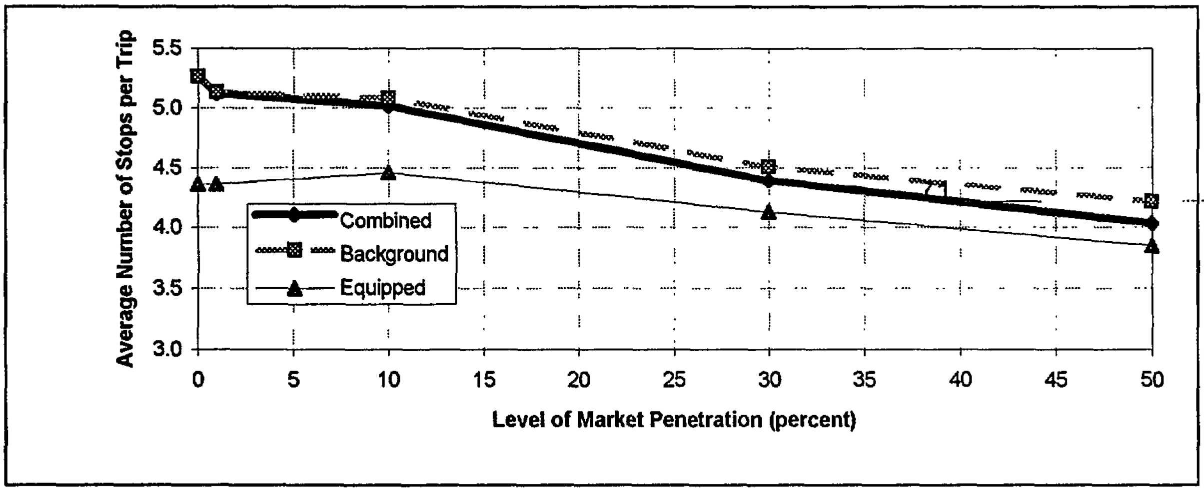

Figure 49: Impact of LMP on average vehicle stops for guided and unguided vehicles (background vehicle error=10 percent, guided vehicle error=5 percent)

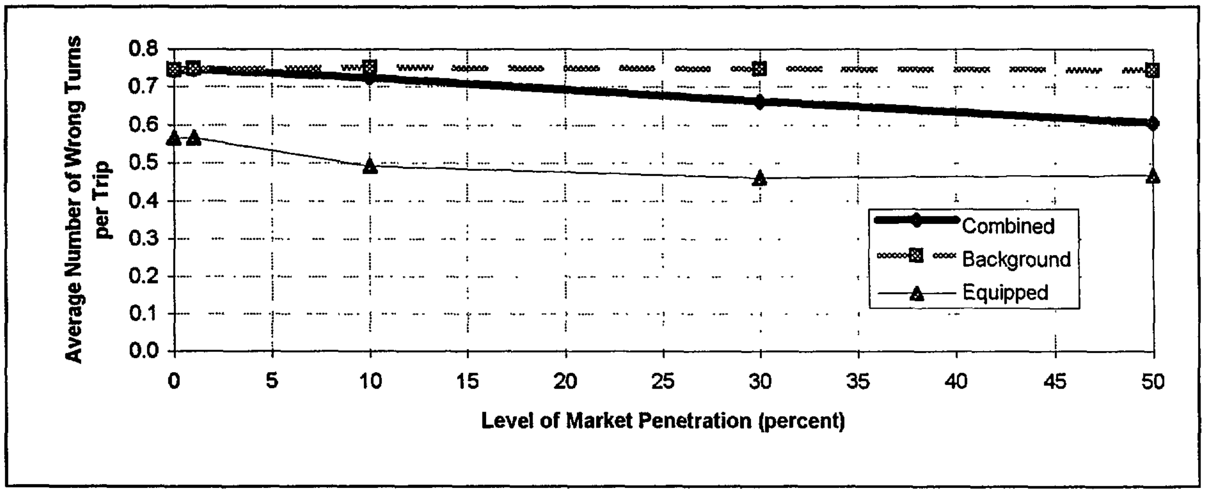

Figure 50: Impact of LMP on average wrong turns for guided and unguided vehicles (background vehicle error=10 percent, guided vehicle error=5 percent)

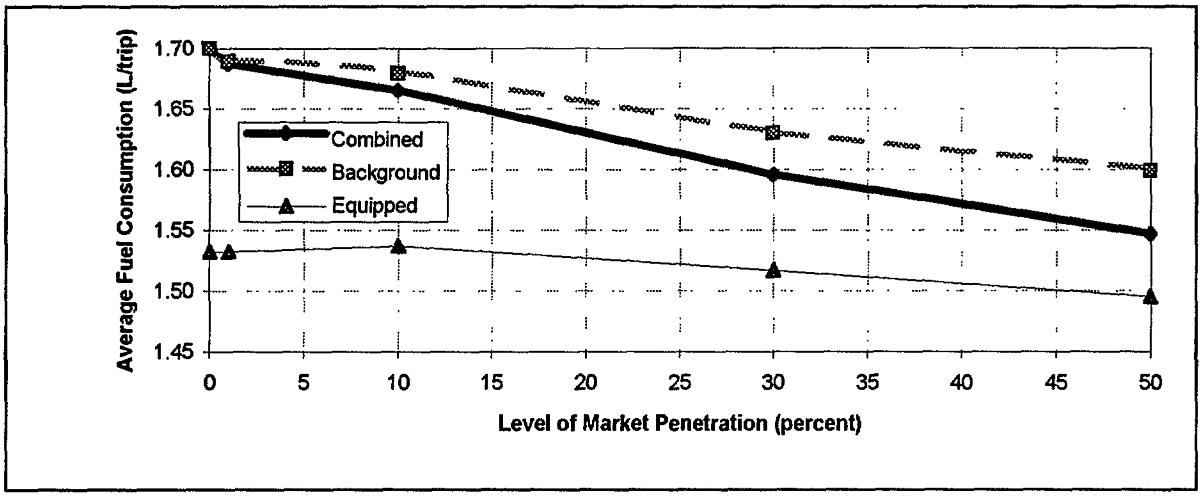

Figure 51: Impact of LMP on average fuel consumption for guided and unguided vehicles (background vehicle error=10 percent, guided vehicle error=5 percent)

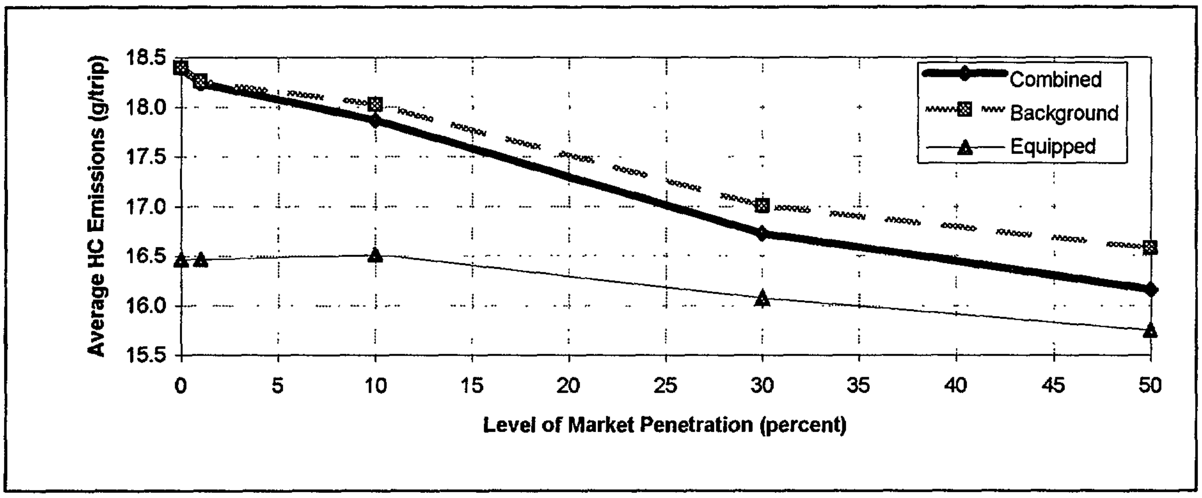

Figure 52: Impact of LMP on HC emissions for guided and unguided vehicles (background vehicle error=10 percent, guided vehicle error=5 percent)

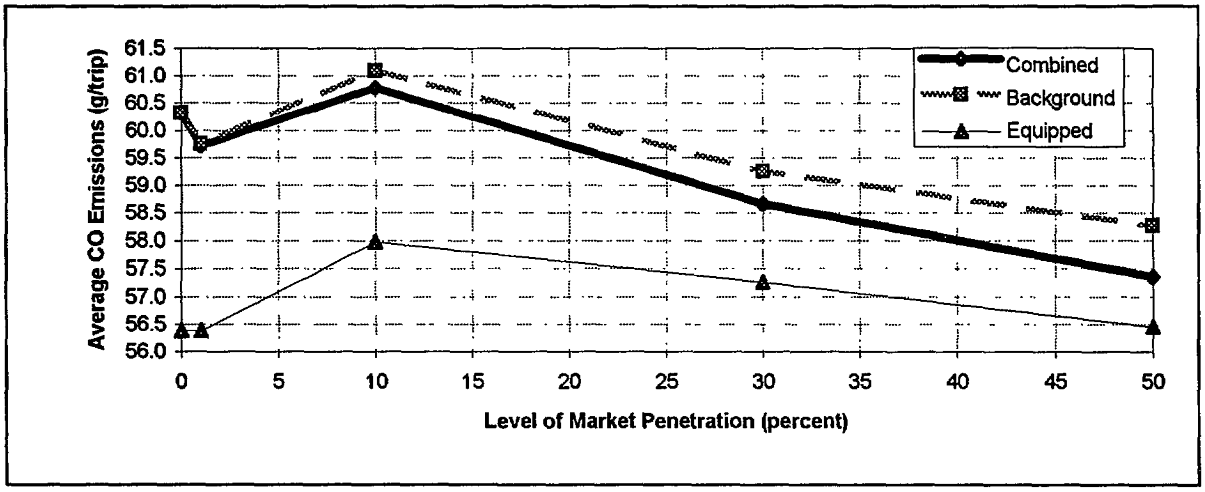

Figure 53: Impact of LMP on average CO emissions for guided and unguided vehicles (background vehicle error=10 percent, guided vehicle error=5 percent)

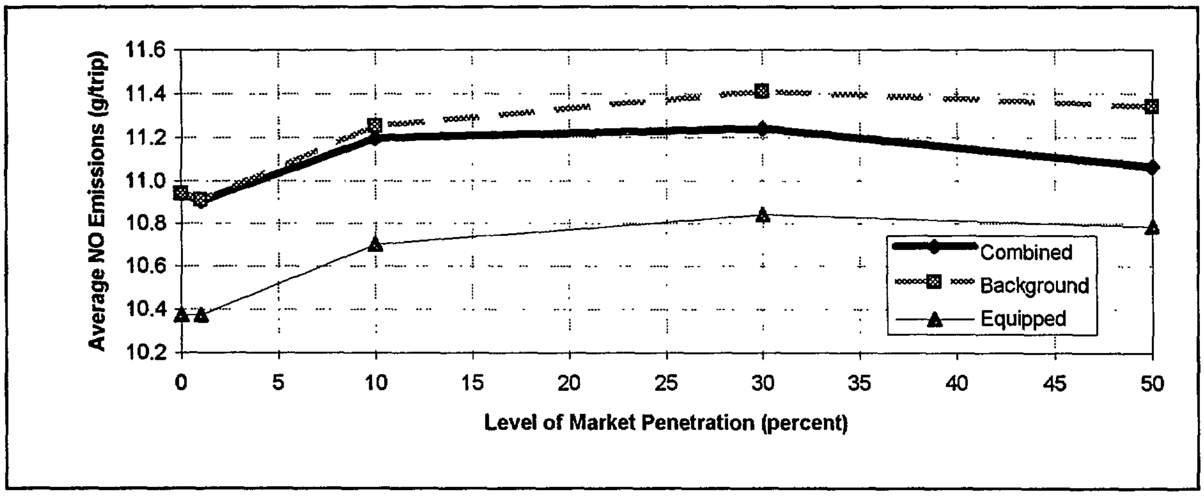

Figure 54: Impact of LMP on NO emissions for guided and unguided vehicles (background vehicle error=10 percent, guided vehicle error=5 percent)

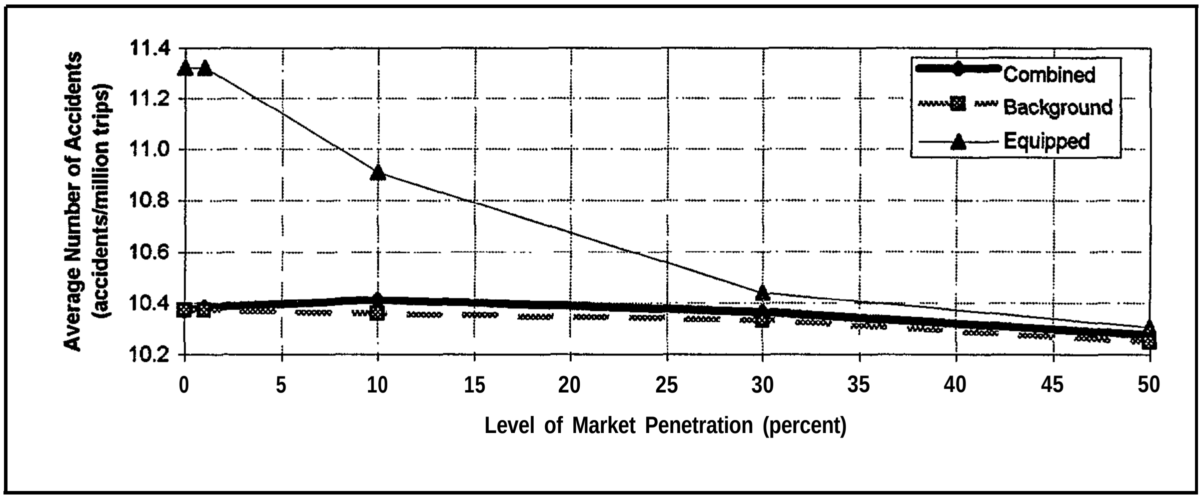

Figure 55: Impact of LMP on average accident risk for guided and unguided vehicles (background vehicle error=10 percent, guided vehicle error=5 percent)

DETAILED STUDY OF IMPACT OF LMP ON NETWORK MOP

In order to further explore the impact of varying the LMP on the network MOP's, this section describes a more detailed analysis in which the LMP was varied at lo-percent increments from 0 percent to 100 percent. A summary of the run coding convention is presented in table 19. In these runs, the amount of error in the routing of the background traffic was reduced from 10 percent to 5 percent in order to investigate if this reduction in error would impact the results of the previous section. A summary of the input files for these analyses is presented in appendix A of this report,

Table 19: Run numbering convention of LMP sensitivity analysis (background error=5 percent, guided error=5 percent)

Level of Market Penetration (LMP)											
0 %	1%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
6	7	8	104	9	105	10	106	107	108	109	110

Aggregate Effects

Figure 56 illustrates a series of sample results for increasing LMP of TravTek vehicles from 1 percent to 100 percent. As in the previous section, in order to plot all of the results on a common scale, each of the nine measures of performance were normalized to be at a level of 100 percent for an LMP of 0 percent (run 6).

It can be noted that, in these sample scenarios, the total trip time experienced by all vehicles at an LMP of 10 percent decreased by about 5 percent, as opposed to 3.5 percent, for a background link travel time error of 5 percent versus 10 percent. At an LMP of 30 percent the travel time was reduced by about 11 percent, and when the LMP was 50 percent, the reduction in travel time was found to be about 13 percent. This value increased to a reduction in travel time of 15 percent at an LMP of 100 percent. These results indicate that there was a diminishing rate of return associated with further increases in the LMP, but that for all levels of market penetration (up to and including 100 percent) there continued to be a net travel time benefit. The rather substantial decrease in total travel time indicates that the TravTek system appears to perform its basic function, namely the avoidance of traffic congestion and associated delays. The savings in travel time were also partially due to the reduced number of wrong turns experienced by TravTek vehicles and the associated reduction in navigational waste.

Trip distance decreased by approximately 1, 2, 3, and 5 percent for LMP's of 10, 30, 50 and 100 percent, respectively. As demonstrated earlier, the reason for the decrease in trip distance is that the TravTek vehicles made fewer wrong turns and that they reduced navigational waste. However, the decrease in trip length was not as large as the decrease in travel time, as the avoidance of traffic congestion typically involves an increase in the distance that is traveled. This figure also demonstrates that the average trip length continues to decrease at all levels of market penetration. A comparison of figures 46 and 56 indicates that the same general trends exist for a background link travel time error of 10 percent versus 5 percent,

-The number of stops decreased by a large amount to a value of approximately 68 percent of the number of stops associated with the base case (run 6) at an LMP of 100 percent. These results again are consistent with the findings for a background link travel time error of 10 percent.

The total fuel consumption dropped by up to 13 percent for an LMP of 100 percent. These results again are consistent with the findings for a background link travel time error of 10 percent.

The reduction in HC emissions for an LMP of 100 percent was estimated to be about 16 percent. The emissions of CO exhibit a less consistent pattern, as the emissions increased slightly by about 2 percent for an LMP of 10 percent, but then decreased by about 8 percent for an LMP of 100 percent. The lack of consistency in the response of CO is largely due to the rather complex response surface of CO relative to fuel consumption. Again, these findings are consistent with previous findings in the report.

Finally, emissions of NOx increased for most LMP's peaking at an LMP of about 30 percent, as was also found for a background link travel time error of 10 percent in figure 46. The NOx emissions were eventually reduced at an LMP of 100 percent by approximately 1.5 percent. The main reason for this initial increase is that NOx emissions per liter of fuel consumed results from the increase in NOx emissions at a constant and rapid rate as travel speed increases.

The ninth and last MOP is one which illustrates the reduction in accident risk of about 2 percent for an LMP of 100 percent. This decrease follows a brief increase in accident risk for a level of market penetration of 10 percent. The main reason for the subsequent decrease in the accident risk measure is that the reduction in number of wrong turns and navigational waste reduce the risk exposure, while the presence of the TravTek unit in the vehicle was shown during the field tests to also decrease accident risk slightly relative to the base case. Again, these findings are consistent with the findings assuming a background link travel time error of 10 percent.

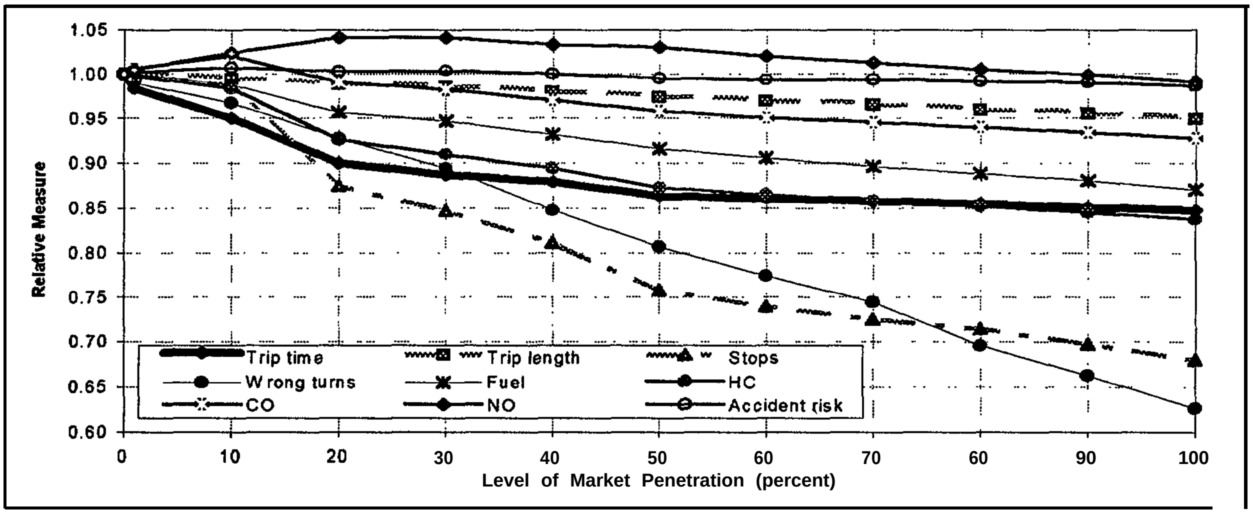

Figure 56: Impact of LMP for base case on network MOP's (background vehicle error=5 percent, guided vehicle error=5 percent)

Disaggregate Effects

In order to verify the effect of LMP on the different vehicle types, equipped and non-equipped, figure 57 illustrates the variation in the average trip duration as a function of the LMP. It can be noted from the figure that the average travel time for both the equipped and non-equipped vehicles continues to decrease until an LMP of 50 percent is reached and then remains virtually constant up to an LMP of 100 percent. Despite the relatively constant trip durations for each trip maker subpopulation at LMP's greater than 50 percent, the overall combined performance continues to improve, as the weighted average of the top and bottom curves again places an increasingly higher proportional weight on the equipped vehicle performances. This figure demonstrates three very important findings, namely: (a) that there is always an incentive for a person to buy a route guidance gadget as he/she would shift from the non-equipped (background curve) to the equipped curve, (b) that at LMP's higher than 50 percent the remaining equipped and non-equipped vehicles are not affected by any new vehicles that purchase this route guidance gadget, and (c) that the system as a whole benefits at all LMP's from the purchasing the TravTek system.

In order to further investigate the findings of figure 56, the nine MOP's are investigated for each of the vehicle types. Figure 58 illustrates how the nine MOP's vary as the LMP varies from 0 percent to 90 percent. The absence of an LMP of 100 percent is because it entails that no non-equipped vehicles exist. One can note from the figure an approximately 12-percent reduction in the average trip time. This reduction occurred up to an LMP of 50 percent and then remained constant. The average trip length remained constant as the non-equipped vehicles remained along their previous routes. The number of vehicle stops was reduced by approximately 27 percent at an LMP of 100 percent because the re-routing of the equipped vehicles reduced the level of congestion on the routes used by the non-equipped vehicles. The number of wrong turns remained approximately constant as the trip distance did not change. The CO emissions were reduced by approximately 13 percent at an LMP of 90 percent. The CO emissions exhibited an increase at an LMP of 10 percent and then decreased by 5 percent at an LMP of 90 percent. Although the non-equipped vehicles remained on their routes, the diversion of the equipped vehicles from these routes allowed the non-equipped vehicles to travel at higher speeds and thus they emitted more NOx emissions. Finally, the accident risk of the non-equipped vehicles was reduced by approximately 2 percent.

In summary, all non-equipped MOP's were improved except for three measures: the average trip length, the number of wrong turns and the NOx emissions. Because the non-equipped vehicles did not re-route, the average trip length remained constant. In addition, because the number of wrong turns is a function of the number of wrong turn opportunities, traveling on the same route would not increase these opportunities and thus the average number of wrong turns remained constant. Finally, the NOx emission increase resulted from the reduction in congestion along the routes utilized by the non-equipped vehicles, that in turn was as a result of the diversion of equipped vehicles.

Figure 59 demonstrates the variation in the nine MOP's for the equipped vehicles for LMP's ranging from 1 percent to 100 percent. These measures are all expressed relative to the performance of the TravTek vehicles in the base run (run 6). One can observe an approximate 7-percent reduction in average trip time, and an approximate constant average trip length, that in each case was shorter than the non-equipped vehicle trip length. The trip length was reduced by the TravTek system because TravTek vehicles experienced a lower probability of making a wrong turn maneuver. This resulted in a reduction in average overall trip length with an increase in the LMP. The average number of vehicle stops decreased consistently as the LMP increased and attained a reduction of 20 percent at an LMP of 100 percent. The number of wrong turns was reduced slightly but remained virtually constant as a result of the constant average trip length. Fuel consumption was reduced slightly by 3 percent at an LMP of 100 percent. In addition to a reduction in HC emissions in the range of 7 percent, the CO emissions decreased in the range of 2 percent, and the NOx emissions increased in the range of 5 percent. However, the overall NOx emissions were reduced to 1 percent less than the base case at an LMP of 100 percent. The lower equipped versus non-equipped vehicle NOx emissions resulted from the shorter average trip time of the equipped versus non-equipped vehicles. It is interesting to note that, unlike the case for the non-equipped vehicles, the accident risk decreased by 10 percent at an LMP of 100 percent versus an LMP of 1 percent. However, initially at an LMP of 1 percent the accident risk for the equipped vehicles was 9 percent higher than for non-equipped vehicles, and thus the overall reduction in accident risk was only 1 percent at an LMP of 100 percent as presented in figure 56.

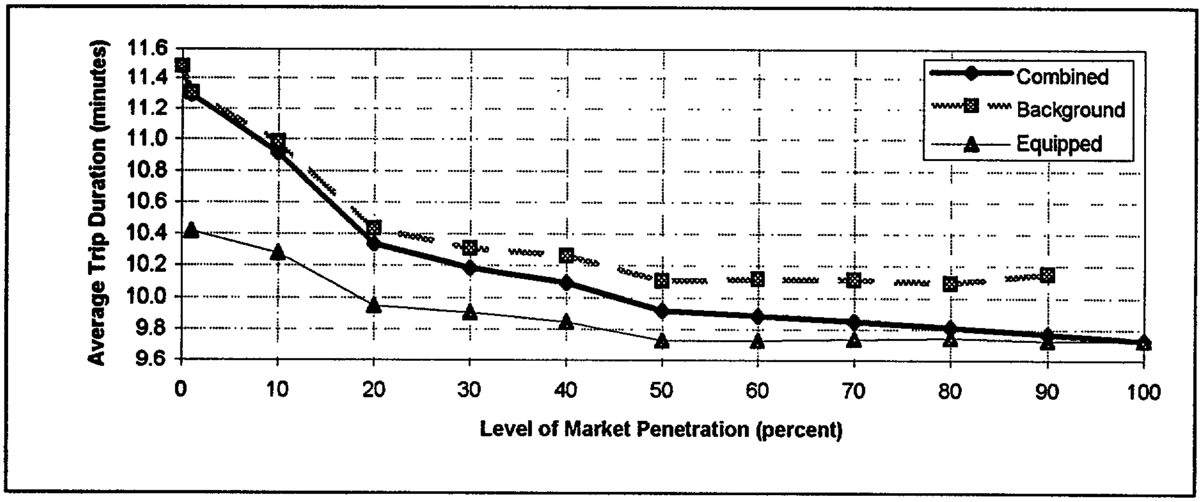

Figure 57: Impact of LMP on average trip travel time for guided and unguided vehicles (background vehicle error=5 percent, guided vehicle error=5 percent)

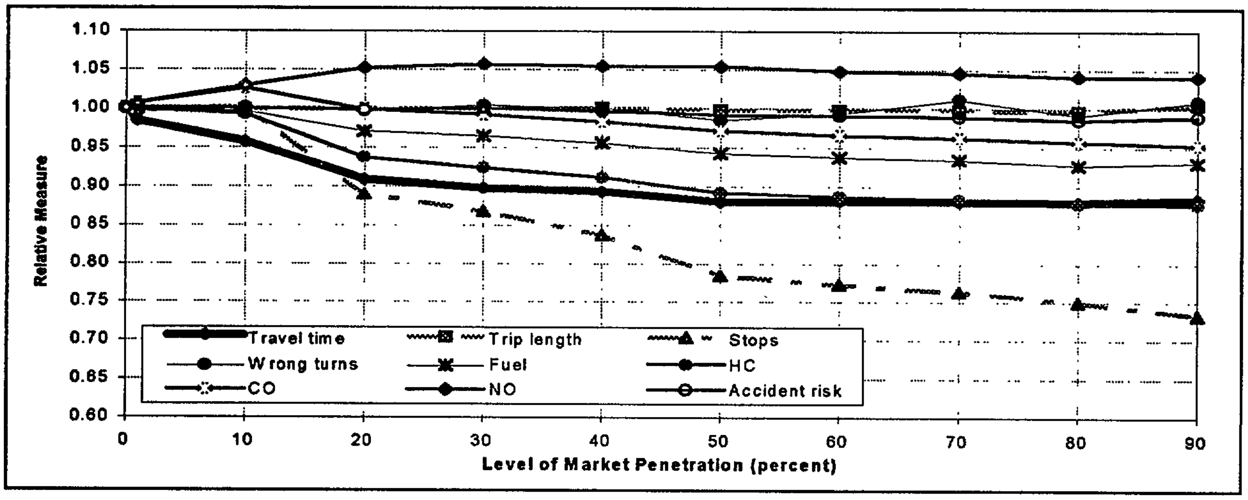

Figure 58: Impact of LMP for base case on background vehicle MOP's (background vehicle error=5 percent, guided vehicle error=5 percent)

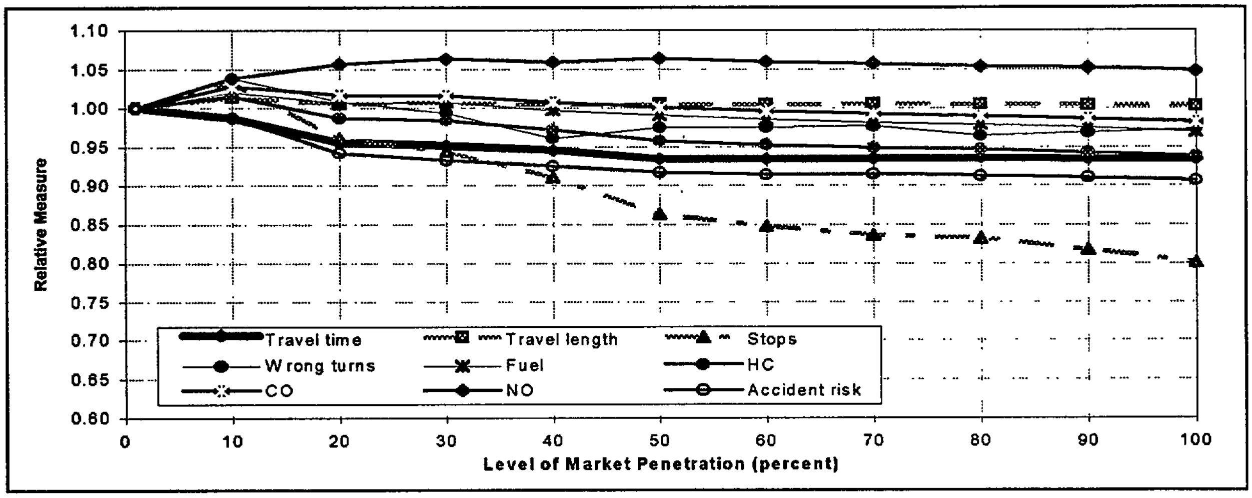

Figure 59: Impact of LMP for base case on guided vehicle MOP's (background vehicle error=5 percent, guided vehicle error=5 percent)

EFFECT OF DIFFERENT RANDOM NUMBER SEEDS

It should be noted that for the previous simulation runs, the random number seed was always fixed. However, in order to investigate the impact of the random number seed on the simulation results, some runs with a background link travel time error of 5 percent and a TravTek link travel time error of 5 percent were repeated six times for different seeds, as indicated in table 20.

Subsequently, an Analysis of Variance (ANOVA) test was conducted on the nine MOP's generated from the runs presented in table 20, where these ANOVA tests were conducted using the SYSTAT model.(5) The results for the trip travel times for different LMP's are presented in figure 60. The center horizontal line in the box represents the median of the batch, while the upper and lower edges of the box split the remaining halves in half again (quartile ranges). The two whiskers extend beyond the quartile hinges to ± 1.5 times the horizontal spread.(5) It appears from figure 60 that the variability between the different LMP's are always statistically greater than the variability within each LMP. It further appears that the confidence limits are reduced as the LMP increases. This important finding demonstrates that, as the LMP increases the average trip time is not only reduced but also the variability in the average trip time is reduced.

Figure 61 illustrates how the average trip time of individual vehicles varies as a function of the random seed. It appears from the figure that the variability within each seed, that resulted from the different LMP's, is consistent with the variability between seeds. Therefore, there does not appear to be any non-random trend to the variation in the seed.

A summary of the two-way ANOVA results for the nine MOP's is presented in table 21. The results demonstrate that the LMP factor was significant for all nine MOP's. After introducing the LMP effect the seed effect was also significant for all MOP's except CO emissions. However, it appears that the LMP factor explained over 80 percent of the Sum of Squares (SS) error for all MOP's except for NO_x emissions and the accident risk. In those cases it explained only 57 percent and 45 percent of the SS error.

In order to further investigate the effect of the random seed, on the simulation results, a single run (run 8 of table 20) was repeated 21 times with different seeds. The nine MOP's were stratified into bins and compared to the normal distribution using type of Chi Squared goodness of test in order to establish whether the normal distribution assumption was valid. The Chi squared type of analysis showed all MOP's to not be statistically different from the expected outcome of a normal distribution at the 95-percent confidence level.

Table 22 summarizes the results for the nine MOP's based on the 21 observations mentioned earlier. For each measure the minimum, maximum, mean, standard deviation, skew and coefficient of variation (COV) was estimated. Based on the results it was found that the COV ranged from 0.3 percent to 4 percent. The maximum value of COV of 4 percent resulted in the total number of stops MOP, which was also found to be the most sensitive measure impacted by the level of market penetration. The reduction in the number of vehicle stops of 32 percent (at an LMP of 100 percent) was much larger than the 4 percent COV, indicating that the effect of LMP is highly significant.

Table 20: Run coding convention for combined seed and LMP impact analysis

		LMP				
		0%	1%	10%	30%	50%
Seed	0	6	7	8	9	10
	1	79	80	81	82	a3
	2	84	85	86	87	88
	3	89	90	91	92	93
	4	94	95	96	97	98
	5	99	100	101	102	103
	6			111		
	7			112		
	8			113		
	9			114		
	10			115		
	11			116		
	12			117		
	13			118		
	14			119		
	15			120		
	16			121		
	17			122		
	18			123		
	19			124		
	20			125		

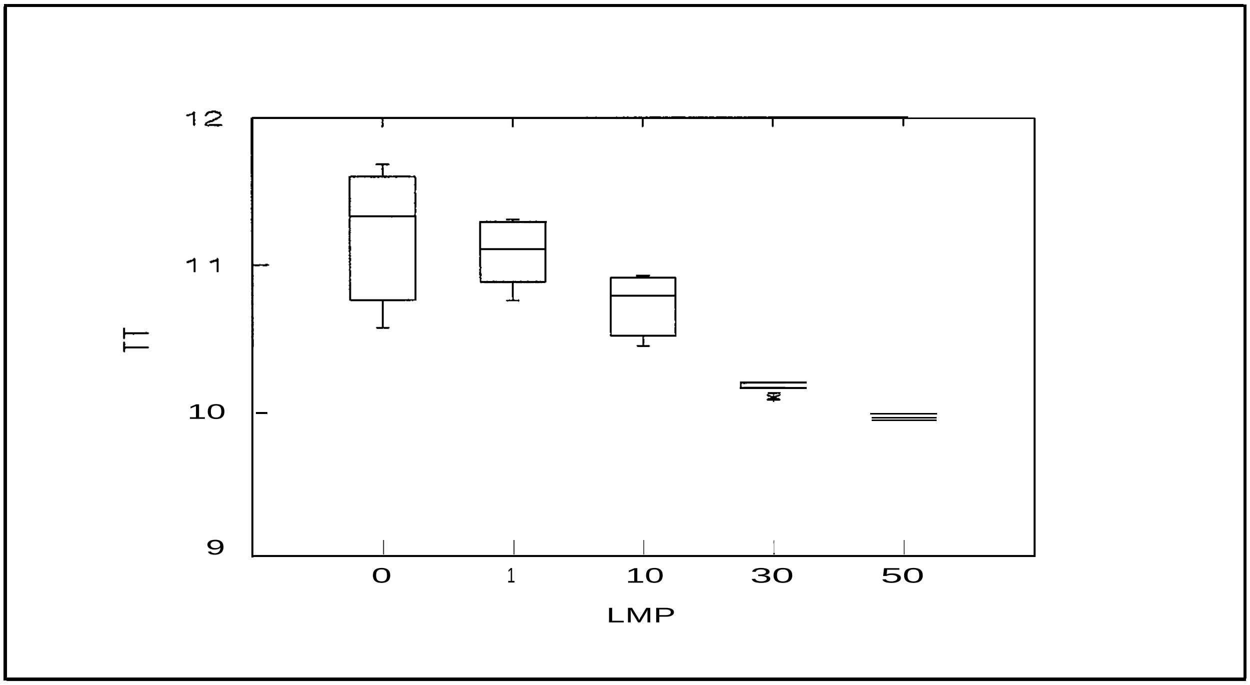

Figure 60: Impact of seed on trip travel time at each LMP

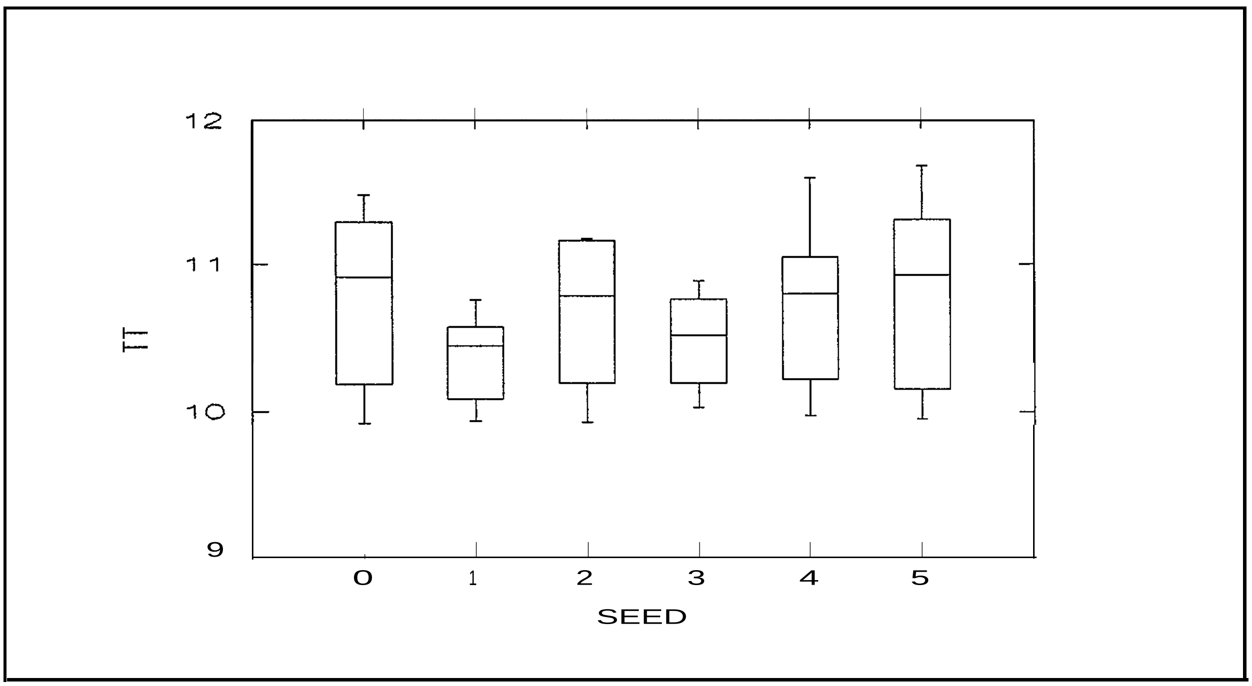

Figure 61: Impact of LMP on trip travel time for each seed

Table 21: ANOVA results of seed and LMP effects

	Sum of Squares (SS)			Relative SS		Probability	
	seed	LMP	error	seed	LMP	seed	LMP
Trip time	0.76	7.30	0.77	9%	83%	0.011	0.000
Trip distance	0.02	0.37	0.01	4%	93%	0.005	0.000
Stops	0.52	6.20	0.42	7%	87%	0.004	0.000
Wrong turns	0.00	0.09	0.00	0%	100%	0.033	0.000
Fuel	0.00	0.09	0.00	4%	92%	0.004	0.000
HC	1.42	20.98	1.11	6%	89%	0.004	0.000
CO	0.95	47.21	5.45	2%	88%	0.631	0.000
NO	0.16	0.45	0.17	21%	57%	0.012	0.000
Accident risk	0.04	0.06	0.03	28%	45%	0.009	0.000

Table 22: Summary results (21 observations)

	TT	Dist	Stops	Wrgturn	Fuel	HC	CO	NO	Accident
Minimum	10.40	10.64	4.381	0.703	1.614	16.95	59.19	11.05	10.25
Maximum	10.99	10.75	5.071	0.74	1.67	18.1	61.12	11.35	10.45
Average	10.65	10.69	4.693	0.717	1.639	17.43	60.10	11.21	10.36
Std Dev.	0.180	0.031	0.19	0.008	0.014	0.335	0.512	0.095	0.058
Skew	0.535	0.035	0.455	1.051	0.489	0.500	0.467	-0.380	-0.110
COV	1.7%	0.3%	4.0%	1.1%	0.9%	1.9%	0.9%	0.8%	0.6%

SUMMARY AND CONCLUSIONS

It was found that the level of market penetration had a significant impact on the network measures of performance. The major findings can be summarized as follows:

- The TravTek system was most effective at reducing those MOP's that are specifically targeted by the routing algorithm, namely travel time, stops and wrong turns. However, with the exception of the emissions of NOx at LMP's less than 100 percent, all MOP's were reduced as well, albeit often to a much smaller extent.
- For LMP's as high as 100 percent, no deterioration in performance was observed, nor was there a reversal of those benefits obtained at lower levels of market penetration.
- There is significant benefit to analyzing the performance of each driver subpopulation by itself, in addition to the performance of the combined population. The analysis of the individual subpopulations enabled better understanding of the mechanisms that may have created the observed aggregate benefits.
- The analysis of each driver subpopulation indicated that, for all LMP's, the marginal increase in LMP produces three benefits: first it improves the MOP's of the drivers who purchase the gadget; second, it improves the MOP's for the background traffic, and third it improves the MOP's for the system as a whole.
- The results also indicated that, for future studies, investigating the LMP effect at intervals of 20 percent would be sufficient to capture the overall trend.

- In terms of specific results the LMP was found to reduce the average trip duration, average trip length, number of vehicle stops, number of wrong turn maneuvers, level of fuel consumption, HC and CO emissions by up to 12, 5, 32, 37, 13, 16, and 7 percent, respectively.

- Emissions of CO were found to increase by no more than 3 percent for an LMP of 10 percent and decreased by up to 7 percent for LMP's beyond 10 percent.

- Emissions of NOx were found to increase by no more that 5 percent for all LMP's below 90 percent and were found to decrease by 1 percent for an LMP of 100 percent.

- At virtually all LMP's, during the PM peak, the equipped vehicles experienced an accident risk that was greater than that of background traffic, that benefited from the diversion of the equipped vehicles.

CHAPTER 6: EFFECT OF TRAFFIC DEMAND AND INCIDENTS ON NETWORK MEASURES OF PERFORMANCE

INTRODUCTION

In the previous chapter the potential impact of the different levels of market penetration (LMP) on the various network measures of performance (MOP's) was investigated. However, this impact is dependent on various assumptions, for example, the expected future level of congestion in the network, the likely existence of incidents, the expected level of error in the routing of background and guided TravTek vehicles, and the frequency of routing updates of guided vehicles. In this chapter the impact of the former two factors, namely: the impact of network congestion and incidents on the benefits of a route guidance system will be investigated. In addition, the impact of the latter two factors will be investigated in this chapter, however, a more detailed analysis is provided in appendix B.

The impacts of the total level of traffic demand on the network MOP's are investigated in the first section of this chapter. In this sensitivity analysis the total traffic demand is varied from 90 percent of the base PM demand to 110 percent of the base PM demand in 5-percent increments. For each total demand level the LMP was varied from 0 percent to 50 percent. Furthermore, in order to investigate the impact of traffic incidents on the potential benefits of a route guidance system (RGS) two potential incidents were also considered in the following section, namely: one along the eastbound direction of the I-4 freeway and another along the westbound direction of the I-4 freeway. The incident durations were also varied from 5 to 30 min in order to investigate the impact of incident duration on the network MOP's. In addition, this chapter examines the impact of the TravTek and background vehicle link travel time error on the network MOP's. The final section concludes the chapter with a summary of the main conclusions of the chapter.

EFFECT OF TRAFFIC DEMAND ON NETWORK MEASURES OF PERFORMANCE

The level of congestion that exists in a network prior to the application of TravTek, may be very important in determining the potential benefits of the system. For example, it has been argued, by some traffic engineers and researchers, that if the entire network is congested, an RGS will be of little benefit because it would only divert traffic from congested routes to other similarly congested routes. On the other hand, it is argued that during congested conditions, improvements of only a small relative percentage would represent very large absolute savings as this benefit would affect a very large number of vehicles.

This section investigates the impact of various levels of traffic demand for different LMP's. In doing so a total of 30 runs were conducted as indicated in table 23. A detailed illustration of the input files is presented in appendix A. These runs, as demonstrated in table 23, investigated the impact of varying the total traffic demand from 90 percent to 110 percent the base demand for LMP's ranging from 0 percent to 50 percent.

Table 23: Run coding scheme for traffic demand sensitivity analysis (background link travel time error=5 percent, guided link travel time error=5 percent)

Demand	Level of Market Penetration (LMP)				
	0%	1%	10%	30%	50%
90%	46	47	48	49	50
95%	51	52	53	54	55
100%	6	7	8	9	10
105%	56	57	58	59	60
110%	61	62	63	64	65

Average Trip Time

Figure 62 illustrates the variation in the overall average trip duration (z-axis) as a function of the LMP (x-axis) and the relative demand (y-axis). The z-axis represents the relative trip duration relative to the base case (run 6) at an LMP of 0 percent and a relative demand of 100 percent. It appears from the figure that the average trip time for an LMP of 0 percent increased by approximately 1.5 percent per 1 percent growth in traffic demand for traffic demands ranging from 90 percent and 110 percent of the base demand. For each LMP greater than 0 percent the average trip duration also increased as the relative demand increased, but such increases were at a more gradual rate.

It can also be noted that at a relative demand of 90 percent the average trip duration as a function of the LMP decreased from the 87 percent to 84 percent, while at a relative demand of 110 percent the average trip duration decreased from 115 percent to 97 percent or by about 18 percent. This trend was found to be consistent over all demand levels as the average trip time following the introduction of 50 percent TravTek vehicles decreased by 3, 7, 14, 15, and 18 percent for relative demands of 90, 95, 100, 105, and 110 percent, respectively. Noteworthy is the fact that for a demand of 110 percent of the base demand a rapid reduction in average travel time occurred for an LMP up to 30 percent, while at an LMP of 50 percent the average travel time did not experience any significant reduction in the average trip duration relative to an LMP of 30 percent.

It is also interesting to note from figure 62 that the traffic conditions for a lo-percent increase in demand at an LMP of 30 percent is superior to the base case with no guided vehicles.

Based on this limited initial sensitivity analysis it can be concluded that as the traffic demand increases there appears to be a greater benefit to providing drivers with a TravTek type system. However, at higher TravTek system is expected to provide most of its benefits at lower LMP's of say less than 30 percent. It is important to note that at higher demand levels the provision of an RGS can provide benefits that offset the dis-benefits of significantly increasing the demand.

Average Trip Length

Figure 63 illustrates the variation in the overall average trip length (z-axis) as a function of the LMP (x-axis) and the relative demand (y-axis). The z-axis represents the relative trip length relative to the average trip length for a base case (run 6) at a LMP of 0 percent and a relative demand of 100 percent. It appears from figure 63 that the average trip length remained relatively constant as the demand decreased down to 90 percent of the base. However, the average trip length increased by 1 percent for each 5-percent increase in total traffic demand above the base case value. This pattern suggests that for the lower demands the user equilibrium routing for the background traffic did not change as the traffic demand was reduced. However, the background vehicles were routed along longer routes for the higher traffic demands. Noteworthy, is the fact that the background routing remained constant throughout the entire simulation run, however, the optimum routes for the background traffic could differ from one simulation run to another depending on the simulated traffic conditions.

The increase in average trip length, as a function of the relative demand, appears to be consistent for all LMP's. The decrease in average trip length as a function of LMP also appears to be consistent for all relative demands. However, for lower relative demands the average trip length decreases equally over all LMP's, whereas at lower LMP's the average trip length decreases at a larger rate for higher relative demands. It must be noted that the above decreases in average trip length were relatively minor compared to the decrease in the average trip duration (3 percent versus 18 percent) for the same scenarios.

Average Number of Vehicle Stops

Figure 64 illustrates the variation in the overall average number of vehicle stops (z-axis) as a function of the LMP (x-axis) and the relative demand (y-axis). The z-axis represents the number of stops relative to the base case (run 6) at an LMP of 0 percent and a relative demand of 1 .O. It appears from the figure that the average number of vehicle stops decreased/increased by approximately 30 percent, relative to the base number of vehicle stops, for an increase/decrease in demand when all vehicles were background vehicles. For each LMP the average number of vehicle stops also decreased as the relative demand decreased, but at a much slower rate.

The reduction in the average number of vehicle stops, as a function of the LMP, was highest for the base demand scenario where a reduction of 24 percent was experienced for an LMP of 50 percent. This reduction in the average number of vehicle stops as a function of the LMP, however, was less significant at higher and lower demands.

In conclusion, based on the above limited sensitivity analysis it can be concluded that there appears to be benefit in equipping drivers with an RGS at all demand levels and LMP's.

Average Fuel Consumption

Figure 65 illustrates the variation in the overall average fuel consumption (z-axis) as a function of the LMP (x-axis) and the relative demand (y-axis). The z-axis represents the fuel consumption relative to the base case (run 6) at an LMP of 0 percent and a relative demand of 1 .O. It appears that the average fuel consumption decreased by approximately 0.6 percent relative to the base fuel consumption for every l-percent decrease in traffic demand.

The reduction in fuel consumption as a function of the LMP was highest for relative demands of 0.95, 1 .OO, and 1.05, where a total reduction of 8 percent was measured for an LMP of 50 percent. This reduction in average fuel consumption as a function of LMP, however, was less at both higher and lower demands.

In conclusion, based on the above limited sensitivity analysis it can be concluded that there appears to be benefit, in terms of reducing average fuel consumption, in equipping drivers with a

TravTek type system for both low and high traffic demands. Also, it was found that if the traffic demand increased by 10 percent, an LMP of 30 percent would be sufficient to attain an average fuel consumption rate consistent with the base traffic demand case.

Average HC Emissions

Figure 66 illustrates the variation in the overall average HC emissions (z-axis) as a function of the LMP (x-axis) and the relative demand (y-axis). The z-axis represents the HC emissions relative to the base case (run 6) at an LMP of 0 percent and a relative demand of 1 .O. It appears that at an LMP of 0 percent the average HC emissions increases by approximately 1 .O percent relative to the base HC emissions for every l-percent increase in demand.

The reduction in HC emissions as a function of the LMP was 12 percent for relative demands of 0.95, 1 .00, and 1.05 at an LMP of 50 percent. This reduction in average HC emissions as a function of LMP, however, was less pronounced at higher and lower demands (relative demands of 1.10 and 0.90) at an LMP of 50 percent. Specifically, the variation in average HC emissions as a function of the LMP was approximately 7 percent for a relative demand of 1.10 and 4 percent for a relative demand of 0.90 at an LMP of 50 percent. However, as these fuel consumption estimates are averages, the absolute fuel consumption reduction would be larger for high demands versus low demands as the denominator in the case of high demands would be greater.

In conclusion, based on this limited sensitivity analysis it can be concluded that there appears to be a large benefit, in terms of reducing average HC emissions, in equipping drivers with a TravTek type system for all traffic demand levels.

Average CO Emissions

Figure 67 illustrates the variation in the overall average CO emissions (z-axis) as a function of the LMP (x-axis) and the relative demand (y-axis). The z-axis represents the CO emissions relative to the base case (run 6) at an LMP of 0 percent and a relative demand of 1 .O. It appears from figure 67 that the average CO emissions experience a much more complex pattern due to the fact that the CO response surface is much more complex as was illustrated in chapter 3.

It can be noted that the average CO emissions are consistently reduced as the LMP increases for relative demands of 0.90 and 0.95. However, this situation is not the case for relative demands of 1 .00, 1.05, and 1.10. For the latter higher demands the CO emissions appear to peak briefly at an LMP of 10 percent and then decrease as the LMP increases.

In summary, it appears that for higher levels of congestion the provision of an RGS may slightly increase the average CO emissions by about 3 percent. However the impact of the LMP on CO emissions is not consistent for all traffic levels.

Average NOx Emissions

Figure 68 illustrates the variation in the overall average CO emissions (z-axis) as a function of the LMP (y-axis) and the relative demand (x-axis). It should be noted that the figure was rotated in order to view the lower valley at higher demand levels and lower LMP’s. The z-axis represents the NOx emissions relative to the base case (run 56) at an LMP of 0 percent and a relative demand of 1 .O. It appears from figure 68, as in the case of CO emissions, that the average NOx emissions experience a complex variation.

Specifically, figure 68 demonstrates that as the level of demand increases the NOx emissions decrease. This trend results from the fact that as the level of demand increases, the average speed decreases, and thus NOx emissions decrease, as was demonstrated in chapter 3. Furthermore, at higher levels of demand, NOx emissions increase for higher LMP's as a result of improvements in traffic conditions. However, for lower levels of demand, increasing the LMP does not increase the NOx emissions, as traffic speeds were already quite high.

Average Accident Risk

Figure 69 illustrates the variation in the overall average accident risk (z-axis) as a function of the LMP (x-axis) and the relative demand (y-axis). The z-axis represents the accident risk relative to the base case (run 6) at an LMP of 0 percent and a relative demand of 1.0. It appears from figure 69 that at an LMP of 0 percent the average accident risk increased by approximately 0.5 to 1.0 percent for every l-percent increase in demand relative to the base accident risk.

The impact on accident risk as a function of the LMP was minor at all demand levels. In addition, for all relative demands the accident risk at a 50-percent LMP was less than that for a O-percent LMP, except for a relative demand of 1.10. In the latter case, the accident risk at a 50-percent LMP was 1 percent higher than that for O-percent LMP. This small increase in accident risk as a function of LMP is expected to have arisen from diverting vehicles from lower risk congested freeways to higher risk arterials. Although, the net accident risk on an arterial is approximately 250 percent that on a freeway, the overall accident risk only increased by 1 percent.

In order to further investigate this increase in accident risk, for higher LMP's during high demand conditions, figure 70 was generated. Figure 70 illustrates how the accident risk for the background and TravTek equipped vehicles varied as a function of the LMP for relative demands equal to 40 percent, 80 percent and 110 percent of the base demand. It is evident from this figure that for a traffic demand of 40 percent and 80 percent of the base demand, the accident risk for the background vehicles is higher than that for the RGS equipped vehicles. The lower TravTek accident risk is a result of the relatively low level of congestion along the arterial routes, where the less congested arterial routes provided low risk alternate routes for the equipped vehicles. However, when the traffic demand was increased to 110 percent the base demand, more of the alternate arterial routes became higher risk routes as a result of the consequent congestion. Figure 70 demonstrates how the accident risk for the equipped vehicles was initially higher by 9 percent than that for the background traffic for LMP's less than 10 percent and for higher relative demands. However, as the LMP increased, more of the TravTek equipped vehicles could remain on the freeway links, thus reducing the total accident risk of the equipped vehicles to within 1 percent of that of the background vehicles. Noteworthy is also the slight increase in the accident risk of the background traffic at higher LMP' s for a relative demand of 110 percent of the base demand. This effect most probably occured because a small percentage of the background traffic was routed along the arterial routes, and by diverting the equipped vehicles to these routes the background accident risk increased slightly (less than 1 percent).

Based on the above limited sensitivity analysis it can be concluded that a TravTek type system can either increase or decrease the overall accident risk depending upon the level of congestion and type of facility of the alternate routes. However, in either case the range of potential impact remains rather small (1 percent to 6 percent). For example if, on the one hand, the available alternate routes are congested and of a lower facility class, then re-routing TravTek vehicles to these facilities would not only increase their own accident risk but also increase the overall accident risk. If, on the other hand, the alternate routes are uncongested lower facility class or less congested equal facility routes, then re-routing traffic to these routes would not only decrease their accident risk but also decrease the accident risk along their initial routes and thus decrease the overall accident risk.

Summary and Conclusions

Based on the sensitivity analysis presented in this section, the following conclusions can be drawn:

- There appears to be a greater benefit in terms of reducing the average trip duration in providing the drivers with an RGS as the traffic demand increases. However, the RGS system produces most of its incremental benefits for higher demands at lower LMP's (less than 30 percent), as higher LMP' s will usually not result in any further diversion of traffic. It was also found that, if by introducing an RGS the improved traffic conditions induce a lo-percent increase in traffic demand, an LMP of 30 percent would be sufficient to reduce the average trip duration to a level consistent with the initial demand at a 0-percent LMP.
- There appears to be a consistent and constant amount of reduction in the number of vehicle stops by equipping drivers with an RGS for both low and high traffic demands. This reduction is in the range of 5 percent for every 10-percent increase in LMP up to 50 percent.
- There appears to be a consistent benefit, in terms of reducing average fuel consumption, in equipping drivers with an RGS for both low and high traffic demands. This reduction in fuel consumption is in the range of 1.5 percent for each 10-percent increase in LMP up to 50 percent. It was also found that, if by introducing an RGS the improved traffic conditions induce a 10-percent increase traffic demand, an LMP of 30 percent would be sufficient to reduce the average fuel consumption rate back to a value consistent with the initial no route guidance base case.
- There appears to be a larger benefit, in terms of reducing average HC emissions, in equipping drivers with an RGS for higher versus lower traffic demands. The reduction in HC emissions is in the range of 1 percent for every 10-percent increase in LMP up to 50 percent.
- It appears that for higher levels of demand the provision of an RGS can increase the average CO emissions. In addition, as the LMP increases the CO emissions can increase by a further amount for these more highly congested conditions. The increase in CO emissions for higher levels of demand is in the range of 0.4 percent for every 10-percent increase in LMP up to 50 percent.
- At higher levels of demand the NOx emissions increase as the LMP increases as a result of improving the traffic conditions. However, for lower levels of congestion, increasing the LMP does not change the NOx emissions as traffic conditions are initially quite good. The

increase in NOx emissions for higher levels of demand is in the range of 1 percent for every lo-percent increase in LMP up to 50 percent.

- An RGS system, such as TravTek, can increase or decrease the overall accident risk depending upon the level of congestion and the class of facility of the current and alternate routes. This safety impact is rather minor in the range of 0.2 percent for every lo-percent increase in the LMP up to 50 percent. The increased risk is directly tied to the fact that equipped vehicles will divert to lower class facilities, to avoid congestion and to minimize trip travel time.

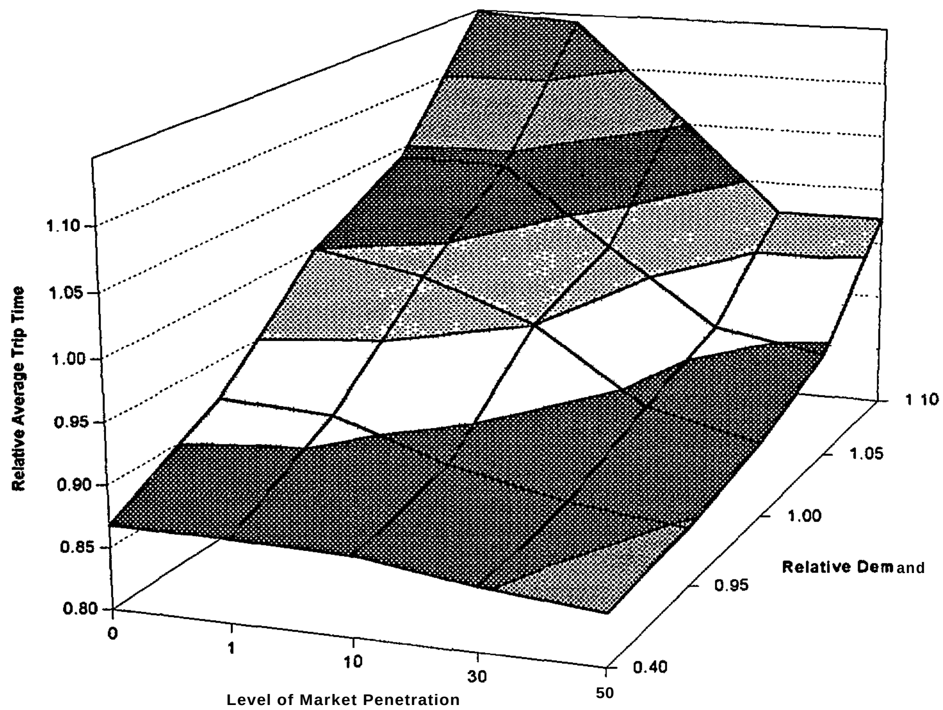

Figure 62: Impact of level of market penetration and demand level on the average trip travel time

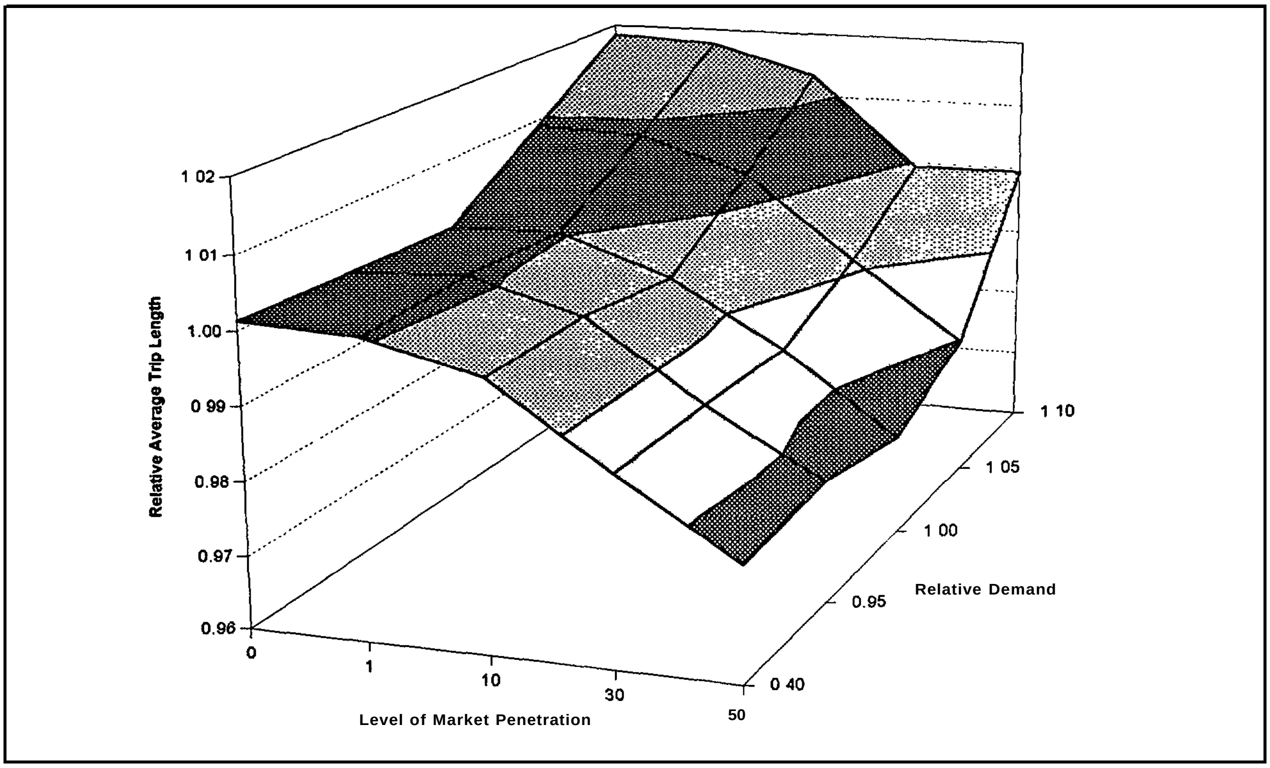

Figure 63: Impact of level of market penetration and demand level on the average trip length

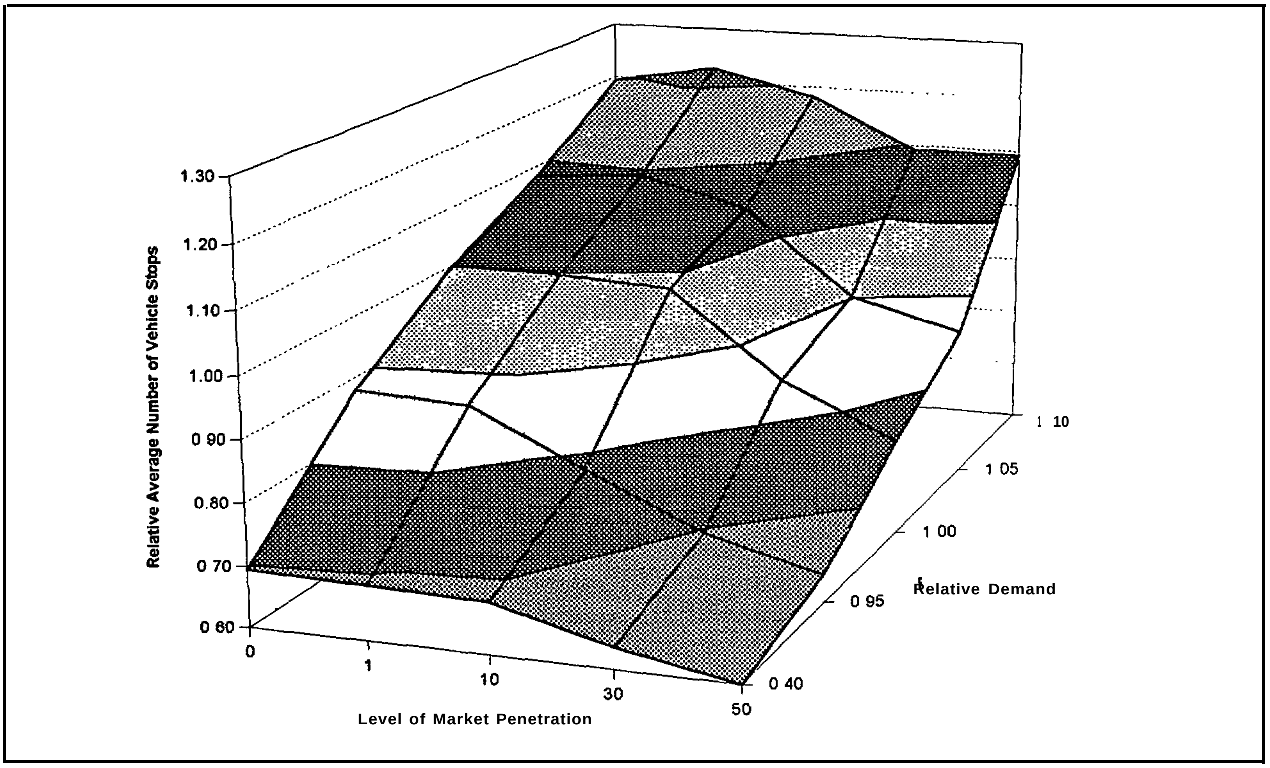

Figure 64: Impact of level of market penetration and demand level on the average number of trip stops

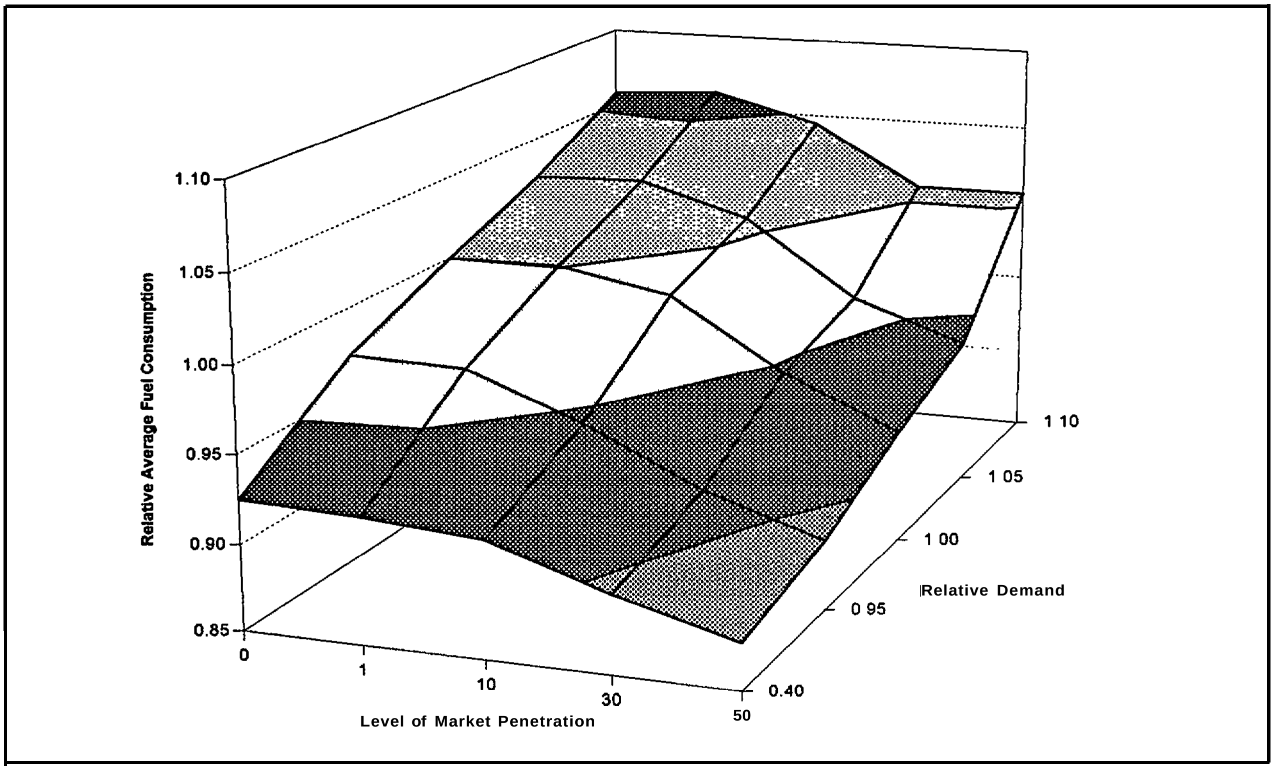

Figure 65: Impact of level of market penetration and demand level on the average fuel consumption

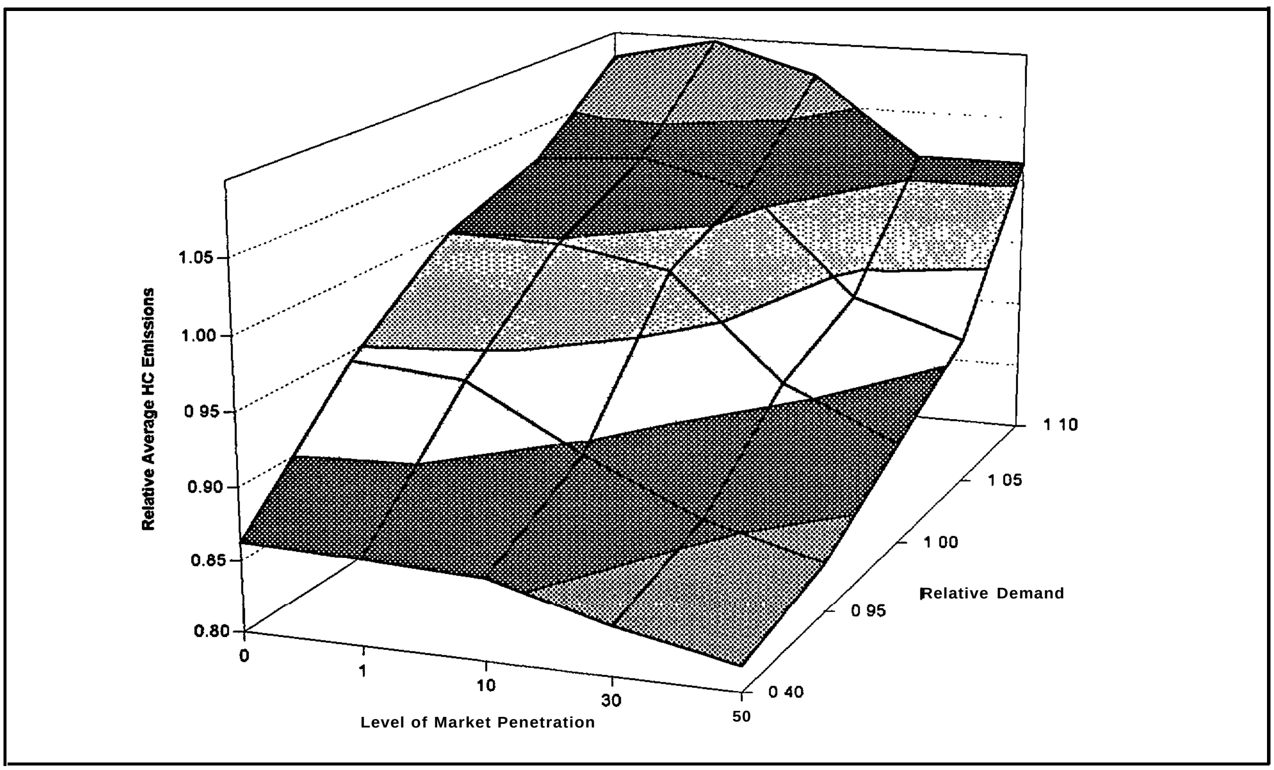

Figure 66: Impact of level of market penetration and demand level on the average HC emissions

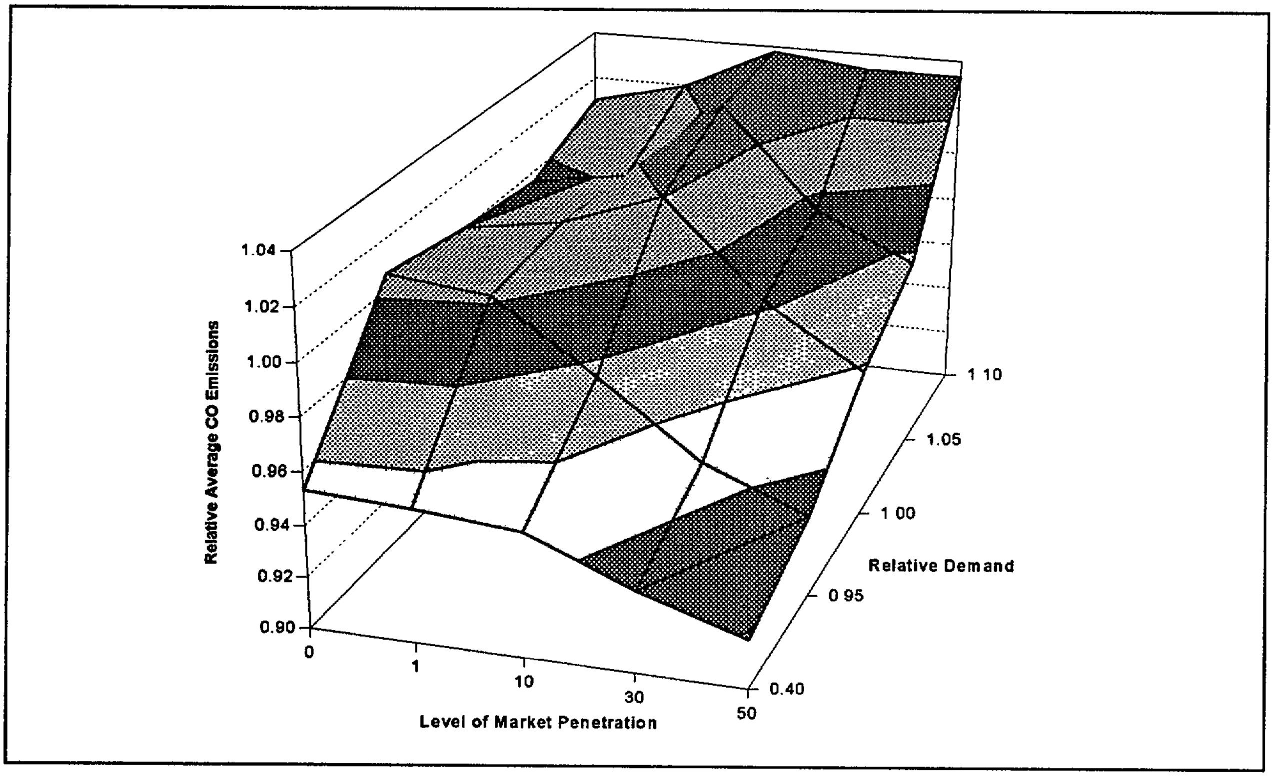

Figure 67: Impact of level of market penetration and demand level on the average CO emissions

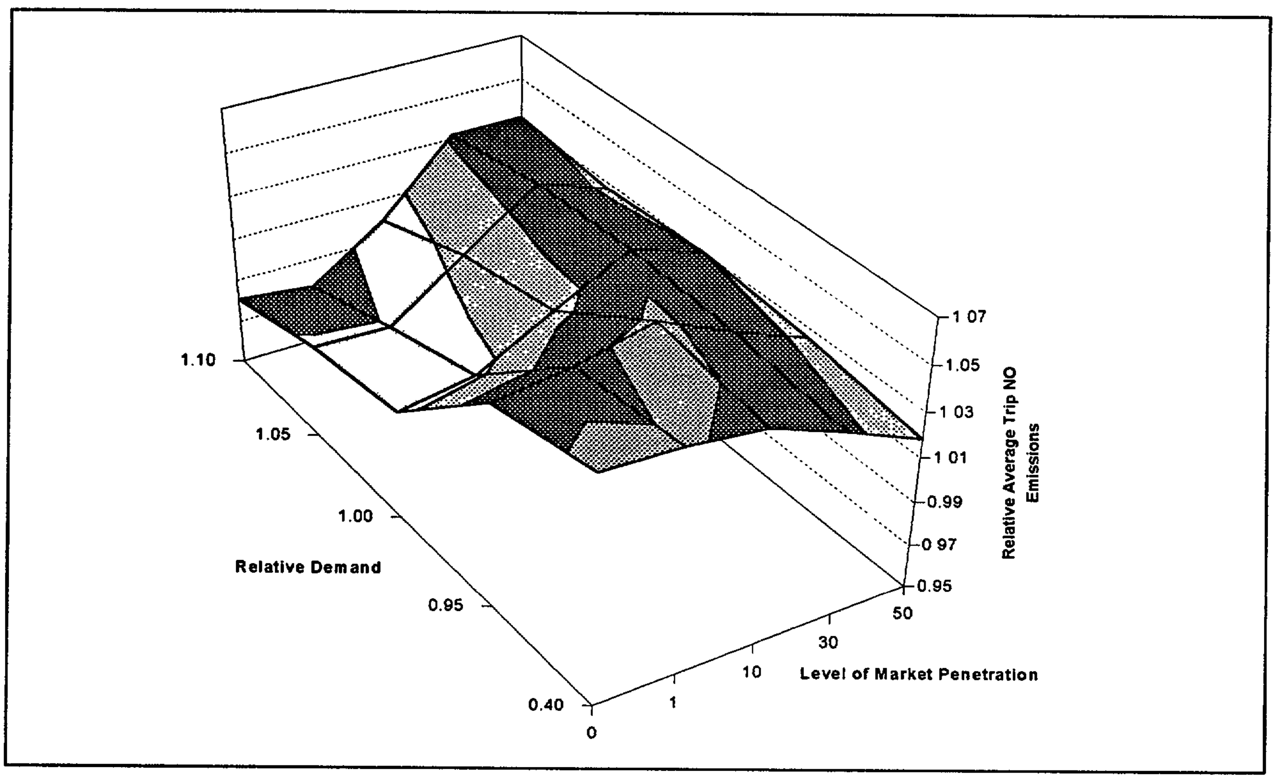

Figure 68: Impact of level of market penetration and demand level on the average NO_x emissions

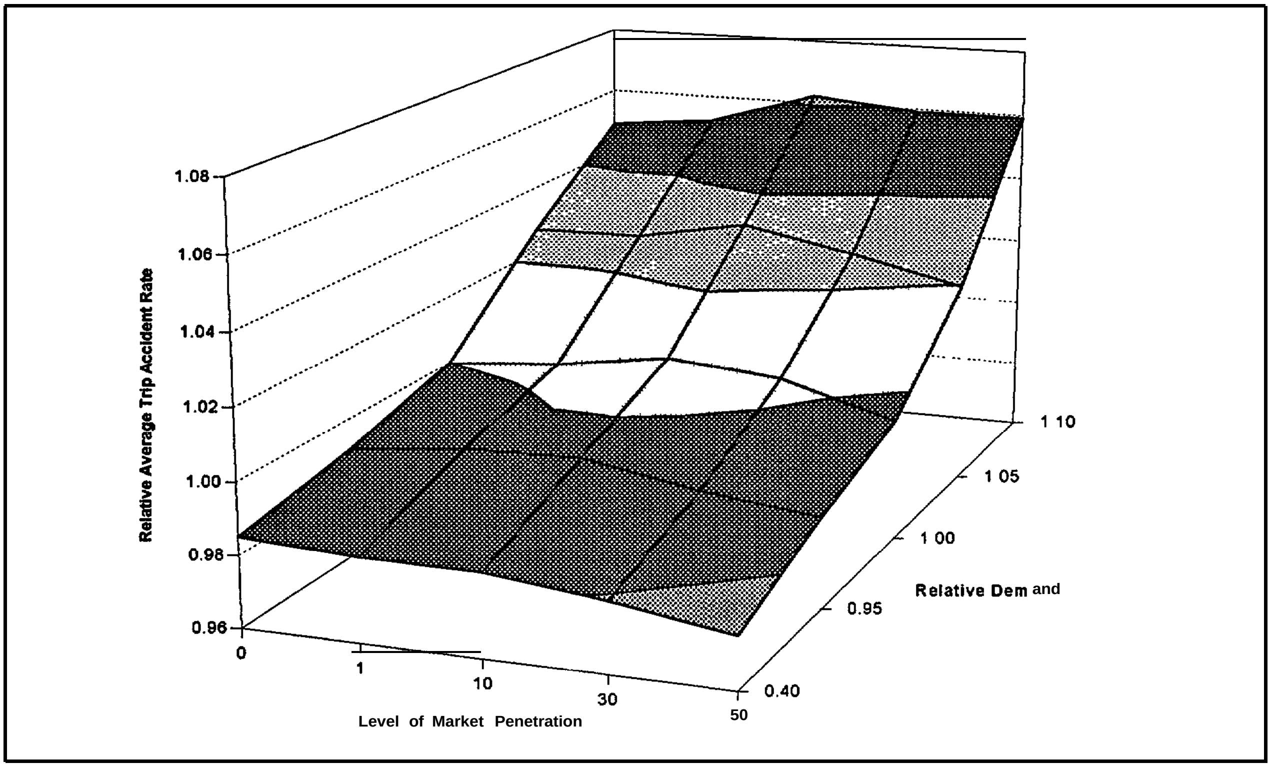

Figure 69: Impact of level of market penetration and demand level on the average accident risk

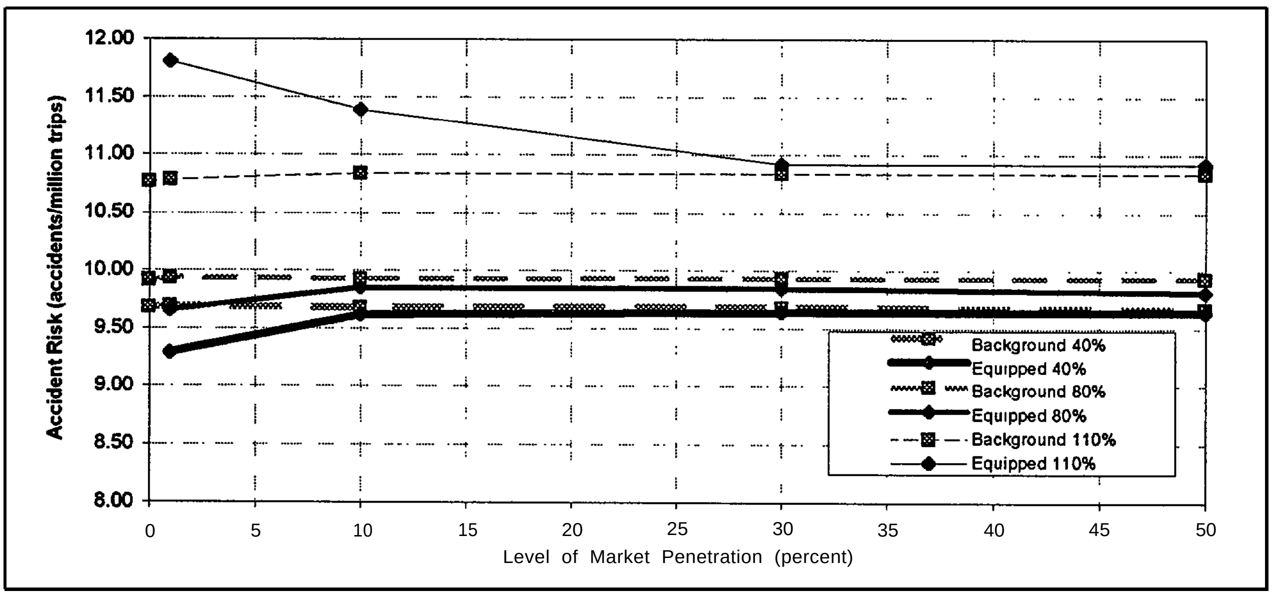

Figure 70: Impact of level of market penetration and demand level on relative vehicle type accident risk

IMPACT OF INCIDENTS ON NETWORK MEASURES OF PERFORMANCE

Another important question that often needs to be addressed by RGS evaluators is to determine what the impact of traffic incidents would be on the overall performance of an RGS. Essentially it needs to be determined if incidents provide an increased or decreased window of opportunity to capture the benefits of an RGS. This section will attempt to address these questions by evaluating two sample incidents along the I-4 freeway. In addition, the duration of the incidents was varied in order to establish a relationship between the incident duration and the potential benefits of an RGS.

A total of eight incident scenarios, one incident for each direction, were examined in which the incident duration varied from 5 to 10, 20, and 30 min as indicated in table 24. For each of these incident durations the incident was located on the I-4 freeway in the downtown area of Orlando. The LMP of TravTek vehicles was initially held constant at 10 percent using the standard base traffic demand level. In addition, the link travel time error for both the background and TravTek equipped vehicles was set at 5 percent.

Table 24: Incident severity sensitivity analysis (background link travel time error=5 percent, guided link travel time error=5 percent)

	Incident duration (min)				
	0	5	10	20	30
Eastbound	8	71	72	73	74
Westbound	8	75	76	78	79

Effect of Eastbound Incident

The eastbound direction experienced congestion (considered as speeds less than speed-at-capacity) between stations 4 and 17. The incident, which was located at station 13, therefore occurred on a congested portion of the freeway. Figure 71 illustrates how each of the network MOP's varied as a function of the incident durations. As illustrated in this figure, the 30-min incident duration resulted in a 14-percent increase in the average trip time, a O-percent change in the average trip length, a 2-percent increase in the average number of vehicle stops, a 2-percent increase in the average fuel consumption, a 4-percent increase in HC emissions, a 4-percent reduction in CO emissions, a 3-percent reduction in NOx emissions, and a l-percent reduction in the accident risk, relative to the base non-incident scenario. The relatively minor increase in the network MOP's is primarily a result of averaging the MOP's over all the 62,899 vehicles in the network rather than quoting an estimate for only the eastbound direction of I-4. These results also appear to be consistent with the findings of the previous section. Specifically, all MOP's increase as the level of traffic congestion increases except for CO and NOx emissions and accident risk.

Figure 72 illustrates the effect of the eastbound incident on the background traffic MOP's only for the various incident durations. All results are estimated relative to the base non-incident background traffic conditions. The results appear to be very similar to the overall total fleet results presented earlier. Specifically, the 30-min incident resulted in a 14-percent increase in the average trip duration, a O-percent increase in the average trip length, a 3-percent increase in the average number of vehicle stops, a 2-percent increase in the average fuel consumption, a 4-percent increase in the average HC emissions, a 4-percent decrease in CO emissions, a 3-percent decrease in the NO_x emissions, and a 0-percent decrease in the accident risk, relative to the base non-incident scenario (run 8). The constant level of background traffic accident risk likely resulted because the incident occurred on an already congested freeway.

Figure 73 illustrates the variation in TravTek equipped vehicle MOP's as a function of the eastbound incident duration. The results in the figure are relative to the base, non-incident, but equipped vehicle MOP's (run 8). They are, therefore, plotted on a different scale than that of figure 72. The MOP's for TravTek equipped vehicles were always better than those for background vehicles except for the accident risk measure. However, this effect cannot be recognized from comparing figures 72 and 73, as both figures are plotted on different scales. Figure 73 demonstrates that apart from the average trip duration, the 30-min duration incident did not result in MOP's greater than the non-incident MOP's. This reduction in most MOP's resulted from re-routing of equipped vehicles from the I-4 freeway to alternative routes. Because these alternative routes involved driving along lower class roads (arterials versus freeways), the accident risk of equipped vehicles was approximately 6 percent higher than that for non-equipped vehicles.

The results also indicated that, for the eastbound incident scenarios, the equipped vehicles experienced on average a 12-percent reduction in average trip duration, a 4-percent reduction in average trip length, an 18-percent reduction in vehicle stops, a 10-percent reduction in fuel consumption, a 10-percent reduction in HC emissions, a 4-percent reduction in CO emissions, a 3-percent reduction in NO_x emissions and a 6-percent increase in accident risk relative to non-equipped vehicles.

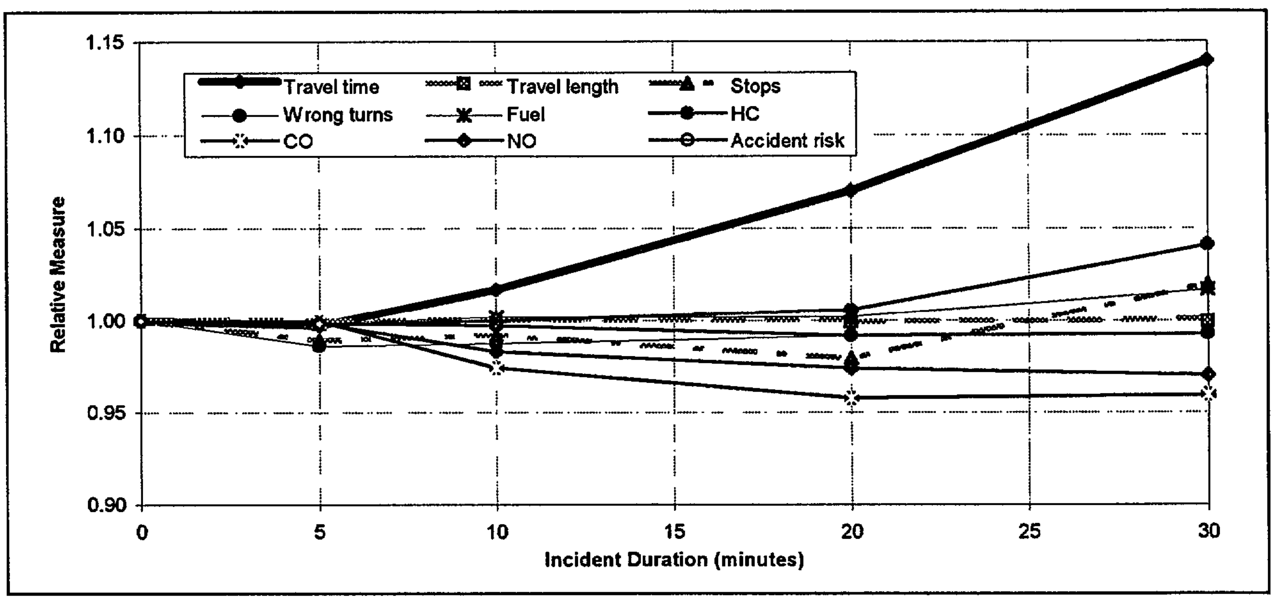

Figure 71: Impact of eastbound incident duration on network MOP's for all vehicles

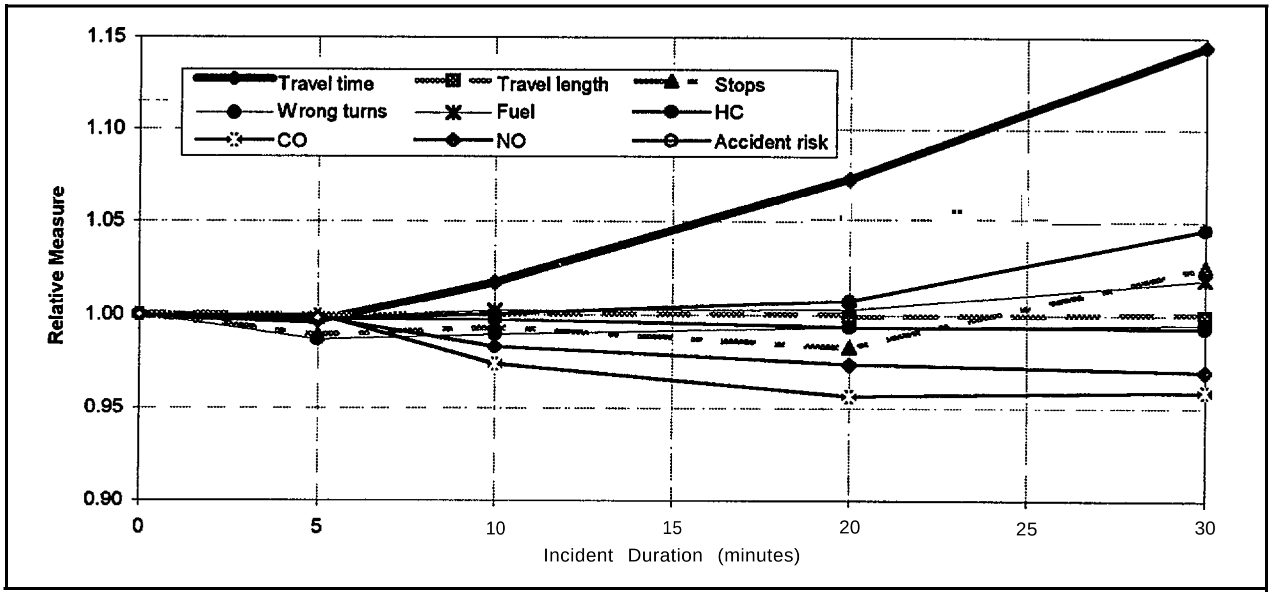

Figure 72: Impact of eastbound incident duration on background vehicle MOP's only

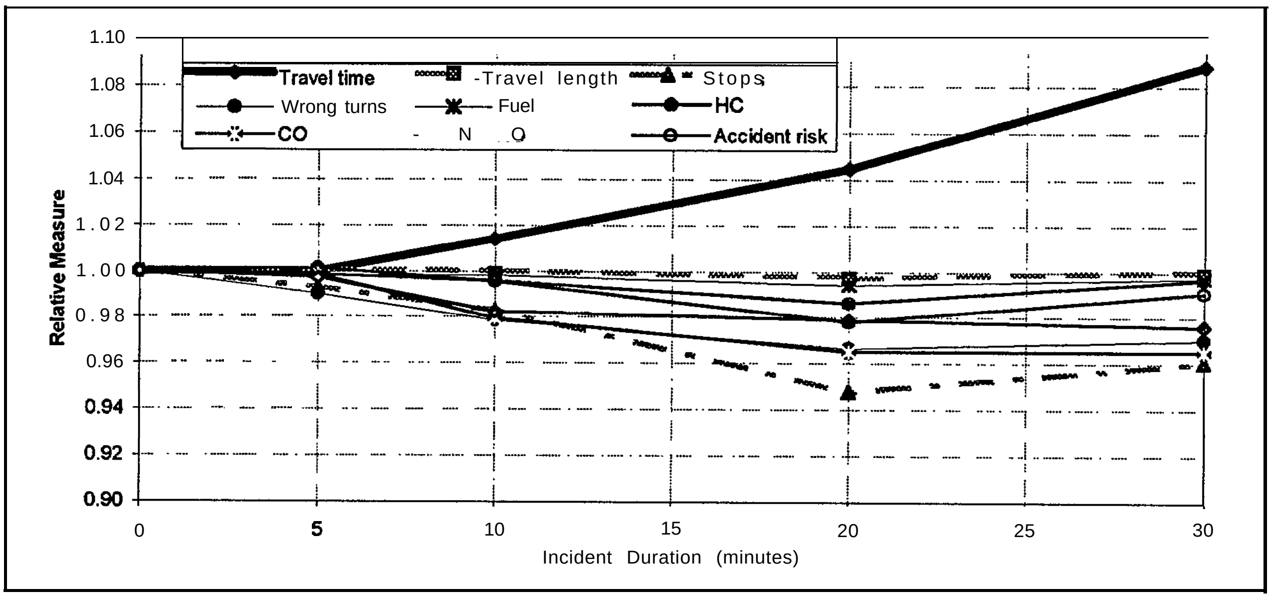

Figure 73: Impact of eastbound incident duration on TravTek vehicle MOP's

Effect of Westbound Incident

The westbound direction, unlike the eastbound direction, did not experience significant congestion along the entire freeway section during the PM peak. Thus, the incident at station 13, occurred on an initially non-congested portion of the freeway. Figure 74 illustrates how the network MOP's varied as a function of the incident duration. As illustrated in this figure, the 30-min incident resulted in an 1 l-percent increase in the average trip time, a O-percent increase in the average trip length, a 1 O-percent increase in the average number of vehicle stops, a 4-percent increase in the average fuel consumption, a g-percent increase in HC emissions, a l-percent increase in CO emissions, a 2-percent reduction in NOx emissions, and a l-percent increase in the accident risk, relative to the base non-incident scenario.

Figure 75 illustrates the effect of the westbound incident on the background traffic MOP's for the various incident durations. All of these results are estimated relative to the base non-incident background traffic conditions. The results appear to be very similar to the overall results presented earlier. The 30-rnin incident resulted in an 11-percent increase in the average trip duration, a 0-percent increase in the average trip length, an 11-percent increase in the average number of vehicle stops, a 4-percent increase in the average fuel consumption, a g-percent increase in the average HC emissions, a 1 -percent increase in CO emissions, a 1 -percent decrease in the NOx emissions, and a l-percent increase in the accident risk, relative to the base non-incident scenario (run 8). In this incident scenario, unlike the eastbound incident scenario, the accident risk of the background vehicles increased as the freeway was initially uncongested.

Figure 76 illustrates the variation in TravTek equipped vehicle MOP's as a function of the westbound incident duration. The results presented in the figure are relative to the base, non-incident, equipped vehicle MOP's (run 8) and, as in the eastbound case, are plotted on a different scale than that of figure 75. The MOP's for TravTek equipped vehicles were always better than those of the background vehicles, except for the accident risk which was approximately 13 percent higher. Figure 76 demonstrates that, apart from the average NOx emissions, the 30-min duration incident resulted in MOP's greater than the non-incident MOP's. This increase in all but one MOP resulted from the fact that, prior to introducing the incident, the westbound direction of I-4 was not congested.

The results, for the westbound incident scenarios also indicated, that the equipped vehicles experienced on average an 11 -percent reduction in average trip duration, a 3-percent reduction in average trip length, a 4-percent reduction in vehicle stops, a 10-percent reduction in fuel consumption, a 12-percent reduction in HC emissions, a 5-percent reduction in CO emissions, a 5-percent reduction in NOx emissions, but a 13-percent increase in accident risk over non-equipped vehicles. The increase in accident risk (13 percent) and the corresponding reduction in average trip length (3 percent) resulted because equipped vehicles were diverted from the congested, shorter and lower risk freeway to longer and higher risk arterial roads, but made fewer wrong turns along their trip.

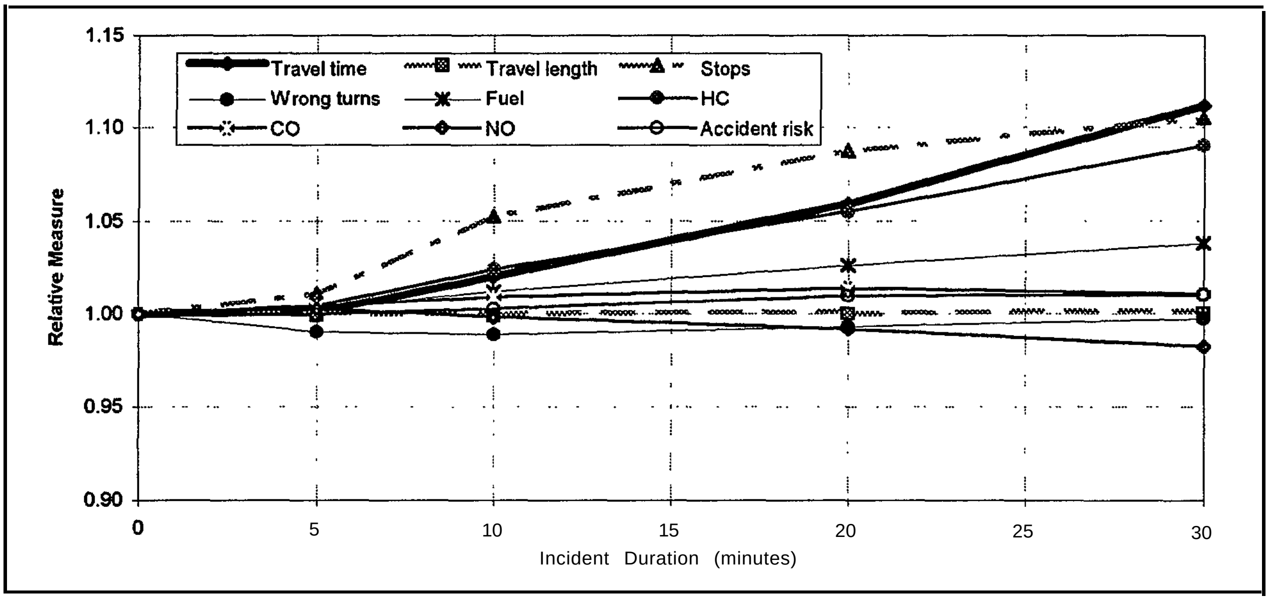

Figure 74: Impact of westbound incident duration on network MOP's

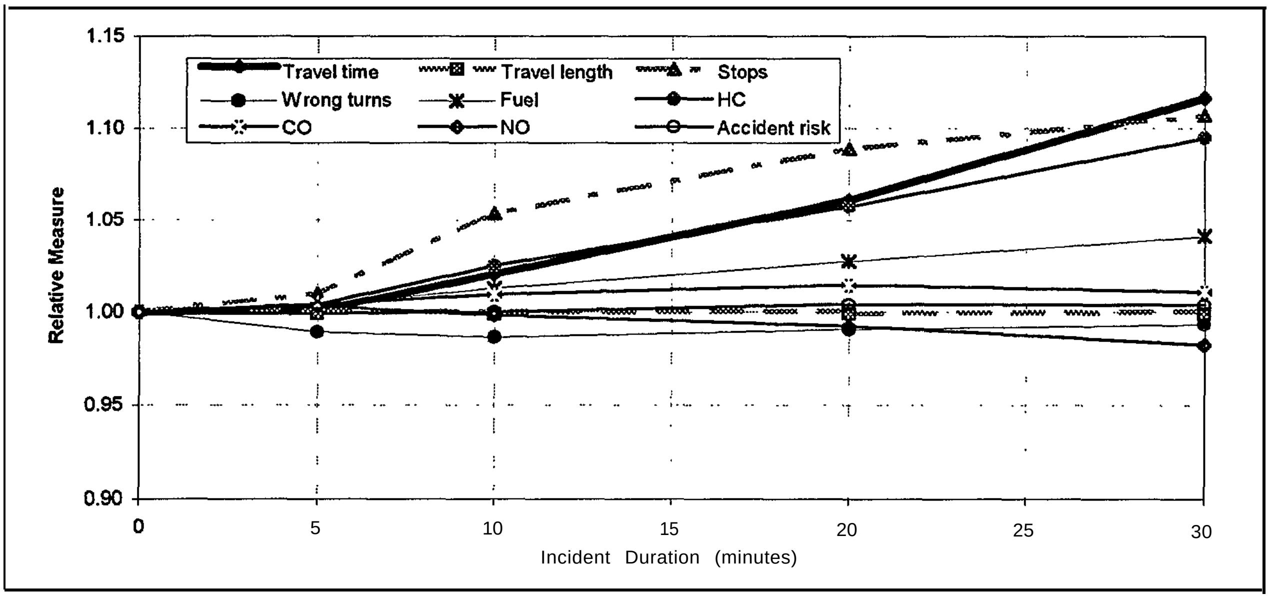

Figure 75: Impact of westbound incident duration on background vehicle MOP's

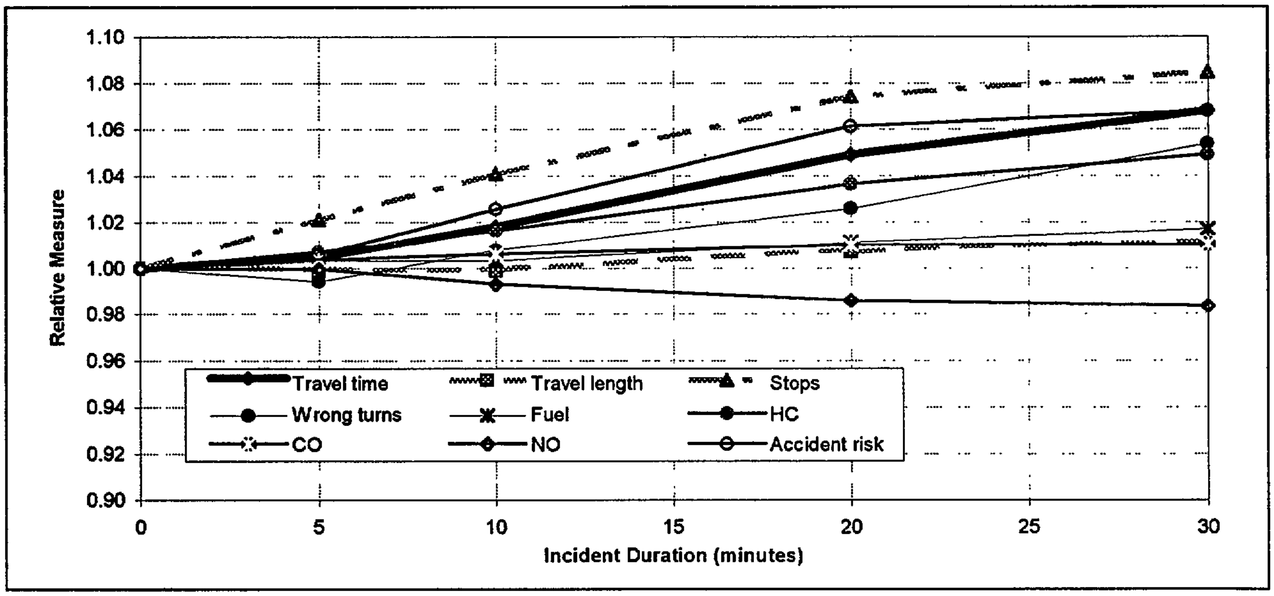

Figure 76: Impact of westbound incident duration on guided vehicle MOP's

Summary

In this section two incident scenarios were investigated in some detail. In the first scenario the freeway was congested prior to the time when the incident occurred while in the second scenario the freeway was uncongested prior to the time when the incident occurred. The results indicated the following:

- For the initially congested freeway, the MOP's of the equipped vehicles experienced on average a 12-percent reduction in average trip duration, a 4-percent reduction in average trip length, an 18-percent reduction in vehicle stops, a 10-percent reduction in fuel consumption, a 10-percent reduction in HC emissions, a 4-percent reduction in CO emissions, a 3-percent reduction in NO_x emissions and a 6-percent increase in accident risk over non-equipped vehicles.
- For the uncongested freeway the MOP's of the equipped vehicles experienced on average an 11-percent reduction in average trip duration, a 3-percent reduction in average trip length, a 4-percent reduction in vehicle stops, a 10-percent reduction in fuel consumption, a 12-percent reduction in HC emissions, a 5-percent reduction in CO emissions, a 5-percent reduction in NO_x emissions and a 13-percent increase in accident risk over non-equipped vehicles. The increase in accident risk of 13 percent and the corresponding reduction in average trip length of 3 percent resulted because equipped vehicles were usually diverted from the congested, shorter and lower risk freeway to the longer but higher risk arterial roads but made fewer wrong turns on their trip.

EFFECT OF LINK TRAVEL TIME ERROR AND ROUTING INTERVAL ON NETWORK MEASURES OF PERFORMANCE

The potential benefits of a Route Guidance System such as TravTek is dependent on the link travel time estimate efficiency of both the background (non-equipped) vehicles and TravTek equipped vehicles. Intuitively, if the initial background link travel time error is large, a wider window of opportunity should exist for an RGS to provide substantial benefits. Alternatively, if the initial background link travel time error is relatively small, only a rather narrow window of opportunity may exist for an RGS to provide substantial benefits. Unfortunately, the quantitative impact of different background and RGS link travel time errors is relatively unknown and, therefore, requires further investigation.

Another factor, that may impact the potential benefits of an RGS, is the interval frequency at which routing updates are made. It can be argued, on the one hand, that if routes are updated more frequently that the vehicles will be able to respond quickly to any re-routing decisions. On the other hand, it can be argued that in re-routing frequently one can respond in an excessive fashion and over react to stochastic fluctuations in demand rather than actual trends, therefore creating certain instabilities.

A limited sensitivity analysis was conducted in order to study the impacts of different link travel time errors for background and TravTek vehicles on the network MOP's. The link travel time error was modeled by introducing some white noise error to the link travel time estimates that were used in generating the minimum path trees. In addition the impact of routing update intervals for TravTek vehicles was studied. The details of this sensitivity analysis is presented in appendix B .

This analysis concluded the following:

- An analysis of the impact of different assumptions about the level of link travel time estimate error in the routings of background and simulated TravTek vehicles showed that errors less than 10 percent had a nominal impact on the overall results, but that errors in excess of this value could significantly alter the observed TravTek benefits.
- An analysis of the impact of changing the frequency of routing updates within the downtown Orlando network indicated that during recurrent congestion the performance of the simulated TravTek system was relatively insensitive to changes in the range from 2 to 60 routing updates per hour.

SUMMARY AND CONCLUSIONS

Based on the limited sensitivity analysis of traffic demand presented in this chapter the following conclusions can be made:

- There appears to be a greater benefit in terms of reducing the average trip duration in providing the drivers with an RGS as the traffic demand increases. However, the RGS system produces most of its incremental benefits for higher demands at lower LMP's (less than 30 percent), as higher LMP's will usually not result in any further diversion of traffic. It was also found that, if by introducing an RGS the improved traffic conditions induce a 10-percent increase in traffic demand, an LMP of 30 percent would be sufficient to reduce the average trip duration to a level consistent with the initial demand at a O-percent LMP.
- There appears to be a consistent and constant amount reduction in the number of vehicle stops by equipping drivers with an RGS for both low and high traffic demands. This reduction is in the range of 5 percent for every lo-percent increase in LMP up to 50 percent.
- There appears to be a consistent benefit, in terms of reducing average fuel consumption, in equipping drivers with an RGS for both low and high traffic demands. This reduction in fuel

consumption is in the range of 1.5 percent for each 10-percent increase in LMP up to 50 percent. It was also found that, if by introducing an RGS the improved traffic conditions induce a lo-percent increase traffic demand, an LMP of 30 percent would be sufficient to reduce the average fuel consumption rate back to a value consistent with the initial no route guidance base case.

- There appears to be a larger benefit, in terms of reducing average HC emissions, in equipping drivers with an RGS for higher versus lower traffic demands. The reduction in HC emissions is in the range of 1 percent for every lo-percent increase in LMP up to 50 percent.
- It appears that for higher levels of demand the provision of an RGS can increase the average CO emissions. In addition, as the LMP increases the CO emissions can increase by a further amount for these more highly congested conditions. The increase in CO emissions for higher levels of demand is in the range of 0.4 percent for every lo-percent increase in LMP up to 50 percent.
- At higher levels of demand the NOx emissions increase as the LMP increases as a result of improving the traffic conditions. However, for lower levels of congestion, increasing the LMP does not change the NOx emissions as traffic conditions are initially quite good. The increase in NOx emissions for higher levels of demand is in the range of 1 percent for every lo-percent increase in LMP up to 50 percent.
- An RGS system, such as TravTek, can increase or decrease the overall accident risk depending upon the level of congestion and the class of facility of the current and alternate routes. This safety impact is rather minor in the range of 0.2 percent for every 10-percent increase in the LMP up to 50 percent.

Based on a limited sensitivity analysis of incident duration and initial freeway conditions (congested versus uncongested), it was found that similar benefits were achieved by the equipped vehicles over the non-equipped vehicles in each case. Specifically, the equipped vehicles experienced on average a 12-percent reduction in average trip duration, a 4-percent reduction in average trip length, a 10-percent reduction in vehicle stops, a 10-percent reduction infuel consumption, an 11-percent reduction in HC emissions, a 4-percent reduction in CO emissions, a 4-percent reduction in NOx emissions and a g-percent increase in accident risk over non-equipped vehicles. The increase in accident risk and the corresponding reduction in average trip length resulted because equipped vehicles were diverted from the congested, lower risk freeway to the higher risk arterial roads.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS OF SIMULATION STUDY

To date the use of traffic simulation models remains the main and virtually only means to extrapolate Level of Market Penetration (LMP) effects from field studies on a limited number of subjects. While these traffic models have advanced rapidly during the past decade, many deficiencies remain. Unfortunately, many of these deficiencies are limitations in the theories that describe the driver behavior and limitations in being able to collect sufficient data to calibrate the models arising from theories. The modeling results presented in this report should therefore be viewed in terms of what trends were observed and what can be improved upon.

Initially the results for the base case scenario is presented followed by the conclusions and recommendations of the report.

BASE CASE NETWORK RESULTS

- The INTEGRATION simulation model was customized to a considerable level to capture both the specifics of the Orlando network, the TravTek system design and the behavior of TravTek users as observed in Orlando during the field test.
- The simulated behavior of the drivers of the TravTek system was consistent with the observed behavior during the field studies and with the data collected from the Orlando Freeway Management Center (FMC).
- The portion of the TravTek network in the vicinity of the downtown of Orlando could be modeled using 2,670 links, 87 O-D zones, 1295 nodes and 49 traffic signals.
- The simulation of the above network from 3:00 to 5:00 PM involved 62,889 vehicles that traveled a total of 679,111 veh-km or 11,882 veh-h.
- The base case scenario involved an average trip length of 10.8 km and an average trip duration of 11.3 min during which, on average, 5.3 stops were experienced and 0.744 wrong turns were made.
- Within the base case scenario the average fuel consumption per trip was 1.7 L, while emissions of HC, CO and NOx were 18.4, 60.3 and 10.9 g.
- The mixture of arterial and freeway vehicle kilometers, as well as consideration of base case congestion levels, resulted in an average accident rate of 10.4 accidents per million trips.

CONCLUSIONS

Based on the above caveats, and the earlier discussions of the sample TravTek modeling results, various sensitivity analyses were conducted in order to extrapolate the potential benefits of the TravTek system. The execution of the simulation study required the use of a 486 DX66 computer with 32 Megabytes of RAM and involved 10 h for each of the 175 sensitivity analysis runs. This resulted in a total of 1750 h of computer time or 73 days of continuous computer execution.

These sensitivity runs were conducted in order to verify the simulation findings for different traffic conditions and assumptions.

In terms of the specific modeling results it can be concluded that:

Level of Market Penetration Effects

- LMP's from 1 to 50 percent were investigated for a background link travel time error of 10 percent and a TravTek link travel time error of 5 percent, and for LMP's from 1 to 100 percent for background and TravTek link travel time errors of 5 percent.
- The observed impacts of the LMP on each of the nine MOP's were not found to be consistent but were, upon reflection, found to be logical and plausible. These improvements were up to 15, 5, 32, 37, 13, 16, and 7 percent for the average trip duration, average trip length, number of vehicle stops, number of wrong turn maneuvers, level of fuel consumption, HC and CO emissions, respectively.
- The total travel time, travel distance, the number of vehicle stops, the number of wrong turn maneuvers, the level of fuel consumption and the HC emissions were observed to monotonically improve for increasing LMP's.
- CO emissions were found to increase by no more than 3 percent for an LMP of 10 percent and decreased by up to 7 percent for LMP's beyond 10 percent. NOx emissions were found to increase by no more than 5 percent for all LMP's below 90 percent and were found to decrease by 1 percent for an LMP of 100 percent.
- For LMP's up to 100 percent the traffic fleet as a whole, during the PM peak, experienced changes in accident risk which were less than ± 1 percent. However, at virtually all LMP's, during the PM peak, the equipped vehicles experienced an increased accident risk that was greater than that of the background traffic, which received the greatest benefit from the diversions of the equipped vehicles. This difference decreased as a function of the LMP from 1 to 30 percent and was within 1 percent at LMP's beyond 30 percent.
- The majority of benefits increased at a decreasing rate for higher LMP's, but benefits accrued at lower LMP's were never subsequently reversed.
- It would appear that the rather stable relationship between each of the MOP's and the LMP would permit future benefit studies to consider LMP step sizes of approximately 20 percent.
- There is a significant benefit to analyzing the performance of each driver subpopulation by itself, in addition to the performance of the combined population. Analysis of sub-populations enables better understanding of the mechanisms that create the observed aggregate benefits.

Impact of Traffic Demand/ Incidents/ Routing Error

- It was found that the travel time benefits of the simulated TravTek system could be expected to increase at higher levels of traffic congestion. At such higher levels a smaller percentage of the fleet needed to be equipped with the simulated TravTek system in order to capture the majority of the available benefits.

- The magnitude of the other non-travel time benefits except for the CO and accident risk were found to also not scale linearly as a function of the level of traffic demand but followed the trends observed at the base case traffic demand.
- The accident risk for the simulated TravTek vehicles was found to increase relative to the background traffic accident risk for demand levels greater than and equal to the base PM traffic demand case, but the relative accident risk became less than the background accident risk for non-congested conditions. This would suggest that for LMP's below 30 percent the simulated TravTek vehicles would have a higher accident risk relative to the background traffic during the peak periods and a lower accident risk during the off-peak periods. The emissions of CO were found to follow a similar pattern.
- It was found that, during peak hour non-recurring congestion on freeways, all MOP's except for accident risk improved for higher LMP's. The increase in accident risk was attributed to increased use of lower class and therefore less safe links during diversion.
- An analysis of the impact of different assumptions about the level of error in the routings of background and simulated TravTek vehicles showed that errors less than 10 percent in the link travel time estimation had a nominal impact on the overall results, but that errors in excess of this value could significantly alter the observed TravTek benefits.
- An analysis of the impact of changing the frequency of routing updates within the downtown Orlando network indicated that during recurrent congestion the performance of the simulated TravTek system was relatively insensitive to changes in the range from 2 to 60 routing updates per hour.

RECOMMENDATIONS

Based on the results of the simulation study it is recommended that:

- The impact of LMP on accident risk be evaluated more thoroughly for a mixture of peak and off-peak conditions.
- LMP's be investigated at increments of 20 percent.
- The impact of TravTek on accident risk be examined in terms of accident rates per unit of time rather than per unit of distance, and that accident severity also be reflected in an overall estimate of accident cost.
- That the impact of temporal and spatial availability of various forms of real-time information be analyzed.
- That the same range of simulation runs executed on the Orlando network be performed on calibrated networks for different urban areas with different road networks and demand patterns.
- That the impact of arterial incidents be examined.

- That a sensitivity analysis be performed to determine at what relative risk of arterials versus freeways, the simulated TravTek system would yield a net accident risk benefit.
- That the impact of changing the frequency of routing interval updates be investigated for a range of non-recurrent congestion scenarios on freeways and arterials.
- That extensive sensitivity analyses be performed not only to establish for what range of conditions the above findings are valid, but also to identify which of the above benefits can be increased most easily and/or economically.
- That future field and laboratory tests be specifically designed and executed to consider the additional types of data that need to be collected to determine the relative differences between equipped and non-equipped vehicles with a known level of confidence.
- That explicit effort be made to better link human performance and traffic models such that their interdependencies and interactions can be more directly incorporated and considered. Neither a sophisticated human performance model without an appropriate traffic model nor a sophisticated traffic model without a reasonable human performance model are likely to produce satisfactory estimates of ITS benefits.
- That an explicit effort be made to determine the potential benefits of implementing, in an in-vehicle unit, a multi-parameter routing objective function that would optimize some weighted combination of the various objectives. Such an implementation would be in contrast to the current single parameter objective functions that attempt to minimize trip time without taking into explicit account the consequent impacts on the other measures of performance.