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EVALUATION OF SIMULATION MODELS FOR CONGESTED DALLAS FREEWAYS

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16. Abstract

Recent and continuing growth has resulted in increased demand for travel on urban freeways throughout Texas. Many freeways are operating under congested conditions throughout much of the day. However, proposed operational improvements for congested freeways are difficult to evaluate or to simulate accurately because under congestion there is increased effect of vehicle interactions and impact of design elements on traffic flow. There have been improvements in recent years in traffic models that offer promise in the simulation of congested freeways or freeway elements including ramps, merges, weaving areas, and basic freeway sections. The more promising models include simulation of vehicle interactions, lane changing, car following, vehicle rerouting, accommodate origin-destination information, and in general try to model driver behavior. However, there is no universally accepted model for simulating congested conditions and thus arises the need for a project to determine which models produce the best results under different congested conditions. The objectives of this project are to select appropriate models for simulating congested freeways, test the calibration and validation performance of those models using data collected on Dallas freeways, and provide recommendations on the use of the best model for congested freeways in Texas.

The CORSIM (FRESIM component), FREQ, and INTEGRATION models were selected for project based on the literature review. Three different freeway sections with bottlenecks that caused recurrent congestion were selected to test and evaluate model performance. Before and after operational data (i.e., speeds and volumes) at each of the sites were used in the attempt to calibrate and validate the chosen models. The research team determined that all of the models performed relatively well for uncongested conditions; however, the performance became sporadic and mostly unreliable for congested conditions. None of the models was successfully calibrated and validated for all of the test sites. The CORSIM model had the best overall performance in this project, but it was effective only on the simplest test site.

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LIST OF ABBREVIATIONS

TxDOT ..... Texas Department of Transportation
LOS ..... Level of Service
IH ..... Interstate Highway
HCM ..... *Highway Capacity Manual*
MOE ..... measure of effectiveness
FRESIM ..... Freeway Simulation
FREQ ..... Freeway Queue
FREFLO ..... Freeway Flow
TTI ..... Texas Transportation Institute
CORSIM ..... Corridor Simulation
TRB ..... Transportation Research Board
vphpl ..... vehicles per hour per lane
HOV ..... high occupancy vehicle
OD ..... origin-destination
K-Waves ..... Kinematic Waves
US ..... United States
FHWA ..... Federal Highway Administration
CORFLO ..... Corridor Flow
TRAF ..... Traffic
NETFLO ..... Network Flow
Caltrans ..... California Department of Transportation
PE ..... Priority Entry
PL ..... Priority Lane
V/C ..... volume-to-capacity ratio
L-W-R ..... Lighthill-Whitham-Richards
WATSim ..... Wide Area Traffic Simulation
INTRAS ..... Integrated Traffic Simulation
NETSIM ..... Network Simulation
HCS ..... Highway Capacity Software
SH ..... State Highway
SMARTEST .... Simulation Modelling Applied to Road Transport European Scheme Tests
CFSF ..... car-following sensitivity factor
RF ..... rubbernecking factor
AYE ..... Ayer Rajar Expressway
GA ..... genetic algorithm
ITS ..... intelligent transportation systems
NCTCOG ..... North Central Texas Council of Governments
SB ..... southbound
WB ..... westbound
EB ..... eastbound

LIST OF ABBREVIATIONS (continued)

NB ..... northbound
DOS ..... Disk Operating System
ASCII ..... American Standard Character Set Number 2
TSIS ..... Traffic Software Integrated System
ITRAF ..... Input Traffic

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND AND SIGNIFICANCE OF RESEARCH

Recent growth in Texas urban areas has resulted in increasing demand for travel on the urban freeway networks. As a result, the Texas Department of Transportation (TxDOT) has seen a general deterioration of level of service (LOS) on its urban freeways. In many areas, freeways are operating in congested conditions throughout much of the work day. Although engineering judgement and experience are useful in finding potential solutions to freeway flow breakdown, fiscal constraints demand a documented analysis and justification of the most elementary solutions. Further, major freeway reconstruction in the future (e.g. Interstate Highway (IH) 635) will require analysis in terms of congested flow. The problem faced by the transportation professional is that the simulation tools available to analyze freeways are better suited to free-flow or unsaturated conditions. There is a need for examination and calibration of microscopic and macroscopic freeway simulation software to identify which is best suited for analyzing congested freeways.

Under free-flow or conditions approaching capacity, traffic flow is generally smooth with near constant speeds and uniform headway. Once demand exceeds capacity, traffic flow becomes unstable resulting in congested or stop-and-go conditions. Under these conditions, traffic flow occurs with variable headway and speeds that may increase or decrease significantly over a short section of freeway. It is easy to understand why it is more difficult to simulate congested traffic flow than free-flow traffic conditions. Congested conditions have the additional variables of changes in speeds and headway, as well as aberrant driver behaviors that are difficult to characterize.

The manner in which the traffic stream is represented is a model's most significant characteristic. A simulation of a freeway is basically an abstraction of reality. Macroscopic models typically use mathematical relationships to represent the traffic stream as a homogenous aggregate group. The *Highway Capacity Manual* (HCM) package of models are an example of macroscopic models. Microscopic models simulate each individual vehicle at each moment in time and explicitly model interaction with other vehicles to better represent the traffic stream.

1.2 RESEARCH OBJECTIVES

The primary objectives of this research are as follows:

1. determine, through literature review and surveys, which traffic models are suited for modeling saturated conditions given the desired measures of effectiveness (MOEs);

2. calibrate the selected models to different congested freeway sections in the Dallas District and test for validity using after data from bottleneck improvements; and

3. document the recommended models and the calibration methodology for applying the models to saturated freeways throughout Texas.

1.3 WORK PLAN

In order to accomplish the previously noted objectives, researchers developed the following work plan:

Task 1: Perform a Comprehensive Literature Review and Surveys

This effort will focus on reviewing research performed in the previous ten years that is considered to be relevant to this effort. The primary areas of interest will be (1) speed-flow relationships for uncongested and congested conditions, (2) freeway simulation model documentation, and (3) freeway simulation model applications. Researchers will contact individuals with experience using different models to determine their opinions of which models should be examined.

Task 2: Select the Better Suited Simulation Models for Further Project

Several freeway simulation models will be selected for further project based on the results of the literature review and the consultation of the project director and advisor(s). The research team anticipates that the FRESIM (Freeway Simulation), FREQ (Freeway Queue), and FREFLO (Freeway Flow) models will be included based on their widespread application and documentation. We anticipate that several additional models could be included depending on the findings of the literature review and the advice of the project director and advisor(s).

Task 3: Identify Congested Freeway Project Sections in Dallas

Three or more congested freeway sections will be identified for use in calibrating and validating the simulation models based on existing traffic operations data and the consultation of the project director and advisor(s). The Texas Transportation Institute (TTI) has collected traffic data at numerous locations for before and after studies of bottleneck improvements, as well as for other research projects. No new data collection is proposed for this research. The research team would prefer the selected sites have some variety in terms of typical cross section, geometric features (ramp spacing, presence of auxiliary lanes, etc.), and operating characteristics.

Task 4: Case Project Evaluation of Selected Freeway Sections

An evaluation of the ability of each selected model to replicate existing conditions will be performed. The first evaluation will involve comparing the simulation results of each of the

models selected using the default values for variable inputs. This comparison will determine which models are best able to reproduce existing conditions using the default values. The second evaluation will involve using actual operational data (i.e., volumes, speeds, and travel times) collected from the selected freeway sections to calibrate each of the models. The third step will validate the calibrated models by using data collected on the same calibration sites, but after geometric changes were made to remove bottlenecks. The research team will use the comparison of the validation results to determine which model is most appropriate for simulating congested freeway operations. This step will also provide insight into the predictive ability of the models for use in benefit assessment. Researchers will use before data from a bottleneck improvement project for calibrating the model and the after data from the same project for assessing the predictive capabilities of the model.

Task 5: Prepare the Research Summary Report

Researchers will document the findings and results of the case project comparison and calibration of the freeway simulation models studied. Specific recommendations about which model or models are most appropriate for simulating different aspects of congested freeway operations will be formulated. It is anticipated that the findings of this project will be useful to transportation professionals during the analysis and benefit determination phases of freeway flow-improvement projects.

1.4 REPORT ORGANIZATION

This report is divided into five chapters. Chapter 1, "Introduction," contains background information, the significance of this research, research objectives, and the work plan utilized to accomplish the stated objectives.

Chapter 2, "Project Background," provides a comprehensive summary of the literature review conducted during the early stages of the project. The literature review concentrated on research performed in the previous ten years that was relevant to the project objectives.

Chapter 3, "Project Methodology," provides a detailed explanation of the methods and procedures used during the project. The simulation model and project site selection procedures and choices are provided. In addition, this chapter describes how the selected simulation models were coded to represent each of the project sites. Finally, an overview of potential model calibration techniques and validation procedures is provided in the final sections of this chapter.

Chapter 4, "Project Results," presents the findings and results of the testing and evaluation of the selected simulation models. Documentation of the calibration and validation efforts is also provided in this chapter.

Chapter 5, "Project Conclusions and Recommendations," contains the significant conclusions and recommendations developed as a result of this project. Both broad-based conclusions and

model-specific conclusions for the FREQ, INTEGRATION, and CORSIM (Corridor Simulation) models are given in this chapter. Finally, several recommendations regarding implementation of the project findings are also presented.

CHAPTER 2

PROJECT BACKGROUND

This chapter documents the work performed for Task 1 of Project 7-3943. Task 1 involved the performance of a comprehensive literature review. This effort focused on reviewing research performed in the previous ten years that was relevant to the project objectives. The primary areas of interest in performing the literature review were (1) speed-flow relationships for uncongested and congested conditions on freeway facilities, (2) freeway simulation model documentation, and (3) studies on freeway simulation model applications. The research team used two methods to gather information for these focus areas. The first method involved obtaining published studies. The second method involved utilizing information from Internet web sites and user guides for the simulation models included in this research.

This chapter is organized into three primary sections. Section 2.1 provides an overview of speed-flow relationships for freeway facilities. It supplies information from the HCM on speed-flow relationships for uncongested and congested situations. It also addresses some of the significant findings from recent research on traffic flow theories under congested conditions. Section 2.2 contains a variety of documentation of traffic simulation models currently available for analyzing freeway operations. Specifically, it gives a basic introduction to simulation modeling and detailed documentation of most of the mainstream macroscopic and microscopic simulation models used in the United States. Section 2.3 summarizes results and findings from studies that document the usage of freeway simulation models. It is divided into subsections for general studies and for model-specific studies.

2.1 SPEED-FLOW RELATIONSHIPS FOR FREEWAY FACILITIES

This section presents information on the relationship between speed and traffic flow on uninterrupted facilities. Uninterrupted flow facilities have no fixed elements, such as traffic signals, that are external to the traffic stream and may interrupt traffic flow. On these facilities, commonly called freeways, traffic flow conditions result from the interactions among vehicles in the traffic stream and between vehicles and geometric and environmental characteristics of the roadway. An understanding of the speed-flow relationship is important to this research project because it forms the philosophical basis for the capacity analysis of uninterrupted flow facilities. Information on the speed-flow relationship for both uncongested and congested conditions will be presented within this section. However, most of the material in this section will be devoted to the congested conditions situation because it is what is most related to the objectives of the research.

2.1.1 Highway Capacity Manual

The HCM is regarded by many as the most comprehensive source for information on analysis techniques for transportation facilities **(1)**. The parameters and procedures in the HCM provide transportation professionals with a systematic and consistent basis for assessing the capacity and performance of key elements of transportation facilities. A significant portion of the manual is devoted to the subject of analyzing freeway facilities. The following subsections present information from the HCM on speed-flow relationships for freeway facilities. The first subsection will summarize key sections of the HCM related to the speed-flow relationship for uncongested conditions. The second subsection will provide similar information for the case where congested conditions exist.

HCM Synopsis: Speed-Flow Relationships for Uncongested Conditions

An understanding of traffic flow begins with the basic relationship between the three variables describing an uninterrupted traffic stream. The relationship between density (D), flow rate (v), and average travel speed (S) is shown in Equation 1 below. Although Equation 1 algebraically allows for a given flow rate to occur at an infinite number of combinations of speed and density, research has identified additional relationships which restrict the variety of flow conditions that may exist at any given location. Although many complex theories of traffic flow exist, the HCM proposes that speed and density have a linear relationship. Figure 1 shows the generalized relationships among speed, density, and rate of flow on uninterrupted flow facilities for uncongested conditions. The flow-density function is placed directly below the speed-density relationship because of their common horizontal scales, and the speed-flow function is placed next to the speed-density relationship because of their common vertical scales.

Equation 1:

$$v = S \, x \, D$$

where: v = flow rate in vehicles per hour (vph);
S = average travel speed in miles per hour (mph); and
D = density in vehicles per mile (vpm).

The actual shape or form of the functions in Figure 1 depends on the prevailing traffic and roadway conditions on the roadway segment under project and on the length of the segment considered in the calculation of density. Although the diagrams in Figure 1 show continuous curves, research by May **(2)** has shown that it is unlikely that the full range of the functions will be found at any particular measurement location. The free speed, denoted by S_f, is the theoretical speed for the condition when no cars are on the facility and the first driver can select whatever speed they desire—most likely a high speed. The density at which all movement stops is called the jam density, denoted by D_j in diagrams in Figure 1. As density continues to increase, the

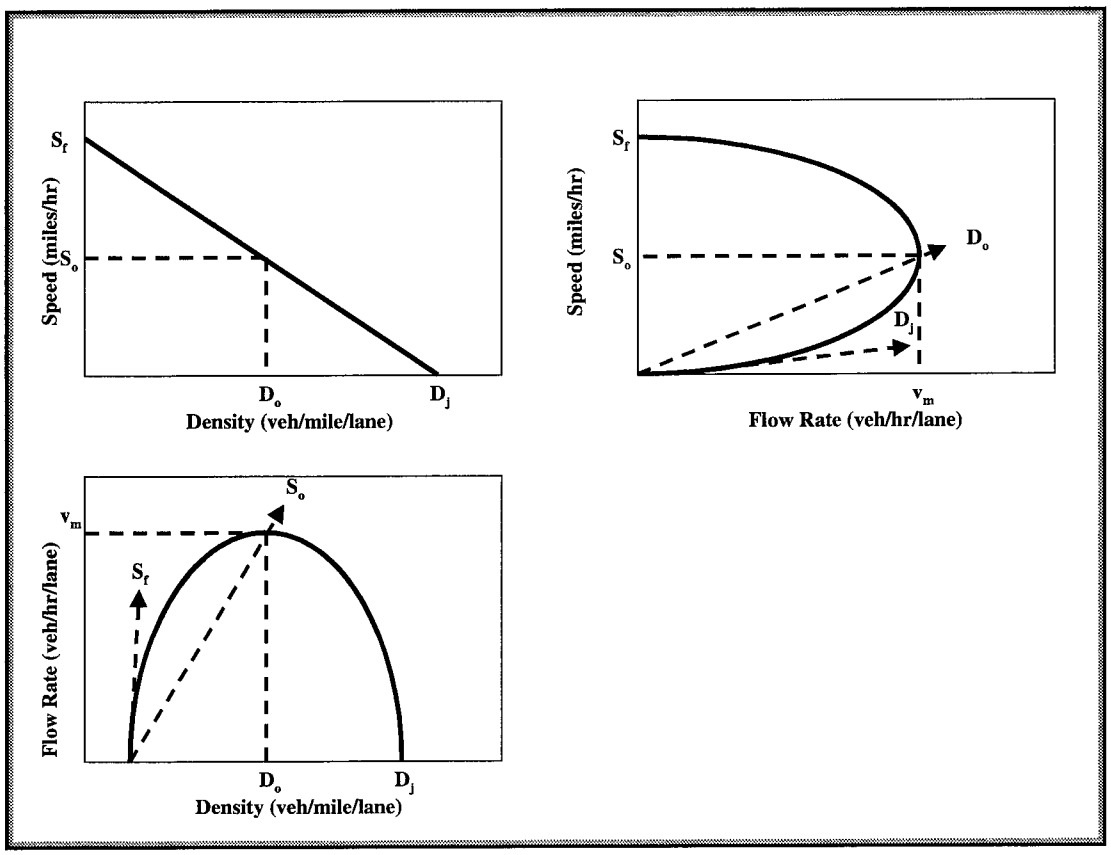


Figure 1. HCM Generalized Relationships Among Speed, Density, and Rate of Flow on Uninterrupted Flow Facilities (1).

curves in Figure 1 suggest that speed decreases significantly before the capacity is achieved. Capacity is reached when the product of density and speed results in the maximum rate of flow. This condition is shown in the diagrams as optimum speed S_o (often called critical speed), optimum density D_o (sometimes referred to as critical density), and maximum flow v_m (otherwise known as capacity).

The speed-density function is used mostly for theoretical work; however, the other two functions are used by the HCM to define the LOS. As shown in Figure 1, any rate of flow other than capacity can occur under two different conditions, one with a high speed and low density and the other with high density and low speed. The high-density, low-speed side of the curves represents forced or breakdown flow. Sudden changes in the state of traffic (i.e., in speed, density, and rate of flow) may occur. LOS A through LOS E are defined on the low-density, high-speed side of the curves, with the maximum flow boundary of LOS E placed at capacity, whereas LOS F, used to describe congested traffic, is represented by the high-density, low-speed part of the functions.

HCM Synopsis: Speed-Flow Relationships for Congested Conditions

The first step in summarizing the HCM information on speed-flow relationships for congested conditions is establishing the definition of congestion. The HCM assigns the meaning of congestion as operations occurring during LOS F. The HCM describes LOS F as:

...breakdowns in vehicular flow. Such conditions generally exist within queues forming behind breakdown points. Such breakdowns occur for a number of reasons:

> a. Traffic incidents cause a temporary reduction in the capacity of a short segment, such that the number of vehicles arriving at a point is greater than the number of vehicles that can traverse it.
>
> b. Recurring points of congestion exist, such as merge or weaving areas, where the number of vehicles arriving is greater than the number of vehicles discharged.
>
> c. In forecasting situations, any location presents a problem when the projected peak hour (or other) flow rate exceeds the estimated capacity of the location **(1)**.

In all cases, breakdown occurs when the ratio of arrival flow rate to actual capacity or the forecast flow rate to estimated capacity exceeds 1.00. Operations immediately downstream of such a point, however, are generally at or near capacity, and downstream operations improve (assuming that there are no additional downstream bottlenecks) as discharging vehicles move away from the bottleneck. The LOS F operations observed within a queue are a result of a breakdown or bottleneck at a downstream point. LOS F is used to describe conditions at the point of breakdown or bottleneck, as well as the operations within the queue that forms behind it. Whenever LOS F conditions exist, there is a potential for them to extend upstream for significant distances. A prerequisite for valid analyses using these procedures is the assumption that the section under consideration is free from downstream effects that propagate upstream" **(1)**.

Analyzing traffic operations and performing reasonable assessment of improvement alternatives for LOS F conditions are what the research team is most interested in projecting. Figure 3-2 of the HCM provides speed-flow curves for values of free-flow speed ranging from 70 to 55 mph for basic freeway sections (four-lane freeways and six-or-more-lane freeways) under ideal conditions **(1)**. It is important to note that these curves do not depict the portion of the curve that occurs within a queue formed behind a bottleneck because there has not been sufficient research to clarify this region of flow. The lack of documented research in the HCM on speed-flow relationships for congested conditions means that transportation researchers and practitioners have to utilize other methods and tools to perform analyses of operations for congested environments.

2.1.2 Recent Congested Flow Research

During the last few years, a significant amount of research has been performed to try to investigate the relationship between speed and flow within congestion (i.e., the lower portion of the speed-flow curve shown in Figure 1). This research has taken place in three major countries. The following subsections present results from studies in Canada, Germany, and the United States on the subject of traffic flow in congested conditions. Each of these studies were part of the program at the 78th Annual Meeting of the Transportation Research Board (TRB) held in Washington, D.C. in January 1999.

Canadian Project

The purpose of this research, conducted by Zhou and Hall **(3)**, was to examine the speed-flow relationship for congested conditions, and in particular to identify an equation to describe this relationship. Loop detector data (speed, volume, and occupancy) were obtained in Toronto, Ontario, from the Gardiner Highway Expressway system, and the Highway 401 system for the afternoon peak period. The data were first filtered to remove dubious data points and to remove observations that were from transitions between congested and uncongested conditions. The data were analyzed using regression analysis for four types of mathematical function: quadratic, cubic, exponential, and power functions. This effort produced three basic conclusions. The first conclusion deals with data and data needs. The second conclusion provides a summary of the statistical results. The final conclusion goes beyond the statistical analyses and gives some observations regarding the Canadian freeway data. The list below supplies each of these conclusions:

- It is important to utilize data from a full range of flows in order to fit a curve to represent the congested part of the speed-flow curve. Before analyzing such data, it is important to remove data which represent transitions between congested and uncongested conditions and to remove data that clearly represent queue discharge flow conditions. To obtain a full range, data from several sites may be necessary. Despite combining sites, there is often what might be termed a data gap between easily available congested data (up to perhaps 1800 vehicles per hour per lane (vphpl)) and flow rates for queue discharge flow. When data for that gap are available, the speeds under congested conditions seem to increase fairly rapidly at high congested flows.

- The statistical results show two things. The first result showed that all four of the functions tested (i.e., the quadratic, cubic, exponential, and power) in the regression analysis had R^2 values between 0.754 and 0.781, a difference of less than 0.03. All of the functions and their corresponding equations indicated that the speed-flow relationship within congestion seems to increase fairly rapidly at high flows and therefore is not as sketched in Figure 3-3 of the 1998 version of the HCM **(1)**. The second result revealed that the relationship under construction conditions seemed, for most functional forms, to be different from normal conditions.

- The final conclusion presented by the authors suggested that there may in fact be a difference in speed-flow relationships within congestion among different freeways, as well as under construction. This result seems reasonable because research has already verified that there are different curves for different freeway (or free-flow) speeds for the top-half (i.e., the uncongested portion) of the speed-flow relationship in the HCM.

German Project

This research, conducted by Kerner **(4)**, developed several new theories and ideas about traffic flow on a congested facility. Before explaining some of the conclusions of this project, it is important to give definitions for several terms that are not found in the HCM:

Synchronized flow—this type of flow occurs when vehicles are almost not able to pass due to the higher density present on a congested facility. Therefore, when all lanes of a highway correspond to the same route without on- and off-ramps or other bottlenecks, drivers move with nearly synchronized average speed on the different lanes of the highway.

Nucleation effect—an avalanche growth of the amplitude of a local perturbation of one of the characteristics (i.e., speed or density) of traffic flow.

Metastable state—this is the state of flow where the nucleation effect occurs.

Critical amplitude—the amplitude at which a local perturbation will begin to grow and lead to the nucleation effect which in turn can lead to the formation of a jam (i.e., congested flow).

Wide jams—a state of congestion where both the vehicle speed and flow rate are nearly zero.

Kerner presented nine hypotheses for congested traffic flow which he based on the results of experimental observations. Kerner made several conclusions in his work including the following:

- There are three different types of phases ((i) free-flow, (ii) synchronized flow, (iii) wide jams), and correspondingly three different types of phase transitions in traffic flow: (1) free-flow ⇔ jam, (2) free-flow ⇔ synchronized flow, and (3) synchronized flow ⇔ jam. Similar looking breakdown and hysteresis effects can accompany all these phase transitions because they are related to the same class of first order phase transitions. However, there is a distinction between them because non-linear features of these phase transitions are qualitatively different.

- The characteristic line for the downstream front of a wide jam determines the threshold of the jam's existence and the jam's excitation.

- The nucleation effect, which is responsible for the phase transition between free-flow and synchronized flow, is linked to an avalanche decrease in the probability of passing in

free-flow. This avalanche decrease occurs if the probability of passing, due to a local perturbation of traffic variables, decreases below some critical value. At the same density of free-flow, the amplitude of the local perturbation which is needed for the phase transition is lower than the critical amplitude of a local perturbation which is needed for the jam's formation.

- The capacity of a freeway facility depends on the phase the traffic is actually in.

United States Project

This research was conducted by Banks **(5)** to investigate whether the results of the German project in the previous subsection were applicable to the United States. Specifically, Banks performed an analysis of flow-occupancy data from loop detectors stations in San Diego, California, to assess the validity of the two new types of congested flow (i.e., synchronized flow and traffic jams) suggested by the German research.

Banks compared the German results with San Diego data collected in the summer of 1989 as part of a project that focused on flow characteristics at freeway bottlenecks. These data consisted of 30-second, lane-by-lane traffic counts and occupancies measured during the morning peak period (6:00–9:00 AM). The data were derived from single-induction loop detectors deployed in conjunction with the San Diego ramp metering system. The data used by Banks in San Diego are generally comparable to those analyzed by the Germans; however, there are three potentially significant differences:

- The San Diego data were taken over 30-second intervals, as opposed to 1-minute intervals for the German data.

- The San Diego data consisted of traffic volumes and occupancies, whereas the German data consist of volumes and speeds. In both cases Banks estimated the missing traffic variable (i.e., speed in San Diego and density for the German work) which was therefore not as accurate as a measured value.

- San Diego drivers were basically urban commuters. The German data were taken at sites in the Frankfurt urban area, but on a facility that has widely spaced interchanges and no direct access to surface streets in the immediate vicinity of the data collection sites.

Banks determined that San Diego data showed that there were qualitative differences in the appearance of flow-occupancy time sequences depending on the flow-occupancy ratio (approximate speed) of traffic, such that for data above a flow-occupancy ratio of 55 mph (approximately 40 kph) transferences (called phase transitions in the German research) have predominantly positive slopes and for flow-occupancy ratios below 55 mph, predominantly negative slopes. These two regions are similar to the proposed synchronized flow and traffic jam phases of traffic flow in Kerner's work but not exactly the same. Banks suggests that the two

regions probably do represent qualitatively different types of traffic behavior, but are explained by random variations in time gaps and the relationship between speed, flow, density, and average time gap. In particular, Banks asserted that the existence of a region of congested flow with positively-sloped flow-concentration transferences does not imply that kinematic waves in such flow move downstream; indeed, for data taken over very short time intervals, such as 30 seconds or 1 minute, the slopes of transferences are not a reliable indicator of wave speed and direction.

2.2 FREEWAY SIMULATION MODEL DOCUMENTATION

This section of the report provides documentation of traffic simulation models currently available for analyzing freeway operations. It is divided into four subsections: introduction to simulation modeling, macroscopic models, microscopic models, and mesoscopic models. The first subsection gives a basic introduction to computer simulation modeling and definitions for common technical terms. The next subsection contains detailed documentation of some of the most mainstream macroscopic simulation models used in the United States for freeways. The following subsection presents information on microscopic models used in the United States. The final subsection addresses a relatively new mesoscopic model, INTEGRATION, being used throughout North America.

2.2.1 Introduction to Computer Simulation Modeling

Computer simulation modeling has been a valuable tool for analyzing and designing complex transportation systems. The inherent value of computer simulation is that it allows experimentation to take place "offline" without having to go out in the real world to test or develop a solution. Specifically, simulation offers the benefits of being able to control input conditions, treat variables independently even though they may be coupled in real life, and most importantly repeat the experiment many times to test multiple alternatives performance. This subsection provides an introduction to computer simulation modeling by providing a list of definitions for some common technical terms used in computer simulation modeling **(6)**. The list follows on the next two pages:

Simulation models—these models predict system performance based on representations of the temporal and/or spatial interactions between system components (normally vehicles), often characterizing the stochastic nature of traffic flow.

Empirical models—these models estimate system performance based on relationships developed through statistical analysis, normally regression, of actual field data.

Analytical models—these models calculate system performance using relationships among system components developed through theoretical considerations (such as deterministic or probabilistic queuing theory) tempered, validated, and calibrated by field data.

Events—this term is used to describe anything that changes the state of the system being analyzed.

Time-Step Logic—time-step logic is the way that time advances in the system being analyzed.

Event-Based Simulation—the time-step logic in this type of simulation varies in length and corresponds to the interval between successive events.

Time-Based Simulation—the time-step logic in this type of simulation normally uses equal time steps; however, the steps may vary in response to how active the system is (i.e., smaller steps for more activity).

Processing Logic—the processing logic in a model determines how that state variables will change with time. There are two common forms of processing logic: (1) if-then rules and (2) predictive equations.

Deterministic—a simulation model is deterministic if no element of the model is subject to randomness. In other words, successive simulations of the same case (i.e., identical data input) give the same outcome.

Stochastic—a simulation model is stochastic when one or more elements are subject to randomness. Random variables are used during the simulation to determine either specific values for model variables or the actions that should be taken. Different random number sequences will produce different model results, so the outcome from simulation cannot be predicted with certainty before simulation begins.

Macroscopic—these models normally describe the movement of traffic as a whole by employing flow rate variables and other general descriptors. Macroscopic models are generally based on deterministic relationships developed through research on highway capacity and traffic flow for freeway sections. Macroscopic simulation takes place on a section-by-section basis rather than tracking individual vehicles.

Microscopic—these models describe the movement of traffic by individual vehicles, based on theories of car following and lane changing. These models contain processing logic, which describes how vehicles behave including acceleration, deceleration, lane changes, passing maneuvers, turning movement execution, and gap acceptance. Typically, vehicles are input into the project section using a statistical arrival distribution (a stochastic process) and are tracked through the section on a second-by-second basis.

Mesoscopic—these models fall in-between macroscopic and microscopic models. They typically model the movement of clusters or platoons of vehicles and incorporate equations that indicate how these clusters of vehicles interact.

Transportation Network Data—most models use the link-node approach to represent the project network, where a link represents a roadway section and a node an intersection or change in roadway geometry.

Traffic Control Data—detailed control data is normally a required input for all control points or nodes, such as street intersections or freeway on-and-off ramps.

Traffic Operations Data—most simulation models take the link-specific operations data as input to model the real-world traffic environment such as roadway capacity, lane use, lane restriction, desired free-flow speed, high occupancy vehicle (HOV) lane(s), lane blockages, etc..

Traffic Demand Data—different models require traffic demand data in different formats. The most commonly used demand data are flows at the network boundary and within the network, traffic turning fractions at intersections and freeway junctions, origin-destination (OD) trip tables, path-based trips between OD's, and traffic compositions.

Model Calibration—calibration is the process of quantifying model parameters using real-world data in the model logic so that the model can realistically represent the traffic environment being analyzed. Vehicle characteristics and driver characteristics are the key parameters, which may be site-specific and require calibration.

Model Validation—validation is the process of comparing model results against corresponding data observed in the field and ensuring that such results realistically represent the real world. Only measurable data from the field can be used to validate model results. Commonly used data are queue length, travel time, delay, speed, and density. Individual vehicle trajectories are often used to validate the model at the microscopic level.

2.2.2 Macroscopic Models

This subsection provides documentation for three macroscopic simulation models currently in use in the United States. It is divided into three subsections: FREFLO, FREQ, and K-Waves (Kinematic Waves).

FREFLO

This section gives an overview of the FREFLO simulation model. FREFLO was developed by Payne in 1977 (**7**). It is a macroscopic simulation model based on the principles of flow conservation and dynamic speed-density relationships. The program is a stochastic/time-based model that represents the freeway system as a series of segments. FREFLO has the capability to simulate any geometric improvements, HOV lanes, bus operations, lane closures, and incidents on a freeway. It also can accommodate freeway-to-freeway connectors, including the analysis of both merge and diverge situations.

FREFLO was updated by the Viggen Corporation for the Federal Highway Administration (FHWA) and is now part of the CORFLO (Corridor Flow) suite in the TRAF (Traffic) family of simulation models. The FREFLO component of the CORFLO package only simulates the freeway system but can be integrated with the NETFLO (Network Flow) component to include surface streets in the network being modeled. Typical input data include roadway geometry (link length and number of lanes), operational characteristics (capacity and free flow speeds), volumes, and turning movement percentages. Model output includes the following MOE: vehicle trips, vehicle miles, travel time, delay, average volumes and speeds, person trips, and person miles. Additional information about the FREFLO model can be found at the following Internet sites **(6)**:

- http://kuhub.cc.ukans.edu/~pctrans
- http://www-mctrans.ce.ufl.edu/
- http://www.viggen.com/trafhome/index.htm

FREQ

This section provides a basic description of the FREQ model **(8)**. The history of the FREQ model started in 1968 at the Institute of Transportation Studies when a California Department of Transportation (Caltrans) research project required the evaluation of alternatives for improving 140 miles of the existing San Francisco freeway system. The first model, called FREQ or FREQ1, was a forerunner of a family of deterministic macroscopic models for a linear directional freeway corridor, which has now reached a tenth-level version. Of particular interest is the split of the model at the Version 6 level into two separate models in 1978. Another major feature was included in 1987 when a synthetic origin-destination trip generator was added to the model structure. The FREQ family of models can be used to evaluate various design and operational improvements for a freeway corridor.

FREQ Component Models: FREQPE and FREQPL. The current model version, FREQ10, contains two models: FREQ10PE (priority entry), a model for analyzing ramp metering; and FREQ10PL (priority lane), a model for analyzing HOV facilities. The same simulation module is the core of both the FREQ10PL model and FREQ10PE model. Upon entering the FREQ interface, the user may select either of the models. Once the user has entered the basic input data in one of the two models, the interface creates a matching data set that then can be accessed by the other model at a later time. The two models themselves do not interact; therefore, the user must model entry control and on-freeway HOV facilities independently.

FREQ Simulation Description. FREQ is a time-based model that analyzes the freeway corridor for each of a possible 24 time slices beginning with the first and continuing to the last. Within a time slice, each of a possible 38 subsections is processed sequentially from upstream to downstream. Simulation of conditions on the freeway is divided into two parts. The first involves ramp queuing, ramp merging, and weaving analysis. All of these analyses are performed in

accordance with the HCM procedures. The second includes mainline travel time and queuing analysis. These analyses are done using a demand-supply analytical approach and speed-volume/capacity ratio curves.

FREQ Bottleneck Analysis. The FREQ model performs a bottleneck analysis when the demand exceeds the capacity (i.e., V/C ratio > 1.0). When the model encounters bottlenecks, the original downstream demands are incorrectly calculated; therefore, these demands are recalculated because excess demands at the bottleneck are being stored upstream and cannot reach downstream freeway subsections. The model compensates by storing the excess demand at a bottleneck in upstream subsections and changes the previous calculated performance of these subsections because of the upstream storage. Furthermore, the model transfers the excess demand created by the bottleneck to the demand schedule for the next time slice because it cannot be served in the original time period. When the model is through with this sub-procedure, it returns to the normal simulation process; however, it still looks for other bottlenecks in downstream subsections and later time slices. Each time another bottleneck is encountered, the sub-procedures described previously are employed again. This process can become very complex when the effects of one bottleneck affect upstream bottlenecks.

A FREQ manual obtained at an educational workshop provides the following advice for users when a simulation run for existing conditions reveals congestion on the freeway that appears to be caused by isolated bottlenecks:

> The user should first try to improve the design of the freeway at the congested areas before considering other options. Such improvements might include adding an extra lane in one or two subsections, adding a lane to an on-ramp or off-ramp, or making other improvements to the freeway design that would increase capacity at the congested areas. The user may discover after trying several possible design improvements that the freeway congestion can be eliminated by making design improvements alone. If, however, the elimination of the original bottlenecks merely results in new problems downstream, a more comprehensive solution such as the implementation of a priority lane, or the implementation of normal or priority entry control should be explored **(8)**.

FREQ Model Input/Output. This section describes the major types of data that the FREQ model needs for input and those that are produced as output. The FREQ10PL model requires four major types of data from the user for the input file:

1. Design features: subsection lengths, capacities, and speed-flow curves, position and capacities of on- and off-ramps, grades, and number of lanes;

2. Demand pattern: origin-destination data and the occupancy distribution at each on-ramp;

3. Alternate route data: specifications (i.e., flow and occupancy distribution) for arterial facilities that are parallel to the freeway. The geometric connection of the arterial to the

freeway and the percentage of vehicles turning off the arterial should be included if spatial shift is requested; and

4. HOV data: position, number of lanes, and cut-off limit of the lane(s) being investigated.

If the FREQ10PE model is being used, ramp control specifications must also be input for each on-ramp in the network. The FREQ10PL model also produces four major types of output data:

1. Traffic performance tables: MOE such as travel time, ramp delay, queue length, average speed, fuel consumption, and emission rate;

2. Visual displays: contour maps of travel time and average speed;

3. Modal assessment: a differential table comparing the results of the day-1 and longer term simulations for travel time, distance, speed, fuel consumption, and emissions; and

4. HOV evaluation: a benefit-cost performance index that can be used to compare different HOV operational designs.

If the FREQ10PE model is being used, a freeway ramp control plan can also be selected for the output file. Additional information about FREQ can be found at the following Internet site **(6)**:

- http://www.its.berkeley.edu/sysunit.html

K-Waves

This section gives an overview of the K-Waves simulation model. K-Waves was developed by researchers at the Georgia Institute of Technology (part of Georgia Tech University) in 1997 **(9)**. The model development was sponsored by the FHWA and Caltrans to support the computer implementation of G.F. Newell's simplified theory of kinematic waves in highway traffic.

K-Waves Background: Newell's Theory. The K-Waves program simulation approach is based primarily on a theory of traffic flow developed by Newell **(10, 11, and 12)**. In his theory, Newell presents a simplified theory of kinematic waves in highway traffic. The original theory, referenced now as the Lighthill-Whitham-Richards (L-W-R) theory **(13)**, postulates the existence of a fundamental relationship between the flow and the density of uninterrupted highway traffic. The L-W-R theory is used in the project of queue formation at highway bottlenecks. Application of the L-W-R theory for the project of highway conditions requires a rather tedious evaluation of the trajectories of any and all shock waves (i.e., discontinuities in discharge flow across the wave boundary) within a traffic stream. These computations become especially difficult when complex highway conditions (e.g., multiple on- and off-ramps) are part of the system being analyzed. Newell's simplification of the L-W-R theory focuses on the evaluation of the cumulative flows past specific points on the highway. Newell argues that the correct solution to

the cumulative flow problem is the lower bound of all possible solutions; therefore, the shock waves need not be considered explicitly. Cumulative flows past a fixed location on the highway are simply a function of the initial and boundary conditions, without concern for other highway conditions. To further simplify propagation of queues both upstream and downstream, Newell proposes use of a triangular flow-density relationship, rather than the typical parabolic relationship. Other research **(14)** has been conducted to test the accuracy of Newell's theory and the adequacy of the piece-wise linear flow-density relationship. The results of this research suggested that the simplifying flow-density assumption is adequate, and that Newell's approach works best under severely congested conditions. This last finding is especially important in considering the application of the K-Waves model to this research.

K-Waves Simulation Description. K-Waves is a deterministic, macroscopic, time-domain simulation model for the estimation of freeway congestion. In the K-Waves model, a directed graph of links and nodes represent the freeway. Nodes are assigned unique identification numbers; directed links are identified by the nodes at each link end-point. A system under project may consist of only the freeway mainline. At this point in time, K-Waves cannot represent multiple freeway systems (e.g., crossing freeways, etc.) or multiple, parallel facilities. The model also does not consider delay experienced by vehicles on ramps. The tool estimates basic freeway characteristics (i.e., delay, speed, flow, and density) on a link-by-link, time-step-by-time-step basis using Newell's shock wave theory. Queues are propagated upstream and bottlenecks are propagated downstream; multiple queues and bottlenecks may be evaluated concurrently.

K-Waves Model Input/Output. This section describes the input and output data elements for the K-Waves traffic model. Inputs include length, number of lanes, per lane capacity, free speed, and jam density for each link. Input demands are represented as flow rates between origins and destinations. Demands (e.g., OD flows) and capacities (e.g., number of lanes and/or per-lane capacity) may vary on an arbitrary time-step basis. Data that is required as input from the user for each link includes the following:

- upstream and downstream node number;
- number of lanes;
- length;
- free speed;
- capacity per lane;
- jam density; and
- backward wave speed and description.

Link properties are assumed to be homogenous. Values may be input in either English or metric units. The backward wave speed is computed internally; therefore it is not necessary for the user to input a value. The model also produces a variety of output variables including the following:

- total travel;
- total delay;
- total time;
- average speed;
- average delay;
- average time;
- extent of queue; and
- time to normal flow.

In addition to these output variables, the model produces two-dimensional and three-dimensional contour plots of flow, density, and speed. Figure 2 provides an example of a flow contour plot for a simple bottleneck. Figure 3 shows the same example, except the contour is now represented as a three-dimensional image. Additional information about the K-Waves model can be obtained at the following Internet site **(6)**:

- http://traffic.ce.gatech.edu/gtwaves

2.2.3 Microscopic Models

This subsection provides documentation for two microscopic simulation models currently in use in the United States. It is divided in two subsections: FRESIM and WATsim (Wide Area Traffic Simulation).

FRESIM

This section gives a brief summary of the FRESIM traffic simulation model. FRESIM is a simulation model developed and supported by the FHWA, representing an extension of an earlier model known as INTRAS (Integrated Traffic Simulation). The INTRAS model was developed in the late 1970s by KLD Associates and was enhanced continuously throughout the 1980s. JFT Associates reprogrammed and enhanced the INTRAS model in 1993, and it was then called the FRESIM model.

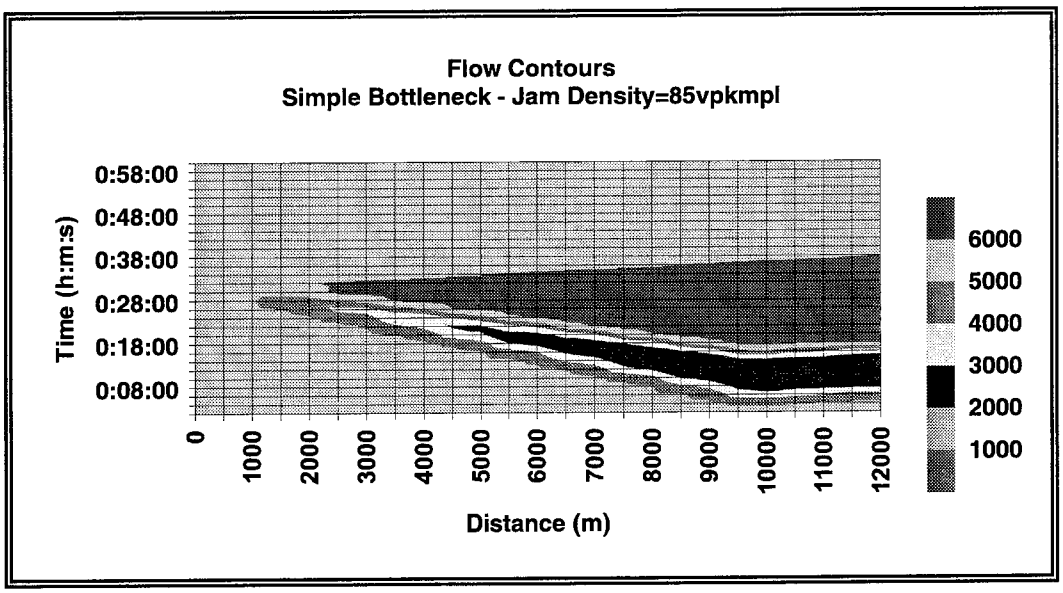


Figure 2. K-Waves 2-D Flow Contour Example (10)

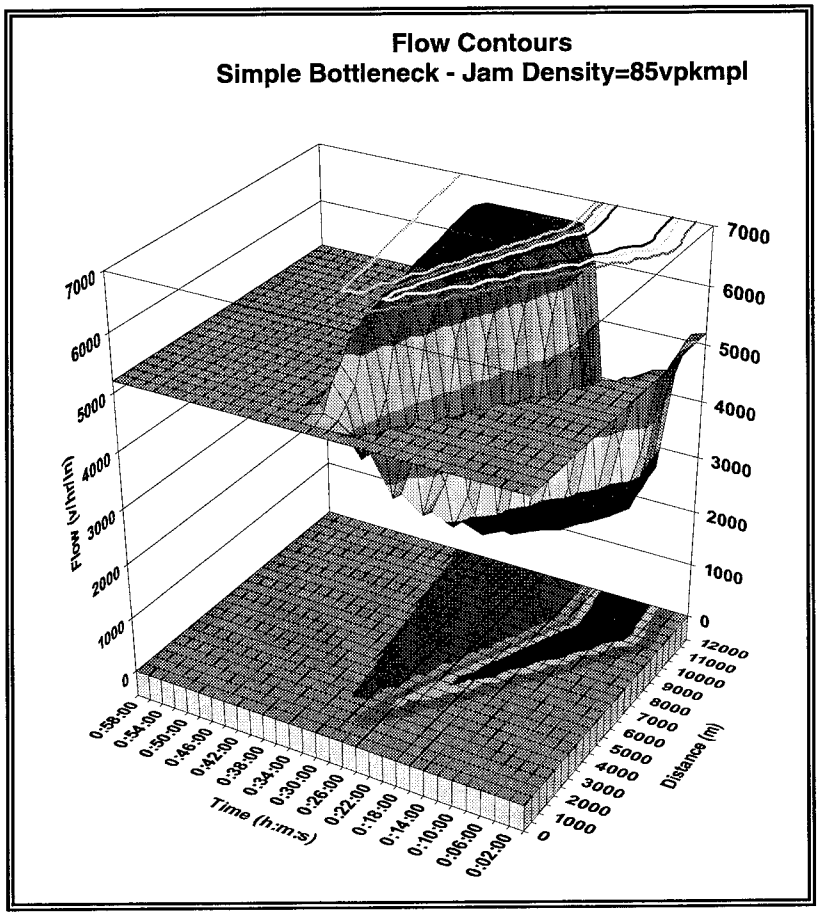


Figure 3. K-Waves 3-D Flow Contour Example (10)

FRESIM Simulation Description. FRESIM is a microscopic, stochastic, time-scanning simulator capable of modeling freeway traffic operations. FRESIM explicitly models individual vehicle movements and driver decisions. The FRESIM network is divided into links (i.e., one-directional roadway sections) and nodes (i.e., geometric discontinuities that serve as joints for adjacent links). The following list provides a detailed description of the logic the FRESIM model uses to simulate vehicle operations **(15)**:

Vehicle Movement Logic—vehicles are classified in time steps of usually one second intervals. Each vehicle is classified as in motion (as leaders and followers), moving in queue, stopped, stopped behind a metering signal, and moving through a metering signal. Vehicle deceleration is controlled by applying car-following logic and the kinematic law. Lead vehicle acceleration is subject to a maximum jerk value, and resulting speeds are kept lower than the desired free-flow speed. Follower vehicles pursue the leader based on the Pitt car-following model.

Lane Changing Logic—the FRESIM model considers three types of lane changing: mandatory, random, and discretionary. Each vehicle is scanned in every time step for the desire to change lanes. After the lane change the vehicle is considered to remain in the lane change condition for a three second hiatus. Random and discretionary lane changes are inhibited during the hiatus period. Mandatory lane changes are not subject to the expiration of the hiatus period and may be performed in any time step in response to downstream geometry. For a vehicle to perform a lane change, an acceptable lead and trailing gap must be available. Acceptance of the lead gap is modeled through the amount of deceleration that is required by the lane changer to avoid collision with its putative leader in the target lane.

Vehicle Behavior on an Acceleration Lane—vehicles on an on-ramp are given a desired free-flow speed. When these vehicles enter the acceleration auxiliary lane they are assigned a new desired free-flow speed to facilitate this merge. This is achieved by first scanning vehicle speeds in the adjacent through lane. These speeds are then averaged and the average speed is assigned to the vehicle on the acceleration lane as its desired free-flow speed. This improves the possibility of a smooth merge into the through traffic. The desired free-flow speed is reset upon completion of the merge.

Vehicle Generation—vehicles enter the freeway from entry nodes at constant intervals. This means, for a flow rate of 1,800 vehicles per hour, one vehicle enters the freeway every two seconds. The initial position of every vehicle that enters the freeway is 0.5 ft from the downstream end of the entry link. Each vehicle that enters the freeway is stochastically assigned vehicle and driver characteristics.

Origin-Destination Logic—the FRESIM model allows percentage turning movements to be input for each ramp junction. A gravity type trip generation model is used to calculate the number of vehicles that travel each link. The OD can also be specified by selecting a specific number of vehicles to traverse particular links at particular entry points. This input overrides the use of the gravity model.

Ramp Metering Control Logic—the FRESIM model simulates four methods of on-ramp control. These are clock time metering, demand/capacity metering, speed control metering, and gap acceptance metering control.

FRESIM Model Input/Output. This section describes the input and output data elements of the FRESIM traffic simulation model. Inputs for the FRESIM model can be divided into three broad categories: geometric properties, flow rate values, and operational features. Specifically, all of the following data elements can be input into the FRESIM model for analysis:

Geometric Properties

- number of lanes;
- lane alignment;
- lane addition;
- lane drop;
- acceleration lane;
- deceleration lane;
- vertical grade specification;
- horizontal curvature; and
- lane separation.

Flow Rate Values

- total volume entering the section through the first node; and
- entry and exit ramp volumes (expressed as percentage of mainline volume).

Operational Conditions

- stochastic driver types;
- vehicle types (percent of large vehicles in the traffic stream);
- rubbernecking factor;
- car-following sensitivity factor;

- incident conditions (placement, impact area, and duration);
- ramp metering (placement, type, and metering rate);
- surveillance systems (placement of loop detectors);
- advanced warning signs (distance from exit ramp node); and
- biased lane assignment of trucks.

Not all of these data elements are required by the model for execution; however, all are available for use in the analysis. The FRESIM model also produces a robust amount of output data including the following:

- vehicle trips;
- number of lane changes;
- vehicle miles;
- vehicle minutes;
- total travel time;
- delay time;
- average volumes and speeds;
- moving time;
- density;
- fuel consumption (optional); and
- emission rates: hydrocarbons, carbon monoxide, and nitrogen oxides (optional).

Another output feature of the FRESIM model is the ability to view and print the freeway network that is being modeled. FRESIM also contains an animation module which allows a user to view the simulated operations on the freeway network being analyzed to see how vehicles are interacting and progressing through the system. Additional information about the FRESIM model can be found at the following Internet sites **(6)**:

- http://kuhub.cc.ukans.edu/~pctrans

- http://www-mctrans.ce.ufl.edu/
- http://www.viggen.com/trafhome/index.htm

WATSim

This section gives a short summary of the WATSim traffic simulation model. WATSim is based entirely on the NETSIM (Network Simulation) simulation model logic. It was first introduced at the TRB annual meeting in 1996. This model is not marketed as a stand-alone software but is offered as part of a contract with its developer, KLD Associates. WATSim extends the functionality of NETSIM to incorporate both freeway and ramp operations simulation with surface street traffic simulation. WATSim's operational features include those in NETSIM plus HOV configurations, light-rail vehicles, toll plazas, path tracing, ramp metering, and real-time simulation and animation **(16)**. The WATSim simulation model also includes an interface with a traffic assignment model. One of the most desirable model features is the ability to explicitly define capacities for freeway links and ramps.

2.2.4 Mesoscopic Model

This section of the report provides some background information and documentation of a mesoscopic (see page 13) model, INTEGRATION, that is being utilized in the United States.

INTEGRATION

The INTEGRATION model was developed in the mid 1980's by Van Aerde **(17)** as an integrated simulation and traffic assignment model. This model was somewhat unique because it used the same logic to represent both freeway and signalized links and that both the simulation and traffic assignment components were also microscopic, integrated, and dynamic. In order for the INTEGRATION model to achieve these attributes, traffic flow was represented as a series of individual vehicles that each followed pre-specified macroscopic traffic flow relationships. The combined use of individual vehicles and macroscopic flow theory resulted in the model being classified as mesoscopic by many practitioners.

INTEGRATION Simulation Description. This section provides a brief overview of the simulation approach used by the INTEGRATION traffic model. The INTEGRATION model considers the behavior of traffic flow in terms of individual vehicles that have self-assignment capabilities. The model assigns individual vehicles sequentially to a network that has already been loaded. INTEGRATION models freeways by treating each unique section as a pipe with a maximum inflow rate, a maximum outflow rate, a maximum vehicle storage capacity, and travel time from entrance to exit which varies according to a user specified link travel time versus flow relationship. INTEGRATION contains shock-wave queuing analysis and queue spill-back analysis. The model traces individual vehicles in queue spill-back from upstream links and in delay in downstream links if arrivals are held up at an upstream bottleneck. INTEGRATION

also allows new arrivals to the network to redistribute themselves to avoid congested links. This redistribution is normally accomplished because INTEGRATION represents several different types of users that have access to different levels of real-time traffic information. Five vehicle types may be simulated with INTEGRATION. They are described as follows:

1. Background vehicles: these vehicles route choice is based on free-flow speed unless historic information or specified path trees are provided;

2. Guided vehicles: these vehicles have access to real-time information at every node or at selected locations on which to base their route choice;

3. Drivers with anticipatory knowledge: these drivers can base route choice on both real-time information and historical information;

4. In-vehicle navigation vehicles: these vehicles are equipped with route guidance systems that provide information to them in their vehicle; and

5. Special facility users: these vehicles have special access to selected links in the network and can base route choice on specified path trees or on real-time information.

INTEGRATION Model Input/Output. This section describes the input and output data elements of the INTEGRATION traffic simulation model. There are five required and four optional input files to the INTEGRATION model. These nine input files are described as follows:

1. Node File: the user specifies x and y coordinates of all nodes in the network in this file (required);

2. Link File: the user enters start and end nodes and physical characteristics of the links in this file (required);

3. Signal File: the user assigns signal timing plans for the traffic signals if the network being modeled contains both freeway and surface street facilities in this file (required);

4. Origin-Destination Traffic Demand File: the user specifies demand rates for all OD pairs for each time slice in the simulation period in this file (required);

5. Incident File: the user inputs the length, severity, and location of any incidents during the simulation period in this file (optional);

6. Average Travel Times File: the user designates average travel times for all links for use as historical information in this file (required);

7. Time Series of Anticipated Travel Times File: the user enters travel time information for each user-specified time slice in this file (optional);

8. Static Path Tree File: the user assigns path trees for the special facility user vehicles in this file (optional); and

9. Time Series of Multipath Background Traffic Routings File: the user enters path trees for the background vehicles in this file (optional).

The OD breakdown for the roadway is required for the *Origin-Destination Traffic Demand File*. A user can develop the OD breakdown, if unknown, using the built-in OD model. This model estimates OD traffic demands based on observed link traffic flow, link travel times, and route choices. The INTEGRATION model produces four types of fundamental simulation outputs for interpretation by the model user:

1. On-screen graphics/text: this output is displayed on video monitor;

2. Simulation run error file: this file lists the execution time and codes for the errors encountered while running the model;

3. Labeled output statistics file: this file provides the calculated measures of effectiveness on both the link level and network level; and

4. Summary file: this file gives the user two additional summary tables. The first one summarizes the number of vehicles that completed their journey (as specified by OD pair), the average journey time per arrival, and the accumulation of the total trip times for all vehicles. A summary of the vehicle demand on the network, the number of vehicles that entered and left the network, and the number of vehicles remaining on the network after the simulation is completed are provided in the second table.

2.3 APPLICATIONS OF FREEWAY SIMULATION MODELS

This section provides summaries of studies that document the usage of freeway simulation models. It is divided into two subsections. The first subsection provides information from studies that compared applications of more than one model to the same problem and also general studies that identify advantages and disadvantages of a variety of simulation models. The second subsection gives an overview of several studies that concentrated on the evaluation or application of one particular simulation model to a test situation.

2.3.1 Model Application: Overview of Comparative Studies

This subsection reviews the results and significant accomplishments of a number of comparative and general simulation model application studies. Each of the studies examined and compared the performance of two or more of the simulation models described in Section 2.2.

JHK & Associates Study: Application of Freeway Simulation Models to Urban Corridors

A 1992 research project, "Application of Freeway Simulation Models to Urban Corridors," was performed by JHK and Associates for the FHWA under a contract entitled "Analysis of Complex Congested Corridor Locations"**(18)**. The purpose of this project was to evaluate the effectiveness and ease of use of three freeway simulation models and the freeway analysis procedures described in the 1985 HCM by applying them to a series of real world situations. The three simulation models tested were FREFLO, FREQ, and FRESIM. JHK researchers applied each of these models and the Highway Capacity Software (HCS) to five case project locations that were experiencing severe operating problems. They used the models to evaluate the problems at each project location and to test a range of possible remedial actions. The model testing revealed some general observations:

- FREFLO and FREQ are best suited to corridor evaluations covering a considerable length of freeway [5 miles (8 km) or more] with an emphasis on determining the best location for transitioning between the basic number of lanes, computing the effectiveness portion of a cost-effectiveness analysis for various geometric alternatives, and evaluating traffic management and traffic control alternatives (such as incident management and ramp metering). A significant weakness of both of these macroscopic modeling systems is the difficulty in dealing with sections longer than the length in which a vehicle can traverse a section in one time slice.

- FRESIM is a more powerful model for testing detailed freeway design features with a particular emphasis on weaving areas, complex ramp merging areas, grades, and the interaction of these elements with certain traffic management measures. FRESIM would typically not be needed for the more standard geometric situations, in which defining basic lane requirements and the transition points (i.e., where to add or drop a lane) are the primary objectives.

- The HCM procedures should primarily be used for refining the basic number of lanes, similar to the application of FREFLO and FREQ. However, the HCS has no ability to analyze the interactive effects between sections (e.g., the effect of a bottleneck section on upstream sections).

- It may be appropriate to select more than one of the analysis tools to take advantage of the strengths of each model for certain conditions.

The results of this research will help the research team to better understand how to use the tested models to evaluate project locations with severe operating problems.

TTI Research Project 1232

A 1992 project entitled "Considerations in the Application of Freeway Computer Simulation Models to Project Evaluation" conducted by TTI focused on characteristics of and the process of choosing a freeway simulation model **(19)**. This project documented the internal characteristics (i.e., traffic stream representation, analysis basis, and analysis objective), input/output parameters, and difficulties encountered for a number of freeway simulation models (HCS, FREQ, FREFLO, CORFLO), INTRAS, and FRESIM). TTI researchers performed a case project comparison of a section of State Highway (SH) 114 in Dallas to display and evaluate the attributes of the basic assumptions (i.e., the default values) for each of the models tested. The FREQ, FREFLO/CORFLO, and INTRAS models produced reasonable results but did not exactly replicate the actual speeds. The HCS produced the least accurate operational results of the models tested. This research did not calibrate the models for the case project comparison or evaluate the FRESIM model because it was still being beta tested at the end of the project. Research project 3943 will address these omissions by attempting to calibrate the models that are selected for evaluation in this project.

University of Purdue Project: Validation and Evaluation of Freeway Simulation Models

A project completed in 1995 by researchers at Purdue University for the FHWA evaluated the performance of several freeway traffic simulation models using detailed data collected from California freeways **(20)**. Purdue researchers performed a literature review in order to identify existing models that are commonly in use, review the basic features and functions of these models, and evaluate historic user experience with these models. This research team selected three models for evaluation and calibration: INTRAS, FREQ, and FREFLO. The basic conclusion of this project was that these models were often unable to faithfully replicate observed freeway conditions on the freeway project sections. The Purdue researchers found this to be particularly true when the models were tested using data collected under conditions varying slightly from the calibration data. The INTRAS model could not be calibrated to the entire 10 mile test section due to its tendency to overestimate the detrimental impacts of bottlenecks. Evaluation of the INTRAS model suggested that modeling individual driver behavior is extremely difficult and perhaps not even possible. Assessment of the FREQ model showed that it was best at emulating observed conditions through separate models (with different bottleneck capacities) for simulating congested and uncongested conditions. Testing of the FREFLO model appeared to corroborate the earlier criticisms of Daganzo [1995] that argued that second order fluid approximations are not reasonable when applied to traffic flow **(21)**. This research was not able to calibrate the INTRAS model and also did not evaluate the newer and more enhanced counterpart, FRESIM. Again, the tasks included in project 3943 will address these omissions by including and attempting to calibrate the selected models for congested freeway sections in the Dallas area.

SMARTEST Project

The SMARTEST (Simulation Modelling Applied to Road Transport European Scheme Tests) Project is an ongoing project involving a consortium of universities and other agencies in Europe that are performing research on microscopic simulation models **(22)**. This project began in January 1997 and is scheduled for completion in February 1999. The project will be directed towards modeling and simulation of dynamic traffic management problems caused by incidents, heavy traffic, accidents, road works, and events. A review of existing models and simulation tools will be performed to find problem areas that need to be modeled when developing solutions to short-term traffic management problems. Generic models and procedures will then be developed and specified to fill in the most important gaps. The new models and procedures will be developed using existing data sets with any data groups being filled using data collection from sites in Barcelona, Toulouse, Stockholm, Turin, and Florence. Existing microscopic simulation models will then be enhanced to include the newly developed models. Comparisons will be made between the new model outputs and the data collected. The main outputs of this project will be an enhanced set of microscopic simulation tools for helping transportation professionals solve their short-term traffic management problems and a best practice manual detailing guidelines and procedures for their selection and use. Project 3943 will benefit from the parallel efforts of the SMARTEST project by keeping abreast of the European progress in the area of microscopic simulation modeling.

TTI Research Project 1994

TTI has performed extensive data collection on congested freeways in the Dallas District **(23)**. Under the freeway operations task of TxDOT project 7-1994, "Highway Planning and Operations for the Dallas District," TTI observed driving behavior on freeways where recurrent congestion occurs. This research identified patterns in driving behavior that create inefficiencies or hazards in the flow of traffic that might be corrected or avoided through design changes or by different signing, markings, or other traffic control devices. Research project 1994 also refined the analytic methods used to evaluate bottleneck or traffic flow improvement. FRESIM, the most widely used simulation model, was evaluated using operational data observed and collected from before and after studies of bottleneck improvements, as well as the driving behavior observations from the previous tasks. Research project 3943 will extend the research from the freeway operational task of project 1994 by evaluating and comparing several simulation models. The real world traffic data that TTI has collected for project 1994, as well as numerous earlier projects, will be essential in calibrating and validating the freeway simulation models which are selected for evaluation in project 3943.

University of Illinois Project: Comparison of Car-Following Models for Simulation

A project, "Comparison of Car-Following Models for Simulation," conducted by researchers at the University of Illinois was presented at the 1999 Annual TRB meeting in Washington, D.C. **(24)**. This project compared the car-following components of the NETSIM, INTRAS, FRESIM,

and CARSIM simulation models. The car-following component forms the basis for microscopic simulation models because it explains the behavior of drivers in a platoon of vehicles. The findings related to the FRESIM model are the most important for application to project 3943.

In FRESIM, drivers are generated with driver sensitivity factors or *k* values. The authors suggested that the average of these *k* values is the determining factor for density and volume outcomes in FRESIM. Therefore, calibration of FRESIM to yield average density and volume figures comparable to field data involves selecting a suitable mean *k* value. FRESIM uses a set of *k* values ranging from 0.6 to 1.5. This range represents the 10 driver types available in the model. The researchers ran tests with randomly generated *k* values within this range and determined that a *k* value of 0.9 provided the closest results to the field data for congested conditions when vehicles were coming to a stop. The authors concluded that a *k* value of 1.06 yielded density and volume profiles identical to the field data for non-congested conditions. Consequently, these results suggest that FRESIM did not provide good results for congested and non-congested conditions at the same time. Furthermore, this project recommended that new equations that simulate stop-and-go conditions be developed.

University of Hawaii Research: Simulation of a Large Network

This research, conducted at the University of Hawaii, investigated the application of three state-of-the-art simulation models on a large (12.5 miles, 20 centerline km) freeway/arterial integrated network. Researchers applied the INTEGRATION, CORSIM, and WATSim models to the network and compared their performance results **(25)**. The freeway portion of the network consisted of the EB portion of the H-1 freeway in Honolulu, Hawaii. The H-1 freeway has a three-lane basic cross section and is heavily congested, especially during the morning peak period. The Hawaiian researchers determined that the main limitation of these models is the large number of parameters that need to be modified in order to replicate real traffic conditions. The research team determined that the default parameters in each of the models never produced satisfactory results. Table 1 provides a summary of some of the strengths and weaknesses (for the freeway portion) identified by the authors for each of the models evaluated.

Macro Vs. Micro Freeway Simulation: A Case Project

This study, conducted in 1992, evaluated improvements to a section of IH 70 in Columbus, Ohio using the FREFLO and FRESIM simulation models **(26)**. The authors considered the FREFLO model, with modest calibration effort, to be an excellent tool for general traffic operations analysis. Furthermore, researchers asserted that FREFLO was easy to use and provided fast turn-around time for evaluating various geometric and control strategies. When the FRESIM model was considered, the researchers contended that it should be used only in cases where microscopic detail is warranted (i.e., complex geometry, determining placement of warning signs and detectors, significant change in vehicle mix, multiple weaving areas, etc.). The authors made several recommendations to aid future model users based on their evaluation:

Table 1. Summary of Model Strengths and Weaknesses (25).

CORSIM Model	
Strengths	Weaknesses
1. Most realistic lane-changing maneuvers (distance for activating mandatory lane-changing maneuvers can be adjusted by the user) **2.** The speed profile corresponded closely to the actual profile from an instrumented vehicle **3.** Produced good replication of freeway link volumes (range between -6.0 to +1.1% error)	**1.** Extensive modification of car-following parameters was necessary to replicate the real traffic conditions **2.** Percentile input for off-ramp volume is inconvenient and causes difficulty **3.** Large number of destination-reassigned and missed destination vehicles **4.** Lower speeds on freeway on-ramp segments
INTEGRATION Model	
Strengths	Weaknesses
1. Suitable for planning analyses that involve significant routing changes (e.g., lane closures, turn prohibitions, ITS applications, etc.) **2.** Produced the best replication of freeway link volumes (range between -2.2 and +1.6% error)	**1.** Difficulty with lane changing because lane-changing propensity gradually increases as a vehicle approaches a "hardwall" at which point a mandatory lane change must be completed. As a result, vehicles give up lane-changing opportunities on less congested links and cannot find gaps to change lanes near the "hardwall" **2.** Tedious origin-destination table determination **3.** Produced the least accurate speed profile
WATSim Model	
Strengths	Weaknesses
1. Freeway capacities may be defined explicitly by the user **2.** Needed fewest modifications to the default parameters to produce a reasonable replication of actual conditions **3.** Produced good replication of freeway link volumes (range between -2.4 to +2.2% error)	**1.** Animation feature is inferior to the other two models evaluated **2.** Globally (both surface street and freeway) applied NETSIM car-following and lane-changing parameters is an undesirable feature that might compromise accuracy **3.** Sensitivity to merging/acceleration lane lengths

1. Maintain an updated data base: successful application of simulation requires accurate input on many traffic and geometric parameters.

2. Validate and /or calibrate the model: the model should reproduce the field conditions reasonably close before use for the evaluation of improvement alternatives.

3. Study the output thoroughly: the set of summary (i.e., network-wide) statistics should not be the sole foundation of the argument for or against an improvement. The output for individual links should always be reviewed to detect significant errors or variations.

4. Dedicate staff and computers for simulation: simulation models are indispensable tools that help engineers do their job better and faster. Personnel and computer resources dedicated to simulation are wise investments for guaranteed productivity increase today and in the future.

Elefteriadou Project: Selecting Simulation Models in Traffic Operational Analyses

This research project developed a framework for selecting simulation models in traffic operational analyses, especially for situations and conditions not addressed in the HCM **(6)**. The author's (Elefteriadou) framework for selecting and applying a simulation model for freeway (i.e., uninterrupted flow) facilities is divided into the following eight steps:

1. Problem identification: the first step involves identifying the problem and to define the purpose of the project. Elefteriadou suggests that a properly defined problem and project scope will lead to a correct selection of models and procedures for the project.

2. HCM assessment: the second step involves assessing whether or not procedures found in the HCM can be successfully applied to the problem. If it is determined that the HCM cannot be successfully applied, then simulation is needed and steps 3 - 8 are necessary.

3. Model selection: the third step involves actually selecting the simulation model or models that will be used to analyze the facility. Elefteriadou advocates that a user should relate relevant model features to problem needs in order to determine which model satisfies the problem needs to the greatest extent. There are several key model features that can be used to evaluate a model's capabilities, such as size of network, network representation, traffic representation, traffic composition, traffic operations, traffic control, and model output. Other important considerations in the selection of an appropriate model are the data requirements and availability, ease of use, available versus required resources, and the level of experience in application of the model(s).

4. Data assembly: the fourth step involves data assembly. This process involves assembling existing data and collecting missing data that is necessary for the simulation analysis.

5. Input file management: the fifth step involves creation and formatting of input files. This is normally accomplished using one of three methods: importing data from a traffic database, converting an input file from another model, or entering the data from scratch.

6. Model calibration and validation: the sixth step includes the processes of model calibration and validation. This process is conducted to ensure that the model does, in fact, provide a reasonable approximation of reality (i.e. observed field conditions).

7. Model output analysis: the seventh step involves analyzing the model output. This step can range from simple reporting to complex statistical analysis of simulation results.

8. Alternatives analysis: the final step involves conducting the alternatives analysis (after satisfactory simulation results are obtained for the baseline existing conditions case). During this step, the model user creates and evaluates data sets for improvement alternatives (different geometry, traffic control(s), and/or traffic demand).

2.3.2 Model Application: Overview of Model-Specific Studies

This subsection reviews the results and significant accomplishments of a number of model-specific application studies. Each of the studies reviewed by the research team evaluated the performance of only one of the simulation models described in Section 2.2.

Calibration of FRESIM to Achieve Desired Capacities, Payne et al. 1997

This project examined methods for calibrating key parameters to achieve desired freeway capacities for the FRESIM model during incident and incident-free conditions **(27)**. Payne et al. explored the impacts of key parameters on capacity through systematic variation. Specifically, the car-following sensitivity factor (CFSF) and the rubbernecking factor (RF) were evaluated for their effect on incident-free and incident capacity respectively.

Payne et al. asserted that the traffic capacity of a freeway segment during incident-free conditions depended primarily on the CFSF parameter. The CFSF parameter in FRESIM, denoted by the variable *k* in the user's manual, controls the aggressiveness associated with the driver population. The lower the CFSF value, the more aggressive the driver will follow their lead vehicle. Therefore, if the CFSF values in the model are lowered, an increase in the resulting traffic capacity can be expected. In order to explore the relationship between the CFSF parameter and freeway capacity, the authors created seven different CFSF distributions (1 to 10, 5.5 mean; 2 to 11, 6.5 mean; 4 to 13, 8.5 mean; 6 to 15 (default factors), mean 10.5; 8 to 17, mean 12.5; 10 to 19, mean 14.5; and 12 to 21, mean 16.5) for testing on four-lane, three-lane, and two-lane nominal freeway segments with an upstream on-ramp. Table 2 shows the results of this analysis (i.e., approximate freeway capacities).

Table 2. Impact of Car-Following Sensitivity Factors on Capacity in FRESIM (27).

Mean CFSF Value	Approximate Freeway Capacities (vphpl)		
	4-lane	3-lane	2-lane
5.5	3,275	2,880	2,800
6.5	3,100	2,810	2,770
8.5	2,775	2,620	2,490
10.5	2,425	2,350	2,230
12.5	2,140	2,100	1,990
14.5	1,900	1,850	1,800
16.5	1,725	1,680	1,680

The next case project performed by Payne et al. examined the effects on the freeway capacity produced by FRESIM when varying the RF. The RF parameter in FRESIM affects the CFSF value of vehicles within the impact area associated with a traffic incident. Specifically, the CFSF value of vehicles within the impact area is given by $k \times (1 + \text{RF})$, where k is the CFSF value of the vehicle outside the impact area. In order to quantify the effects of the RF parameter with regard to segment capacity, Payne et al. conducted systematic experiments for each of the CFSF scenarios identified in Table 2 for various types of incident conditions. The types of incidents investigated included shoulder incidents and one-lane blockages of the mainline for a typical three-lane freeway segment. The results of this analysis indicated that the RF parameter directly controls capacity at the incident site for shoulder incidents. Payne et al. also concluded that for low traffic demands, the value of the RF parameter has little effect on the segment output volume. The results of the right-lane blocking incident case again showed that the RF parameter significantly affects segment capacity. Payne et al. asserted that for fixed values of CFSF and RF, the capacity for an incident in the right lane is significantly less than when the incident is on the shoulder. The results for the middle-lane blockage incident case were very similar to the right-lane case with a few exceptions. Payne et al. determined that the maximum freeway capacity associated with an incident in the middle lane of a three-lane segment is approximately 1,800 vphpl. These results will be of great assistance to research being conducted in project 3943. Specifically, the documentation of how a wide range of CFSF and RF factor values affect freeway capacity will help the TTI research team calibrate the FRESIM model for the selected test sections.

Calibration of FRESIM for Singapore Expressway Using Genetic Algorithm, Cheu et al. 1998

This project applied the FRESIM model to simulate traffic operations in Singapore on a 3.6 mile (5.8 km) segment of the Ayer Rajar Expressway (AYE) **(28)**. The main objective of this research

was to calibrate the FRESIM model using the genetic algorithm (GA) approach so that the model detector outputs matched the 30 second speed and volume data from loop detector stations along the AYE. GA is a heuristic optimization technique based on the mechanics of natural selection and evolution. At any time step during a search (or generation), GA progresses towards the optimum solution from a population of points, instead of a single point commonly found in conventional optimization techniques. Cheu et al. successfully used the GA approach to calibrate FRESIM against field data for both the evening peak traffic and for midday off-peak traffic. After the calibration process, the authors concluded that the calibrated parameter values indicated that drivers in Singapore are more aggressive in car-following and lane-changing compared to the default parameters in the FRESIM model. This project produced several other important findings that indicate directions for future research:

- The free-flow speed, minimum car-following distance, and car-following sensitivity factors are the most important and sensitive parameters in FRESIM simulation; therefore, more effort should be devoted to the calibration of these parameters.

- The use of different car-following equations in FRESIM may need to be examined.

- FRESIM should incorporate the ability to input different free-flow speeds for different vehicle types (e.g., heavy trucks vs. passenger cars) to make the model more useful.

The findings of this project seem to reinforce earlier studies on the calibration of the FRESIM model. This project will also assist our research effort, particularly in the examination and calibration of the FRESIM model.

Computer Simulation of IH-95 Lane Closures Using FRESIM, Dixon et al. 1995

This research project evaluated the suitability of the FRESIM freeway model (Version 4.5) for simulating a simple freeway lane closure at a work zone **(29)**. Dixon et al. used two simulation techniques in FRESIM to represent a work zone that reduces a two-lane freeway section to only one lane. The first simulation technique treated the work zone as an incident with complete lane blockage for the entire 4 mile geometric constriction. The second technique simulated the closure as a permanent 4 mile geometric constriction (i.e., a lane drop at the beginning of the work zone). The project also used two data sets to evaluate the FRESIM model performance. Data Set 1 consisted of moderate traffic volumes with a queue present at the work zone (1032 vehicles, 35 percent trucks). Data Set 2 consisted of very light traffic volumes at sunset with no observed queue present (466 vehicles, 48 percent trucks).

The results of the simulation experiment, shown in Table 3, indicated that FRESIM provided reasonably accurate results using both the incident and permanent geometry scenarios for low volume, free-flowing conditions (i.e., Data Set #2). The speeds reported in Table 3 are end of taper speeds. The simulation comparison also revealed that results were less accurate for the higher volume conditions of Data Set #1. Dixon et al. concluded that the FRESIM model does

not provide credible results for congested work zone conditions. They contend that constricted flow conditions are the primary condition sought when simulating a work zone.

Table 3. Speed Comparison for FRESIM Work Zone Project (29).

Variables		Speed (mph)	
		Data Set 1	Data Set 2
Observed Mean (Standard Deviation)		39 (16.1)	60 (2.6)
FRESIM Mean (Standard Deviation)	Incident Scenario	54 (2.1)	55 (2.9)
	Permanent Geometry Scenario	56 (2.6)	54 (2.2)

Complex Freeway Design Solutions Using Microscopic Simulation, Jackson et al. 1994

This project, conducted by Jackson et. al., evaluated the application of the FRESIM microscopic simulation model to three complex operational problems encountered in the segment of IH 94 between IH 894 and US Highway 45 in Milwaukee, Wisconsin **(30)**. The three operational problems in this vicinity are a complex cross weave, a multi-lane merge, and a high volume off-ramp in a weaving section. Jackson et al. decided that these complex operational problems required the use of a microscopic simulation model because conventional analytical methods, such as those in the HCM, were not able to sufficiently analyze the situation. This type of situation is also the basis for research project 3943 being conducted by TTI. The 3943 project team has often encountered severe and complex operational problems, such as those on the IH 94 project section, which seem to require a simulation approach to produce the type of analysis necessary. Jackson et al. concluded that the FRESIM model provided the tools needed to analyze the complex operational problems on IH 94. Furthermore, there was the assertion that microscopic simulation provided the opportunity to test design alternatives that violate some of the traditional standards of lane balance, spacing, and maintaining of basic lanes. This type of flexibility is important because unconventional improvement alternatives are sometimes necessary for solving complex operational problems because conventional approaches may be unfeasible for implementation.

CHAPTER 3

PROJECT METHODOLOGY

This chapter provides an overview of the methodology used during this research. The research team divided the project methodology into six distinct steps which are explained in the remainder of this chapter. Section 3.1 describes of the process of selecting the simulation models for further project. It also provides some general information on why the selected models were chosen. Section 3.2 gives an overview of the project site selection process and some basic information on each of the selected sites. Section 3.3 explains the network coding process and how the performance of each of the selected models was evaluated using the default parameters (i.e., the base case). Section 3.4 discusses the model calibration procedures and techniques used to improve the performance of the selected models. Finally, Section 3.5 outlines the model validation portion of this project.

3.1 MODEL SELECTION

The first task in this research, after completion of the literature review, was to select the simulation models that would be included in this project. The research team decided that three simulation models would be selected for further project in order to have a good basis for comparison of their performance. The literature review revealed that a number of mainstream simulation models are available for analyzing freeway facilities including: FREQ, FREFLO, K-Waves, INTEGRATION, WATSim, and CORSIM (FRESIM component).

3.1.1 Model Selection Criteria and Considerations

In order to choose the most promising models for inclusion in this research, the research team developed several selection criteria and considerations. The following list provides the six selection criteria and considerations that were used to identify the three most promising models:

1. Models must be able to simulate traffic operations on freeway facilities.

2. Models should have the capability to simulate vehicle operations on both main lane and ramp facilities.

3. Models should be suited to evaluating congested conditions.

4. At least one microscopic and one macroscopic model should be included in the project.

5. Models should have widespread use and documentation (i.e., user's manuals, published studies, etc.) that is readily available for users.

6. Some level of ongoing development and technical support is desirable.

Based on these criteria and considerations, with input and approval of the project director and advisory team, the research team selected the following three models for inclusion in this project:

1. FREQ;

2. INTEGRATION; and

3. FRESIM.

The research team selected the FREQ model because it is macroscopic and because it was consistently cited in the literature for good analysis of congested conditions and for evaluation of HOV facilities. The team did not include FREFLO because it has not been widely used and a University of Purdue project **(20)** cast doubt on the traffic flow theory used by the model. The INTEGRATION model was also chosen because it is mesoscopic and the literature review suggested that it has produced good results, mainly in the evaluation of benefits of intelligent transportation system (ITS) projects on freeway operations. K-Waves was not included because it is a relatively new and untested model and because it does not have the capability to have ramps as part of the modeled network. The FRESIM model was the final model selected because it is the most widely documented, it is microscopic, and a lot of information on calibration techniques is available in the literature. FRESIM was selected over the other microscopic model, WATSim, because it is much more widely used throughout the United States.

3.2 SITE SELECTION

The next task in this research project was the selection of project sites to test and evaluate the simulation models that were chosen. Similar to the model selection process, the research team decided that three sites would be selected for the model evaluation in order to have a good basis for comparison of their performance. A candidate list of sites (approximately 10) was developed by the research team and presented to the project director and advisory team at a meeting on March 24, 1999. One of the primary purposes of this meeting was to discuss the positives and negatives of each site and gain input on which sites would be selected for inclusion in the project.

3.2.1 Site Selection Criteria and Considerations

In order to choose the most best project sites for inclusion in this project, researchers developed several selection criteria and considerations. The following list provides the four selection criteria and considerations that were used to identify the three best sites:

1. Sites must be within the boundaries of the Dallas/Fort Worth metropolitan area (as defined by the North Central Texas Council of Governments (NCTCOG)).

2. Sites should have a variety of features (e.g., geometric layouts, congestion level, etc.) so that the models can be evaluated for different types of freeway sections.

3. Sites must experience some degree of recurrent congestion during either the morning or evening peak traffic period.

4. Existing operational data must be available because no new data collection was proposed for this project.

Based on the review of the candidate sites, the attendees at the March 24th project meeting decided that the following three sites would be selected for this project:

- Site 1—southbound (SB) Spur 408 to westbound (WB) IH 20;
- Site 2—EB IH 635 (LBJ Freeway) to northbound (NB) US 75 (Central Expressway); and
- Site 3—NB State Highway (SH) 360 between Mayfield and Randol Mill.

Each of the chosen sites met all of the selection criteria and considerations. The following subsections (i.e., 3.2.2–3.2.4) provide basic information (site description, time period, before conditions, improvements, and after conditions) on each of the selected sites. Figures showing the geometric layout (e.g., number of lanes, entrance and exit ramps, etc.) of each site both before and after the bottleneck improvement are also provided in these subsections. These figures depict a portion of each site that is included in the coded network of the three simulation models used in this research.

3.2.2 Site 1: SB Spur 408 to WB IH 20

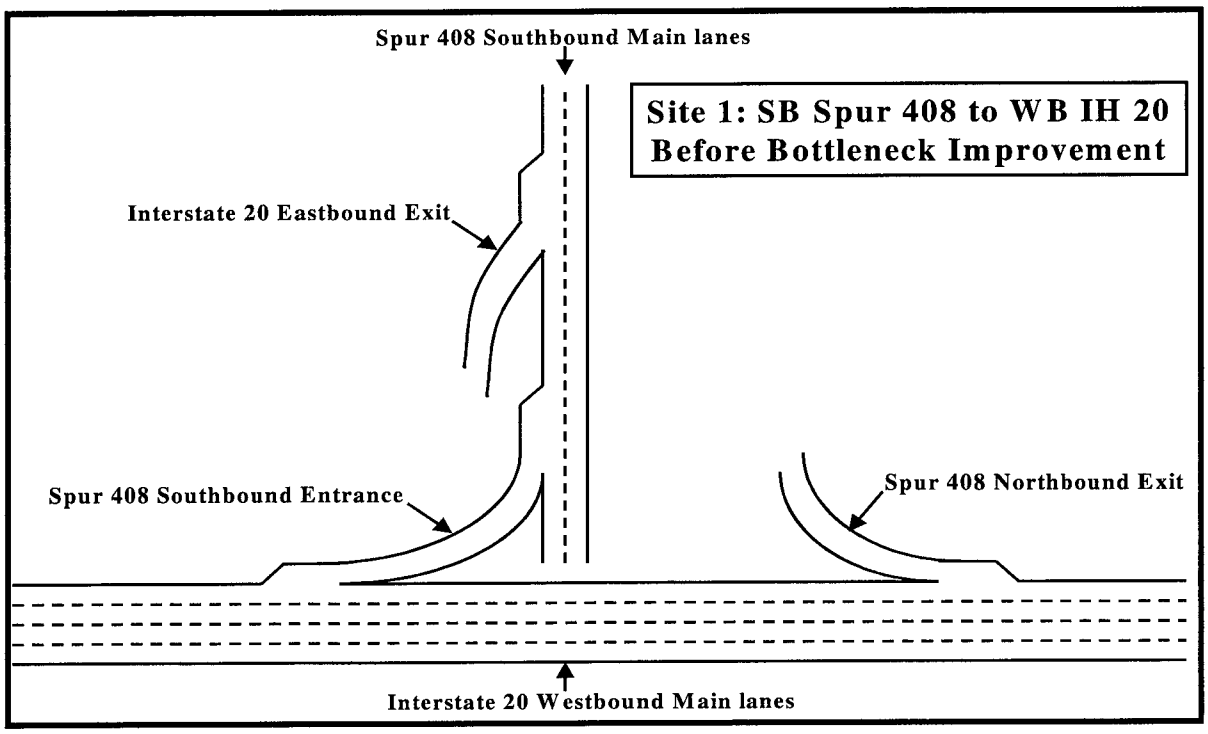
Site Description: This site contains portions of both Spur 408 and IH 20 in southwest Dallas County. The portion of SB Spur 408 included in the project is between just south of Grady Niblo road to IH 20 (approximately 2 miles). This section of Spur 408 consists of a two-lane basic cross section and also has two exits (IH 20 EB and IH 20 WB). The portion of WB IH 20 included in the project is between just west of Cedar Ridge entrance ramp to just prior to the Mountain Creek Parkway exit ramp (approximately 2 miles). This section of IH 20 consists of a four-lane basic cross section and also has one exit (NB Spur 408) and one entrance (SB Spur 408). The terrain is hilly and a greater than average percentage of heavy trucks use both facilities on a daily basis. The entire site (i.e., the portions of both Spur 408 and IH 20) can probably be characterized as rural in nature due to the lack of any significant development adjacent to the freeways.

Time Period: Evening peak period (4:00–7:00)

Before Conditions: The top frame of Figure 4 shows the geometric layout of this site prior to the bottleneck improvement. This site experienced moderate congestion during the evening peak period on a recurrent basis. The congestion was primarily due to the high demand for the SB Spur 408 to WB IH 20 movement. Because this traffic had a forced merge to join IH 20, queuing and low speeds were experienced on the Spur 408 main lanes in the vicinity of this interchange.

Improvements: The bottom frame of Figure 4 shows the geometric layout of this site after the bottleneck improvement was implemented. This improvement involved three major elements: (1) addition of a deceleration lane on Spur 408 from EB IH 20 exit to the SB Spur 408 entrance, (2) striping the SB Spur 408 entrance ramp for two-lane operation, and (3) striping out the rightmost lane of IH 20 between the NB Spur 408 exit ramp and the SB Spur 408 entrance ramp. The first two improvements added capacity on Spur 408 to accommodate the high demand volumes going to IH 20. The third improvement reduced the number of through lanes from four to three for WB IH 20 traffic at the Spur 408 interchange. Therefore, the right lane on IH 20 became an exit-only lane to the NB Spur 408 exit ramp and, more importantly, the SB Spur 408 entrance ramp now entered as a lane addition instead of a forced merge.

After Conditions: The bottleneck improvement significantly improved the traffic flow and average speed on SB Spur 408 between the EB IH 20 exit and the SB Spur 408 entrance. The average speed in this section prior to the bottleneck improvement was approximately 25 mph (from 5:15 to 6:30 PM). The average speed improved by 30 mph to just over 55 mph after the bottleneck improvements were in place. It should also be noted that the reduction of the IH 20 main lanes from four to three did not have an adverse impact on the speeds for westbound through traffic.



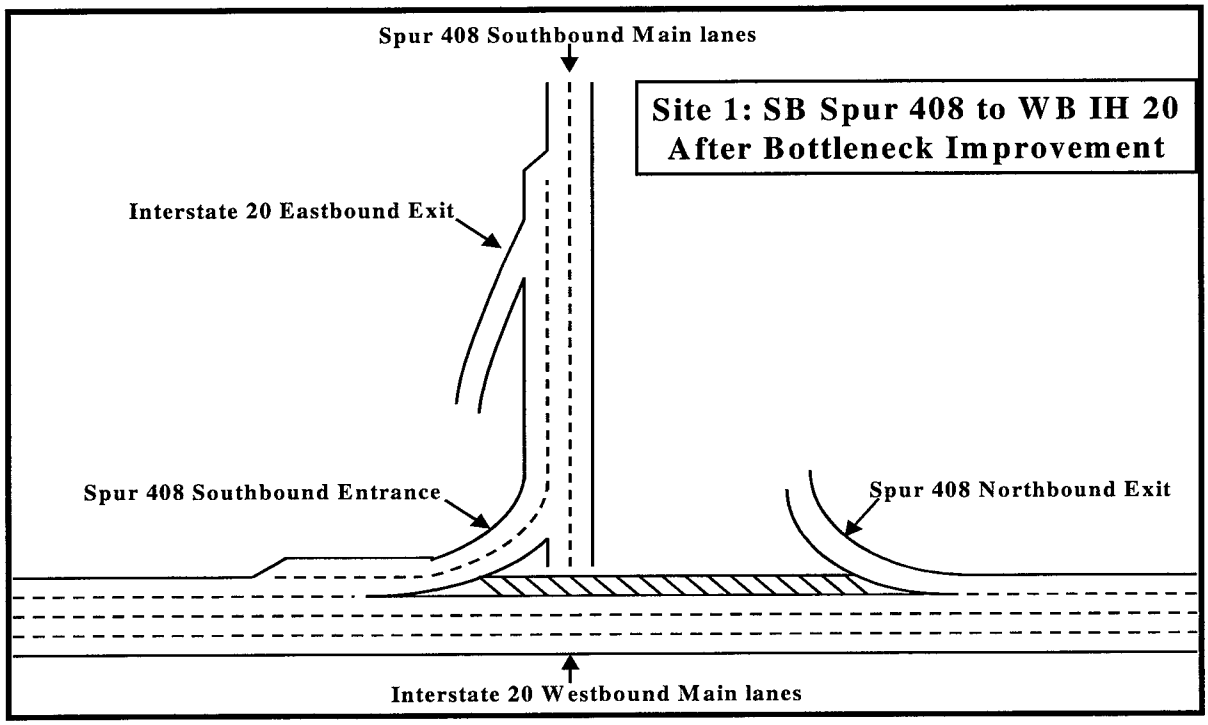


Figure 4. Site 1: SB SP 408 to WB IH 20: Before and After Bottleneck Improvements.

3.2.3 Site 2: EB IH 635 to NB US 75

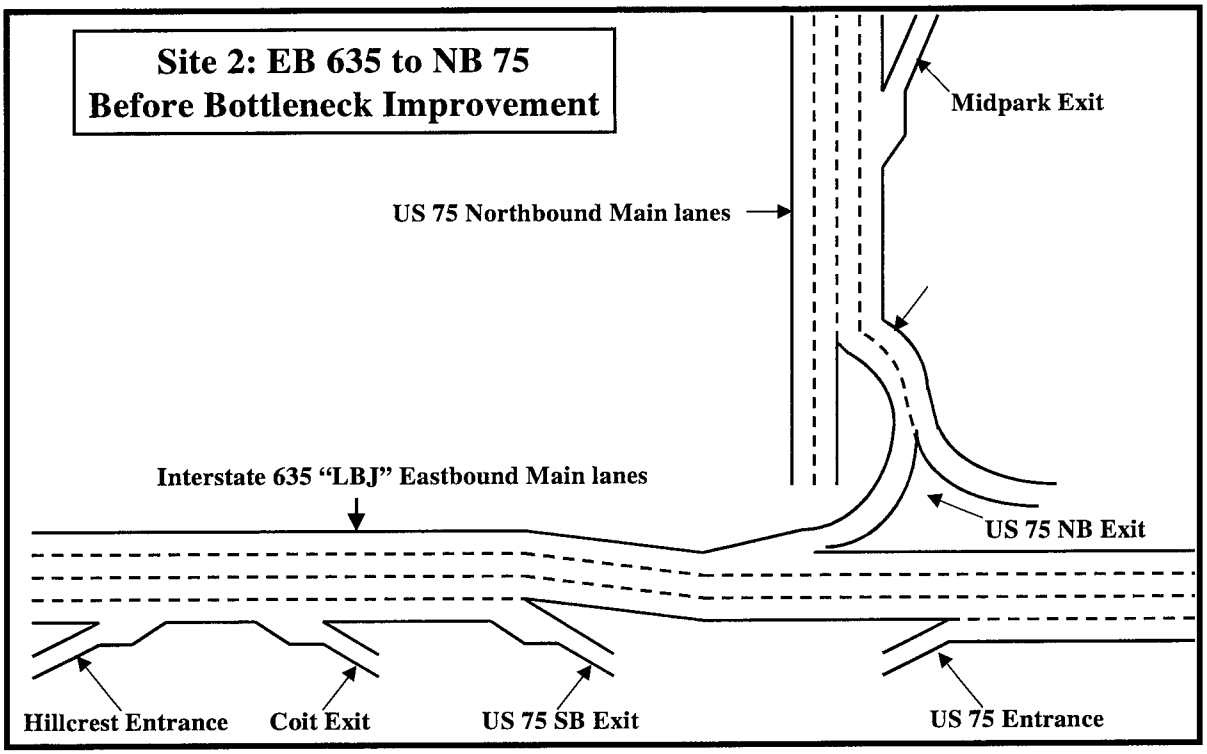
Site Description: This site contains portions of both IH 635 (LBJ Freeway) and US 75 (Central Expressway) in far north Dallas County. The portion of EB IH 635 included in the project is between just west of the Hillcrest entrance ramp to just prior to the Floyd Road exit (approximately 1.9 miles). This section of IH 635 consists of a four-lane basic cross section with three exits (Coit, SB US 75, and a left side exit to NB US 75) and two entrances (Hillcrest and the combined US 75 ramps). The portion of US 75 included in the project is between just north of IH 635 to just past the Midpark Road exit (approximately 0.9 miles). This section of US 75 consists of a two-lane basic cross section and also has one exit (Midpark Road) and one entrance (IH 635 combined WB and EB ramps). The terrain is basically level, and this site is located in one of the most heavily developed and traveled corridors in all of the Dallas/Fort Worth metropolitan area.

Time Period: Evening peak period (4:00–7:00)

Before Conditions: The top frame in Figure 5 shows the geometric layout of this site prior to the bottleneck improvement. Traffic on the LBJ main lanes experienced a significant amount of recurrent congestion during the peak periods on the eastbound approach to the interchange with US 75. This congestion was primarily caused by the lane drop at the southbound US 75 exit ramp and the extremely high traffic demand to exit to northbound US 75. This exit had several properties that made it a bottleneck, including being on the left side of the freeway, having severe horizontal curvature and sight distance problems, and being only one lane.

Improvements: The bottom frame of Figure 5 shows the geometric layout of this site after the bottleneck improvement. The improvement involved conversion of the left shoulder between the SB and NB US 75 exits on IH 635, elimination of the lane drop to SB US 75, and widening of the NB exit ramp to two lanes to accommodate the high NB traffic demand.

After Conditions: The bottleneck improvements created significant improvements to the evening peak period operations. The average speed on this facility was raised from 30 mph to 42 mph because of the new capacity provided by the bottleneck improvement. The improvements increased throughput (i.e., average volume per hour past a point on the freeway) of the facility by approximately 40 percent.



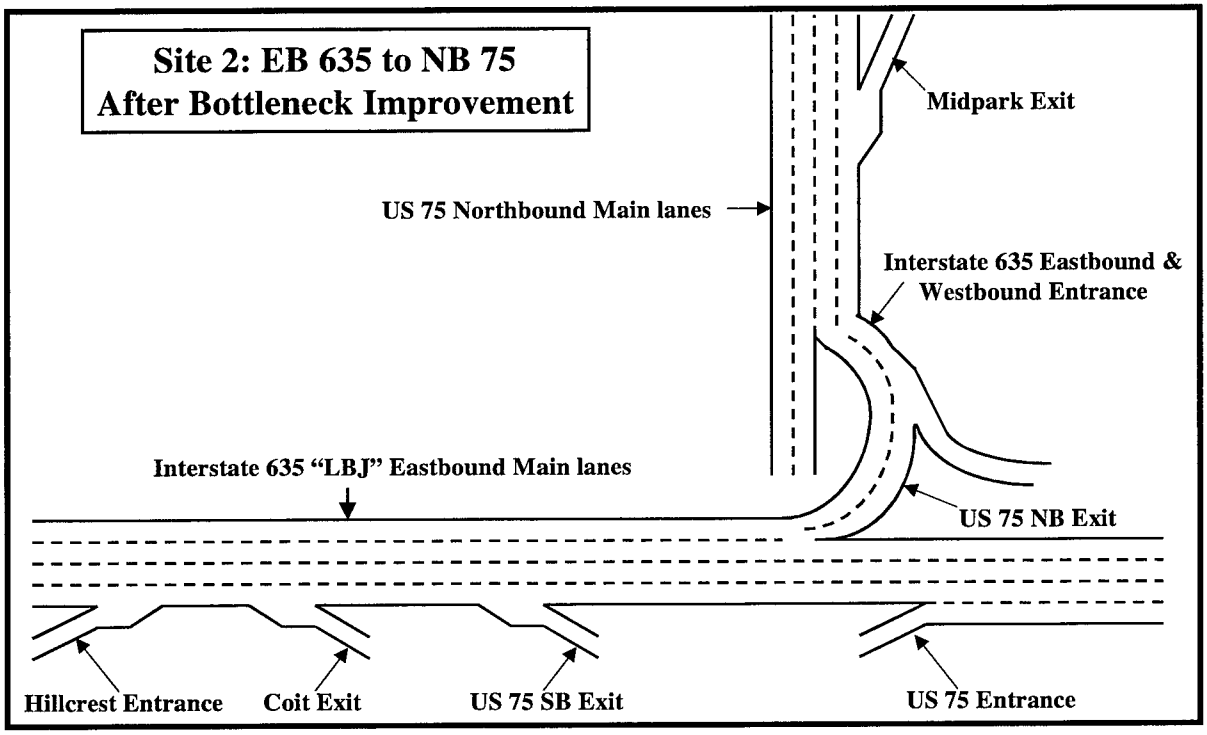


Figure 5. Site 2: EB IH 635 to NB US 75: Before and After Bottleneck Improvements.

3.2.4 Site 3: NB SH 360

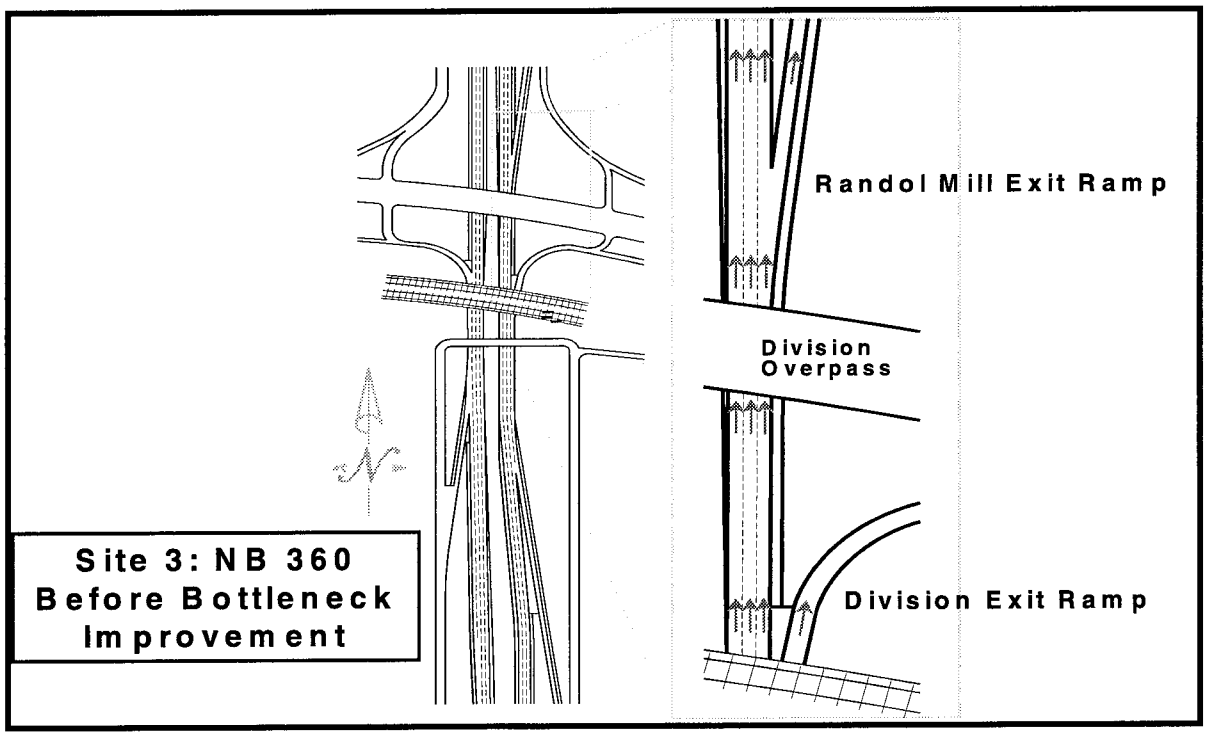
Site Description: This site contains the portion of SH 360 between the Mayfield and Randol Mill (approximately 4 miles). This section of SH 360 consists of a three-lane basic cross section and also has six exits (Arkansas, Spur 303, Park Row, Abram, Division, and Randol Mill) and five entrances (Mayfield, Arkansas, Spur 303, Park Row, and Abram). The terrain is rolling, and this facility services a number of large traffic generators (Six Flags/Hurricane Harbor, Ballpark in Arlington, Great Southwest Industrial Park, American Airlines Corporate Headquarters, DFW International Airport, etc.).

Time Period: Morning peak period (6:00–9:00)

Before Conditions: The top frame of Figure 6 shows the geometric layout of this site prior to the bottleneck improvement. This is a heavily traveled north/south freeway that experienced congestion during the morning peak period. A significant bottleneck existed because of the geometric restrictions in the vicinity of the Division interchange. The geometric restrictions included narrow lanes due to the railroad bridge and a lane drop at Division, high volume of traffic entering at the Abram entrance ramp, and some vertical profile issues (i.e., grade) of the main lanes. Traffic queued back from the Division ramp area, sometimes all the way back to Arkansas, for a significant portion of the morning peak.

Improvements: The bottom frame of Figure 6 shows the geometric layout of this site after the bottleneck improvement was constructed. The bottleneck improvement involved the extension of an auxiliary lane between the Abram entrance ramp and the Randol Mill exit ramp. This extension was approximately 600 ft in length. This auxiliary lane was created by shifting the lane striping and adding some new pavement and "beefing up" the existing right shoulder. This improvement allowed four lanes to pass under the railroad bridge at Division instead of three and provided the Abram entrance ramp more distance to merge into NB SH 360 traffic.

After Conditions: The implementation of the bottleneck improvement on SH 360 produced somewhat mixed results. For the section of freeway between Abram and Randol Mill, traffic volumes and travel speeds each increased by almost 10 percent during the morning peak period as a result of the added capacity in this section. Benefits were not as apparent for the rest of the project section (i.e., between Mayfield and Abram) probably because a secondary bottleneck still exists somewhere in this area.



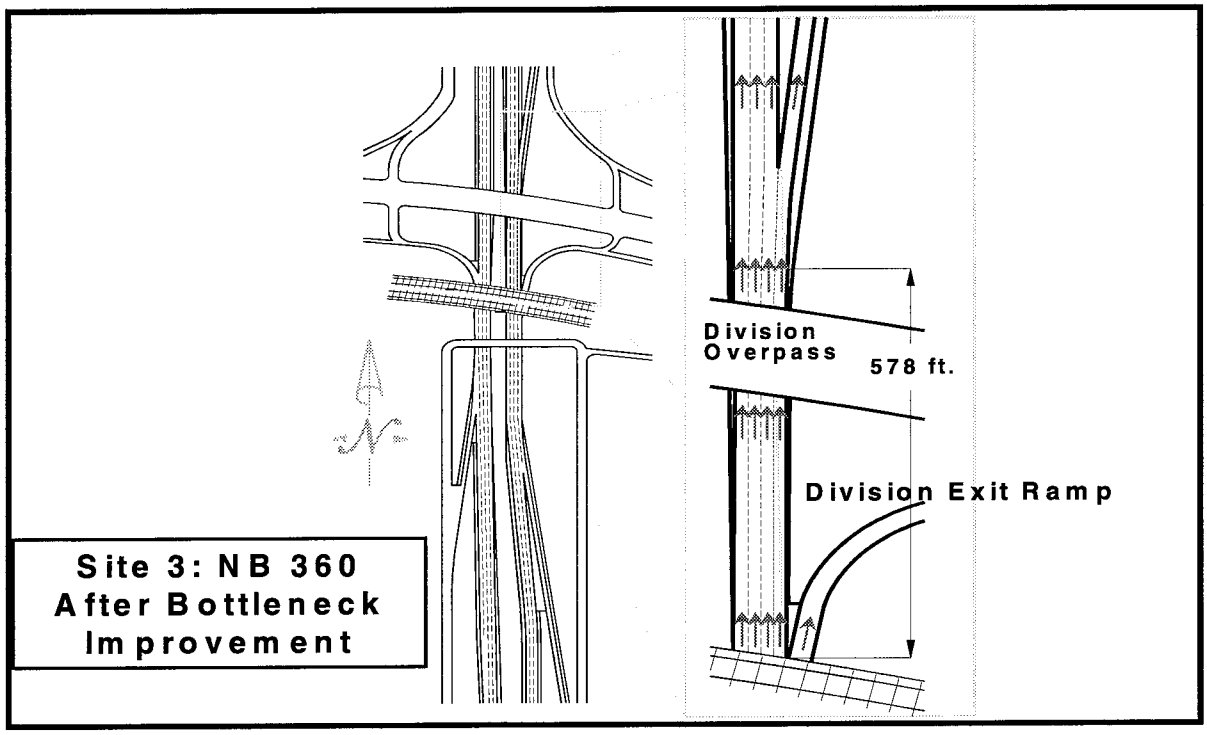


Figure 6. Site 3: NB SH 360: Before and After Bottleneck Improvements.

3.3 BASE CASE SIMULATION

After the research team completed the selection of simulation models and project sites, the next step involved performing the actual case studies. The first phase of the case studies consisted of simulating the conditions that existed before the bottleneck improvement (i.e., the base case). In order to evaluate the performance of each of the models before any adjustments or calibration measures were considered, the research team used the model default parameters to simulate the base case conditions.

3.3.1 Base Case Network Coding

All of the simulation models included in this project basically use the same approach for representing the physical freeway network (in this case the three project sites) within the computer model. The physical freeway network is described in terms of links (referred to as subsections in FREQ) and nodes. Links represent one-directional segments of roadway having constant geometric features. Nodes represent changes in continuity such as ramp merges, changes in grade, changes in curvature, etc. The following three subsections describe the basic procedures and methods used by the research team to code the project site networks.

3.3.2 FREQ Network Coding

The coding of a network using the FREQ software is a very straightforward process. The following text describes the general process used by the research team to code each of the three project sites in the FREQ software.

Step 1: FREQ is a DOS (Disc Operating System)-based program that seems to run more efficiently outside of the Windows operating environment. Therefore, the first step in the coding process was to shut down Windows and then execute the FREQ program in DOS.

Step 2: Once inside the FREQ program, select the 'Priority Entry' option (press 1) and then 'Start a New Problem' option (press 1) on the 'Main Menu' screen.

Step 3: At this juncture, the software will take you to the 'General Description' screen where the user inputs the following information: route, direction, beginning time, ending time, date of data, date of investigation, investigator, and comments.

Step 4: Once the user has exited the 'General Description' screen by pressing F10, a screen will appear where the user can put in the geometric properties (i.e., number of lanes, on-ramp/off-ramps, type of merge analysis, mean freeway gradient, and percent trucks including the percent of these which are diesel) for the first subsection of the freeway network.

Step 5: Once the user has accepted the data on the geometric properties input screen by pressing F10, a screen showing the actual geometry of the subsection just defined in Step 4 will appear with default values for (1) ramp capacity, (2) subsection description, (3) subsection length, (4) subsection capacity, and (5) free-flow speed. The user can edit any of the values to match the data for the subsection of the freeway network.

Step 6: After pressing F10 to accept the data on the subsection default values screen, the user will be sent back to another geometric properties screen. At this point in time the user would repeat Steps 4 and 5 until all of the subsections in their network had been input.

Step 7: When Step 6 is complete, the user can press F10 to access the 'Main Menu' screen. The user can then press option 4 to access the 'Modification Menu.' In order to access the 'Time Slice Demand Input' screen, the user should again select option 4.

Step 8: Once the 'Time Slice Demand Input' screen has been accessed, the user can enter the values for the following freeway time slice demand data: (1) number of time slices (maximum of 24), (2) number of time slices per hour, (3) type of demand data, and (4) time at the beginning of the first time slice.

Step 9: When the user is satisfied with the time slice data entered in Step 8, the user can press F10 to move to the screen where traffic volumes for each designated time slice can be input for each of the subsections that have been created in the freeway network.

Step 10: After completing the entry of traffic volume data, the user can the access the 'Main Menu' and save the file prior to making a simulation run.

Use of the methodology described in Steps 1 through 10 will produce a FREQ input file that is ready for processing and analysis. The FREQ software does allow the user the option of printing out the freeway geometry (i.e., all of the subsections in the coded network) with capacity, speed, and time slice data shown in order to check the accuracy of the input data.

3.3.3 INTEGRATION Network Coding

The coding of an integration network is a relatively straightforward process, and the following steps describe how the researchers utilized this model.

Step 1: The first step in creating an INTEGRATION network is to access the DOS prompt from Windows. All the input data is entered as ASCII (American Standard Character Set Number 2) characters in a free format style using the

DOS editor. All numeric fields can be separated by spaces, and the exact placement of information in the row or line is not required.

Step 2: The first file to be created is the master control file. The master control file gives the title of the simulation, the length of the simulation, the frequency of output, and a directory path and listing of the input and output files. The researchers saved the master control file in the INTEGRATION directory and all the input and output files in a separate subdirectory.

Step 3: The researchers then created the node coordinate file. This file specifies the X and Y coordinates for each node in the network. Each node must have a specific identification number. The researchers entered the nodes using kilometers to define the location of each node; however, the units do not have to be exact since this file is used primarily by the graphical display.

Step 4: The next file is the link characteristic file. This file contains all the geometric data and speed-flow information for each link in the network.

Step 5: The third required file is the signal timing plan file. The researchers created this file as required by the model, though no data was input since there were no signals in any of the networks studied for this research.

Step 6: The researchers input traffic volumes in the origin-destination traffic demand file. The researchers entered a specific volume for each origin and destination node pair for each time period.

Step 7: The fifth required input file is the incident characteristic file. The researchers created this file, but it also contained no data since no incidents were included in this research.

Step 8: The next step in running the integration model is to type 'intgrats' and the name of the master control file at the DOS prompt, which initiates the model and the graphical display.

Step 9: The researchers then reviewed and printed the output files created by the model using the DOS editor.

3.3.4 FRESIM Network Coding

The coding of a FRESIM network using the TSIS (Traffic Software Integrated System)/CORSIM software package can be a time- consuming and difficult process. The research team utilized two different approaches to create the input files for each of the three project sites considered in this project.

ITRAF Software

The first method used during the coding of FRESIM networks for this project was the ITRAF (Input Traffic) software. FRESIM is a very complex model with many interactions among the different types of links (i.e., mainline, on-ramp, and off-ramp links). ITRAF is designed to simplify the data entry by keeping these interactions transparent to the user as much as possible. ITRAF is a Windows-based graphical input editor that allows the user to create input files for all of CORSIM. However, to achieve the maximum benefits in entering data with ITRAF for this model, the user must follow a few simple rules:

- When the user adds an entry link, its default type will be mainline link.
- When adding a link, ITRAF will assign the same type (mainline or ramp) as the feeding link if no other links are attached to the downstream node.
- If the downstream node already has another outgoing link, ITRAF will consider the current added link as an on-ramp link.
- If the upstream node of the currently added link already has an outgoing mainline link, ITRAF will consider the current added link as an off-ramp link.
- If you hold down the control and R key simultaneously when adding a link, ITRAF will create a ramp link.

In summary, the user should first add the mainline links. After all the mainline links have been added, the entry on-ramp links should be added and their type changed to ramp by either holding down the control and R keys simultaneously while adding or by editing these links and checking the Ramp radio button. Then all the other links should be added. In this way, ITRAF will automatically identify the type of link and also the type of turning movements. It should also be noted that FRESIM requires one-way links; therefore, the user should make sure that the one-way link button on the toolbar is pressed when adding links.

The following text describes the general process used by the research team in the ITRAF software to code the networks for the three project sites. Figure 7 shows the ITRAF software with a portion of the network for Site 3 (i.e., NB SH 360) already completed.

<u>Step 1:</u> To start building the data set for a new network, select the File New command (or press the corresponding button on the toolbar).

<u>Step 2:</u> Select Viewing Area from the Display menu and change the minimum and maximum values for the x and y directions to define the area that is displayed on the screen. [Note: ITRAF defaults to a Working Area of 30,000 by 30,000 ft. If the network occupies a larger area, make the corresponding changes. If, on the

other hand, it is going to be substantially smaller, the user should change it also, to have a greater zooming resolution.]

Step 3: If most of the nodes have coordinates such that they may fall on the vertices of a grid, then select Set - Grid from the Options menu (or click on the Grid button with the right mouse button) and define the grid's vertical and horizontal separation values. Select Use Grid and then Show Grid. These two options will allow the user to place the nodes very easily because you will need to "drop" the nodes only in the vicinity of the corresponding grid vertex; ITRAF will position the node in the right place. [Note: the user may turn the grid on or off (same effect as the Show Grid command) by clicking on the Grid button on the tool bar. Also, ITRAF displays the coordinates (x and y) of the cursor at the bottom of the main screen.]

Step 4: Enter the network nodes (see Create, Delete, Change, Move, and Find Nodes for more details). Specify the network entry/exit nodes, internal nodes, and interface nodes if you are building a combined model.

Step 5: Enter the network links (see Add, Delete, Copy, Edit, Find, and Name a Link for more details).

Step 6: Enter the network traffic controllers (see Create, Delete, Copy, and Edit Traffic Controllers for more details).

Step 7: Define the network time periods (see Define Time Periods for more details).

Step 8: Enter the network volumes (see Add, Delete, Edit, and Copy Volume Data for more details) and centroids (see Define Centroids for more details).

Step 9: Enter the network turning movements (see Add, Delete, Copy, and Edit Turning Movement Data for more details).

Step 10: Enter other information (see Specify Incidents, Specify Surveillance Detectors, Add, Delete, Copy, Edit, and Move Bus Stations, Create, Delete, and Edit Bus Routes, Define an Urban Interchange, Specify Interchange OD Turning Movements Information, and Enter Other Simulation Data for more details).

Step 11: Save the file with the .trf extension and the file is now ready for processing in the TSIS/CORSIM software.

Figure 7. Example of ITRAF Software Screen.

Georgia Tech Input File Creator

The second method used to code FRESIM networks during this research was an input file creator, GTNewTRF (an executable program for Win95/NT only), created by researchers at the Georgia Tech University Civil Engineering Department. This program can be downloaded from the following Internet site:

- http://traffic.ce.gatech.edu/corsim/gtnewtrf.htm

Creating TRF files from scratch is perhaps the most time-consuming part of any CORSIM modeling project. From the user's perspective, it is much simpler to modify an existing data file than it is to create one from scratch. Once given a complete, working TRF input file, the user may then modify default values, add new records, etc. GTNewTRF is a program that creates a "starting" TRF data file. Currently, GTNewTRF creates TRF files for simple unidirectional

freeways only; on-ramp, off-ramp, lane-add and -drops, and surface street records are not added. GTNewTRF creates a working data file. The resulting TRF file may be immediately evaluated using CORSIM. All necessary input values are provided in the data file. While the user may modify a TRF data file using GTNewTRF, the software is not a specialized data file editor. The purpose of GTNewTRF is to quickly create a working TRF data file. This file may then be edited (e.g., values modified, new cards added) from TSIS. Figures 8, 9, and 10 illustrate the process of using this method to create at least a portion of a FRESIM input file. Figure 8 shows the entry screen that a user sees once the GTNewTRF program is executed. After the user selects the 'new' option from the 'file' menu shown in the upper right corner of Figure 8, the screen depicted in Figure 9 appears. This screen is where the user can input values for basic network properties such as number of links, node numbering, link length, number of lanes, free speed, and time period information. After these data have been entered, the program creates the corresponding FRESIM working file like the one depicted in Figure 10.

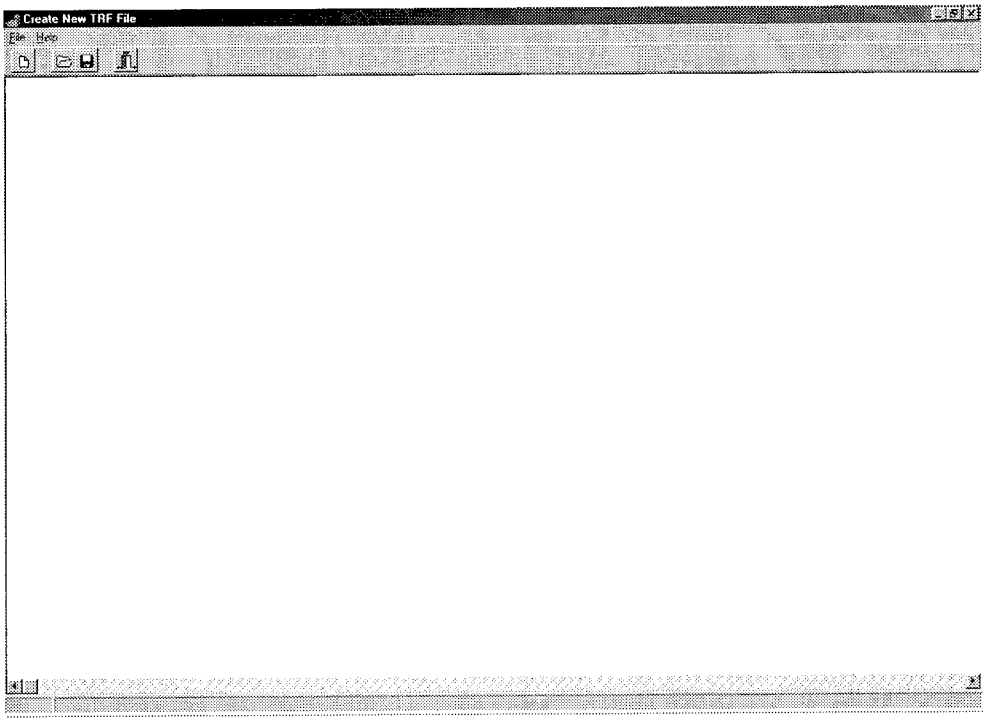


Figure 8. GTNewTRF Program Entry Screen.

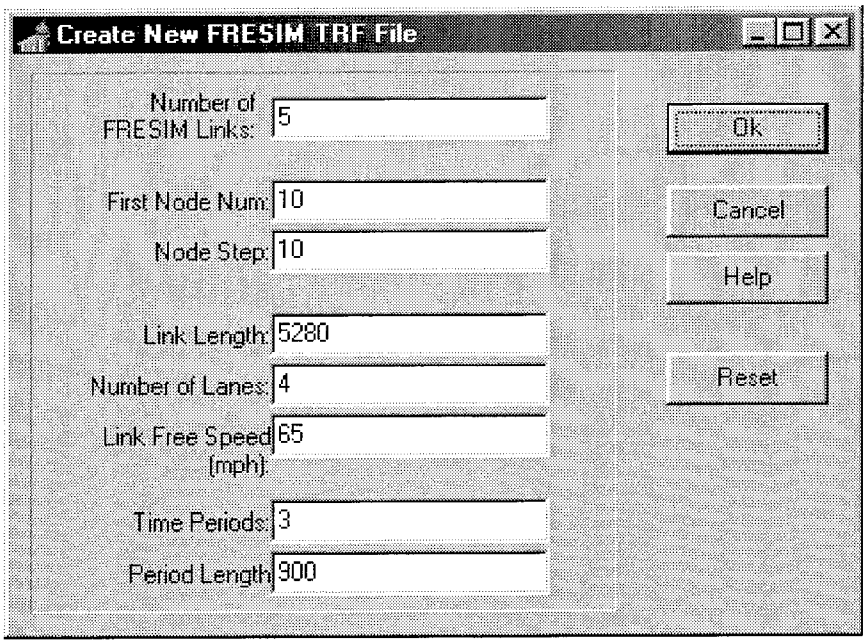
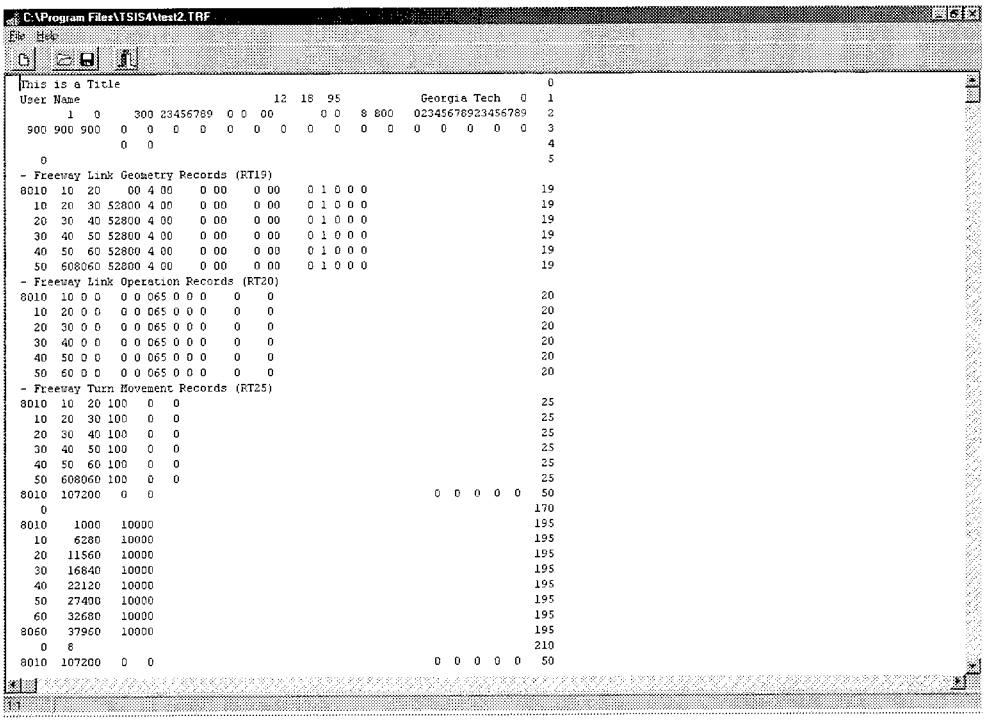


Figure 9. GTNewTRF Program Network Properties Screen.



```
C:\Program Files\TSIS4\test2.TRF
File  Help
This is a Title                                                                  0
User Name                                12  18  95          Georgia Tech   0   1
       1   0     300 23456789  0 0  00       0 0   8 800   023456789234567 89   2
  900 900 900   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   3
                0   0                                                            4
   0                                                                             5
- Freeway Link Geometry Records (RT19)
8010  10  20     00 4 00    0 00    0 00    0 1 0 0 0                           19
  10  20  30 52800 4 00    0 00    0 00    0 1 0 0 0                           19
  20  30  40 52800 4 00    0 00    0 00    0 1 0 0 0                           19
  30  40  50 52800 4 00    0 00    0 00    0 1 0 0 0                           19
  40  50  60 52800 4 00    0 00    0 00    0 1 0 0 0                           19
  50 608060 52800 4 00    0 00    0 00    0 1 0 0 0                           19
- Freeway Link Operation Records (RT20)
8010  10 0 0   0 0 065 0 0 0    0    0                                          20
  10  20 0 0   0 0 065 0 0 0    0    0                                          20
  20  30 0 0   0 0 065 0 0 0    0    0                                          20
  30  40 0 0   0 0 065 0 0 0    0    0                                          20
  40  50 0 0   0 0 065 0 0 0    0    0                                          20
  50  60 0 0   0 0 065 0 0 0    0    0                                          20
- Freeway Turn Movement Records (RT25)
8010  10  20 100   0   0                                                        25
  10  20  30 100   0   0                                                        25
  20  30  40 100   0   0                                                        25
  30  40  50 100   0   0                                                        25
  40  50  60 100   0   0                                                        25
  50 608060 100   0   0                                                        25
8010  107200   0   0                                          0  0  0  0  0    50
   0                                                                           170
8010    1000  10000                                                            195
  10    6280  10000                                                            195
  20   11560  10000                                                            195
  30   16840  10000                                                            195
  40   22120  10000                                                            195
  50   27400  10000                                                            195
  60   32680  10000                                                            195
8060   37960  10000                                                            195
   0   8                                                                       210
8010  107200   0   0                                          0  0  0  0  0    50
```

Figure 10. Example of FRESIM Input File Created by GTNewTRF.

TSIS/CORSIM Input File Editor

In both of the methods mentioned in the previous two subsections, the research team still had to use the TSIS/CORSIM input file editor to make necessary additions and modifications to the input files. This part of the input file creation process is probably the most onerous because editing the text file is time consuming, and errors are not easily identified. Basically, the research team used this utility to make adjustments to the input file created by the ITRAF software or to complete the necessary data for the input file created by the GTNewTRF program. Figure 11 shows the TSIS/CORSIM input file editor screen with an example file loaded into it.

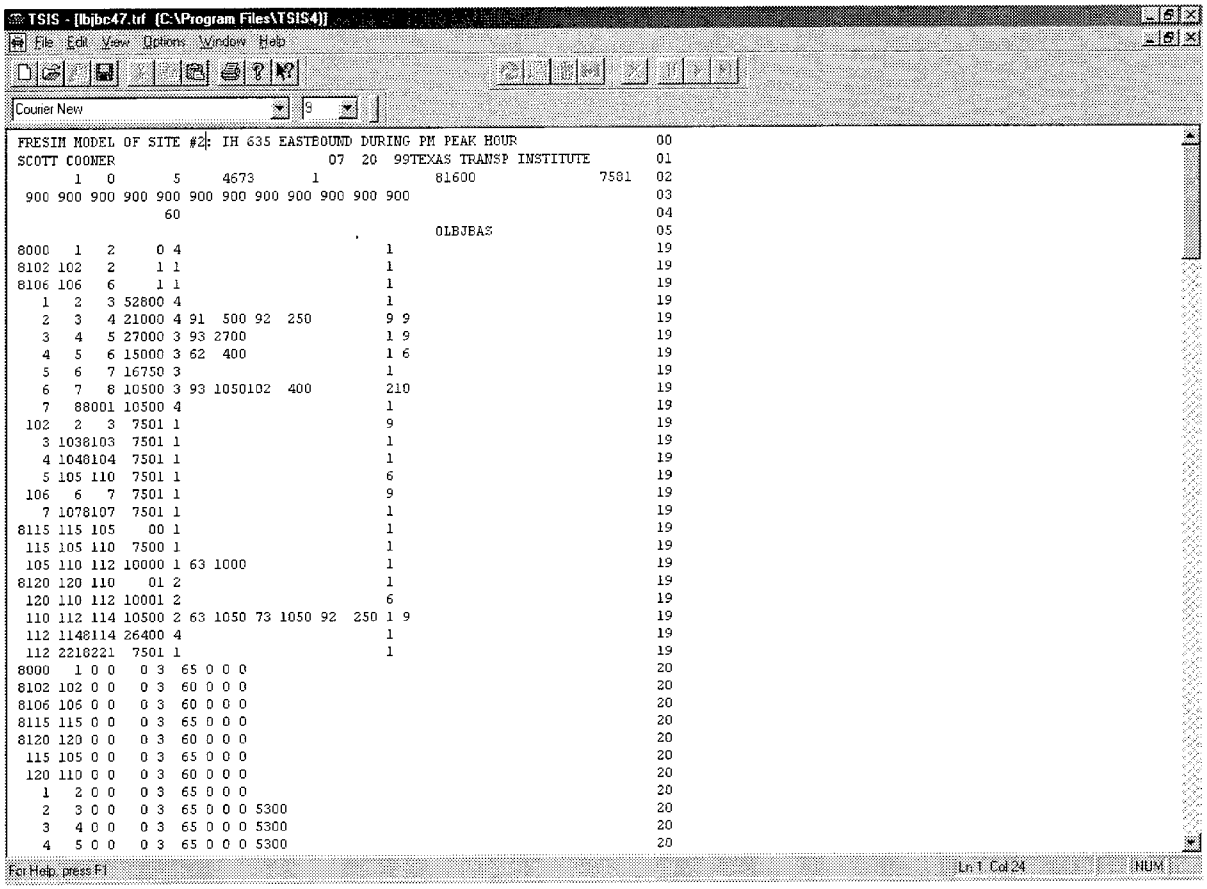


Figure 11. TSIS/CORSIM Input Editor Example.

3.3.5 Embedded/Default Parameters for Simulation Models

As mentioned previously, each of the models included in this project have default parameters embedded in their logic which control traffic operations. This section provides an overview of these key default parameters that were used during the simulation of the base case.

FREQ Key Default Parameters

The FREQ model has only a few default parameters because it is macroscopic and therefore requires less input for the simulation. The three major default parameters in FREQ are as follows:

- ramp capacity limit = 1,500 vphpl;
- main lane capacity limit = 2,000 vphpl; and
- design (i.e., free-flow) speed = 65 mph.

The default design speed value of 65 mph corresponds to one of the five speed-volume/capacity ratio curve families stored in the FREQ model. The user can select one of the other four embedded curves (i.e., 50, 55, 60, or 70 mph) or define a custom one to be used in the simulation.

INTEGRATION Key Default Parameters

The INTEGRATION model is somewhat different than the other two models because there are not really any true default parameters. All of the data must be input into data files in order for the model to run the simulation. Another difference between INTEGRATION and the other models is that metric units are used to define all of the model parameters. The following list provides the values for the model parameters that were used to simulate the base case conditions:

- free-flow speed = 105 kph (65 mph);
- ramp capacity limit = 2,000 vphpl;
- main lane capacity limit = 2,200 vphpl;
- jam density = 100 vehicles per kilometer (62 vehicle per mile); and
- speed at capacity = 80 kph (50 mph).

CORSIM Key Default Parameters

The CORSIM model has a significant amount of parameters that have default values. This section will give an overview of several of the key default parameters associated with the FRESIM component of the CORSIM model. The input data for the CORSIM model is organized into numbered record types. Default parameters for some of the important record types are located in the subsections below.

Record Type 2: Run Control

This record type controls the basic aspects of how the simulation model will run when executed by the user. CORSIM sets all vehicle entry headways to the default uniform headway, defined as 3,600 seconds/N vehicles/hour/lane. This is a non-stochastic method of distribution. The user can override this default value and generate vehicles stochastically using either a normal or Erlang distribution.

Record Type 20: Freeway Link Operation

This record type contains the vital parameters that control freeway link operations within the coded network. Some of the key defaults include the following:

- The default pavement is dry concrete.
- The default mean start-up delay (in tenths of a second) is 10. This input is used by the model to discharge vehicles from a ramp meter onto the freeway. The user can override the default value with values ranging from 0 to 60 mph.
- The desired free-flow speed default value is 65 mph.
- The default truck movement code is zero which means that trucks are neither biased nor restricted to certain lanes.
- 2,500 ft is the default distance from the downstream end of a link to a warning sign at which drivers begin to react to the off-ramp exiting from the subject link.

Record Type 68: Car-Following Sensitivity Factor

This record type contains the CFSF used in the model to control the following behavior of drivers. The CFSF in FRESIM are based on the premise that drivers desire to follow the car in front of them at a given value of the sensitivity factor between them. This sensitivity factor differs from driver to driver, and the default values are shown in Table 4 below:

Table 4. Default Car-Following Sensitivity Factors in CORSIM.

DRIVER TYPE:	1	2	3	4	5	6	7	8	9	10
SENSITIVITY FACTOR:	15	14	13	12	11	10	9	8	7	6

The Pitt car-following model is also used in FRESIM. A separation constant of 10 ft is used as the model default; however, the user can override this value and change it from 3 to 10 ft.

Record Type 69: Pavement Friction Coefficients-Lag to Accelerate and/or Decelerate

The pavement friction values are used in the computation of maximum speed on a curve. The embedded (i.e., default) value is 0.16 for all pavement codes. The user can change this value. Acceptable entries range from 0 to 1.0. There are also embedded values for lag to accelerate and lag to decelerate of 0.3 tenths of a second. These values can also be modified; however, no acceptable range of replacement values is suggested.

Record Type 70: Lane Change Parameters, Minimum Separation for Vehicle Generation, and Maximum Non-Emergency Deceleration

This record type controls most of the parameters associated with lane changing, vehicle generation, and non-emergency deceleration. Some of the key defaults include the following:

- time to complete a lane-change maneuver = 3.0 seconds;
- minimum separation for generation of vehicles = 1.8 seconds;
- percentage of drivers that want to yield the right-of-way ("courtesy factor") = 20%; and
- maximum non-emergency freeway deceleration = 8.0 ft per second.

All of these default values can be changed; however, no ranges for potential replacement values are provided.

Record Type 71: Vehicle Type Specifications

This record type contains all of the vehicle type specifications that are used to define the operational performance characteristics of the fleet of vehicles within the simulation model. The default bumper-to-bumper lengths for the nine vehicle types in the FRESIM model are provided in Table 5 on the following page. Some additional default parameters in this record type include the following:

- The default jerk value (i.e., rate of change of vehicle acceleration allowed from one time step to the next) for all vehicle types is 7.0 seconds.
- The default maximum deceleration on level grade and dry pavement is 15 ft/sec^2 for all vehicle types. The user can change this to any value within a range between 0 and 15.
- The default vehicle type and vehicle performance index values are provided in Table 6.

Table 5. Default Vehicle Type Specifications in CORSIM.

FLEET COMPONENT	VEHICLE TYPE	LENGTH	% OF FLEET COMPONENT
Passenger Car	1 Low Performance 2 High Performance	14 16	25 75
Truck	3 Single unit 4 Semitrailer w/ medium load 5 Semitrailer w/ full load 6 Double-bottom trailer	35 53 53 64	31 36 24 9
Bus	7 Conventional	40	100
Carpool	8 Low Performance 9 High Performance	14 16	25 75

Table 6. Default Vehicle Type and Vehicle Performance Index Values in CORSIM.

VEHICLE TYPE	VEHICLE PERFORMANCE INDEX	PERFORMANCE DESCRIPTION
1	1	Low-performance passenger car
2	2	High-performance passenger car
3	3	Single-unit truck
4	4	Semitrailer truck with medium load
5	5	Semitrailer truck with full load
6	6	Double-bottom trailer truck
7	7	Conventional bus
8	1	Low-performance passenger car
9	2	High-performance passenger car

3.4 MODEL CALIBRATION

3.4.1 Generation of Potential Calibration Techniques

After they successfully completed the simulation runs using the model default parameters, the research team generated potential techniques for calibrating each of the models. The techniques were generated in three distinct ways. The following subsections briefly discuss these three ways.

Techniques Described in Published Studies

The literature review portion of this research, documented in Chapter 2, generated several calibration techniques. For instance, review of the user's manual for each of the models identified several potential methods of calibration. Any parameter that can be adjusted by the user in a model essentially becomes an opportunity for calibration. Also, some published studies documented how particular parameters were manipulated in order to successfully calibrate the simulation model.

MOE Comparisons

The research team identified differences between the model output and the actual field data collected by TTI at the project sites prior to implementation of the bottleneck improvements. Several comparisons were performed in order to discern the discrepancies between the model output and the field data. Specifically, graphical plots comparing speed profiles and volume level were helpful in evaluating the ability of each of the three models to replicate the field data.

Animation Output Processing

Another tool that was useful before attempting to calibrate the FRESIM and INTEGRATION models was the use of the animation output feature. TSIS has a separate animation module that shows an graphical representation of the modeled network. INTEGRATION shows an animation screen while the model is running the simulation. Figure 12 shows an example of what a small portion of the SH 360 network (a zoomed view of the Abram entrance ramp) looks like in the TSIS/CORSIM software. This utility allowed the research team to actively view how the vehicles were operating within the networks created within these models. This type of activity was useful to the research team in making sense of the MOE output values produced by these models. The saying "a picture is worth more than a thousand words" was found to be true in these cases because researchers were able to view operations and develop potential calibration ideas and techniques. It should be noted that the FREQ model does not provide the user with the ability to view an animation of the simulated conditions. Only a text file containing designated MOEs was available in the instances where the FREQ model was being evaluated.

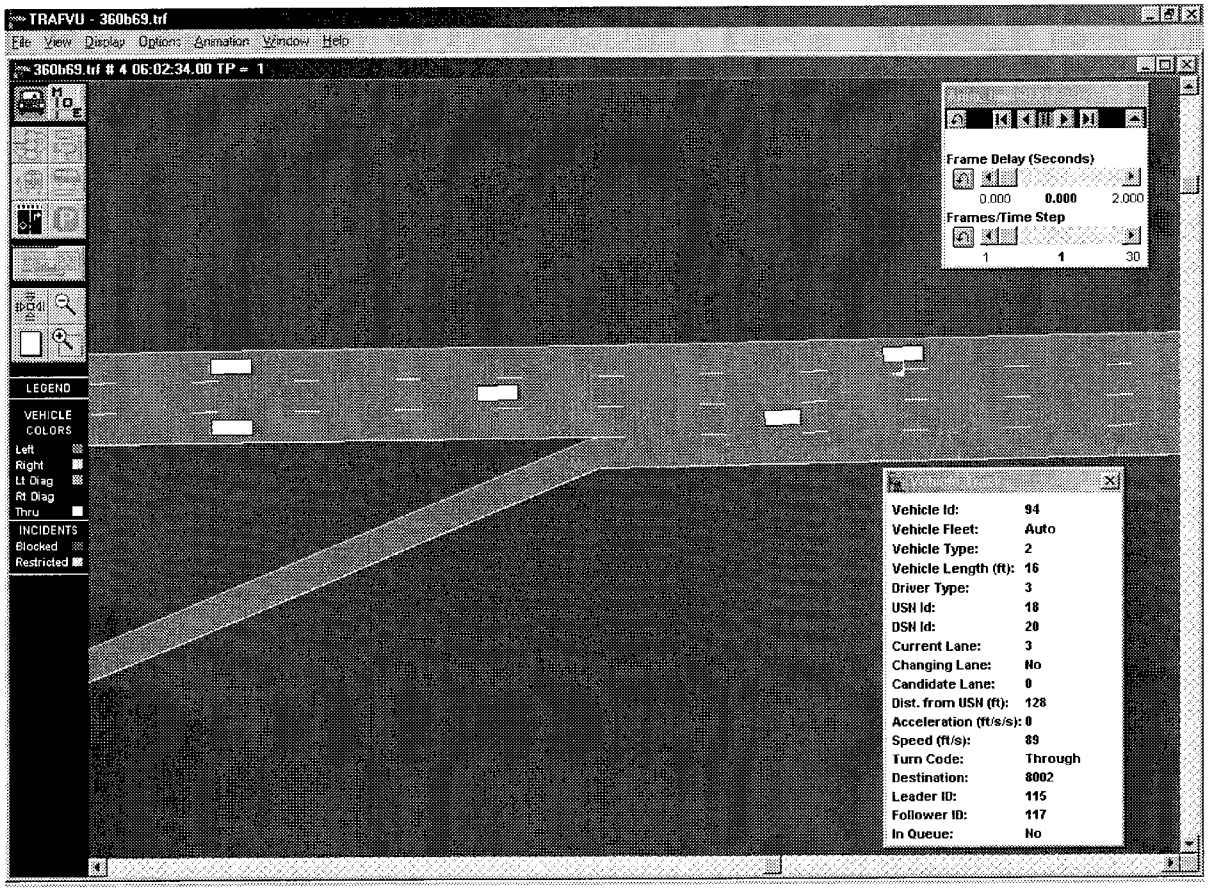


Figure 12. Example TSIS/CORSIM Animation Screen.

3.5 MODEL VALIDATION

After performing calibration of each of the three models, the next task was validation of the models. The research team divided the model validation process into three basic steps:

1. Alter the network geometry created for the base case to represent the bottleneck improvements described in Section 3.2.

2. Change the input volumes from the "before" values used in the base case to the actual "after" volumes which were collected in the field after the bottleneck improvements were already in place.

3. Run each of the simulation models and then compare the output to the "after" field data.

CHAPTER 4

PROJECT RESULTS

This chapter documents the results of the case project simulations performed during this research. The case studies were divided into three distinct categories: base case (i.e., simulation with model default parameters), model calibration, and model validation. Section 4.1 provides the results of the base case simulation case studies. Section 4.2 explains the model calibration efforts and subsequent results. Section 4.3 describes how each of the models performed during the validation case studies.

4.1 BASE CASE SIMULATION RESULTS

This section presents the base case results for each of the project sites for the CORSIM, FREQ, and INTEGRATION simulation models. The base case conditions (i.e., before the bottleneck improvement) were simulated using the default parameters contained within each of the models (i.e., see Chapter 3). The base case evaluation of the models for the three project sites shows how well they perform without any adjustments or other calibration measures being taken.

4.1.1 Site 1: Spur 408/IH 20 Base Case Results

The base case results for Site 1, SB Spur 408 to WB IH 20, are presented in this section. The output from the three models is compared with the data collected during field studies before the implementation of the bottleneck improvement. The first item compared is the speed profiles. The speed profiles produced by the models for the 5:45–6:00 PM time period are compared to the profile obtained via a travel time run that occurred at approximately the same time of day. This time period was selected because of the presence of congestion. Figure 13 shows this comparison with a legend identifying each speed profile. Ramp locations along this freeway section are designated with text just above the x-axis. The "before" profile corresponds to the speeds gathered during field studies. The "checkpoints" label in the legend refers to the series along the x-axis that designates where travel time data was collected. The data points in the figure represent the average speed between the checkpoints. It should be noted that the speed profiles produced by the models and the "before" data do not start at the same location (i.e., prior to the Grady Niblo exit vs. at the Grady Niblo entrance) and they do not end at the same place (at the Mountain Creek exit on IH 20 for the models vs. at the Beltline exit on IH 20 for the "before" data). This discrepancy is the result of a lack of volume data being collected at some of the ramps on IH 20. This data would be necessary to include these sections in the coded network in each of the simulation models used in the project. It should be noted that the FREQ model does not provide speed output for ramps; therefore, no value is shown in the FREQ profile between the WB IH 20 exit and the WB IH 20 merge.

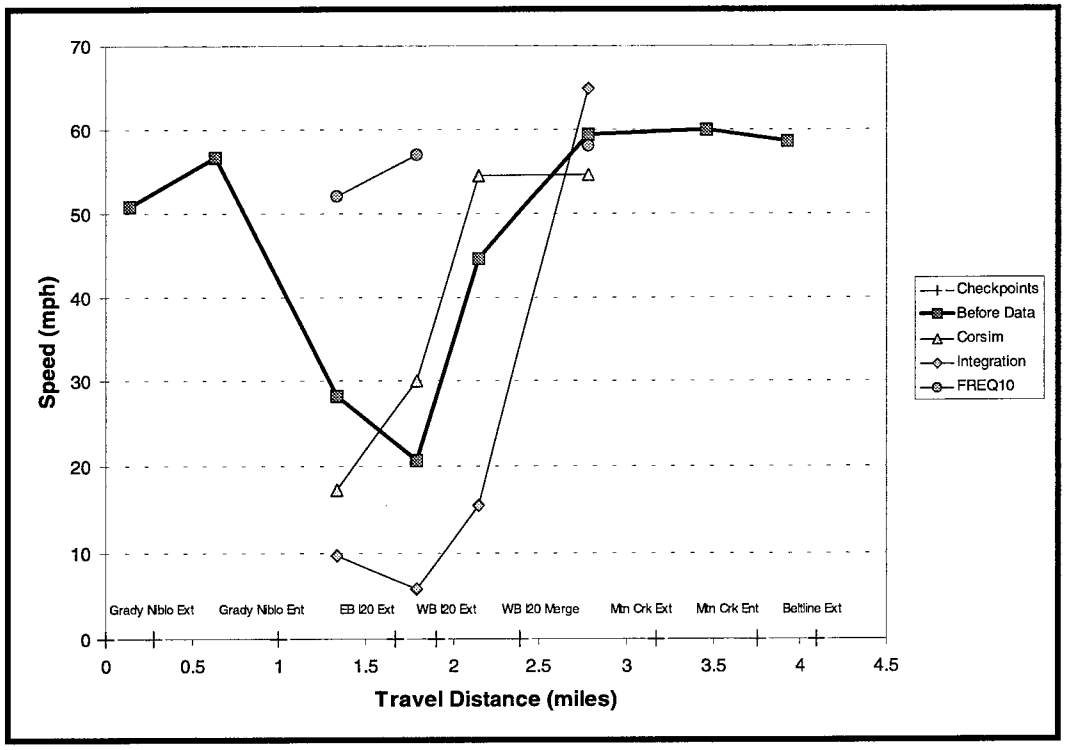


Figure 13. Site 1: SB SP 408 to WB IH 20: Default Speeds (5:45–6:00 PM).

In Figure 13, the size of the modeled networks and the number of data points was limited by the amount of upstream and downstream volume data collected in the field project. The FREQ speed profile does not capture the effect of the bottleneck during the 5:45 to 6:00 PM time period. It is apparent that the default parameters in FREQ do not reflect the slower speeds observed in the "before" profile. The INTEGRATION model captures the effect of the bottleneck; however, the speed profile is lower than what was observed. Finally, the CORSIM speed profile is closest to the "before" profile; however, it is uncertain whether the lack of upstream data affected the shape of the profile.

The second comparison item in the evaluation of the Site 1 base case is the volume level at a key location within the project section. The volumes produced by the models for the entire evening peak period (i.e., 4:00–7:00 PM) on the SB Spur 408 to WB IH 20 connector are compared to the volumes obtained from field studies (automatic count using a pneumatic road tube) at the same location. Researchers selected the connector ramp between Spur 408 and IH 20 for the comparison because the volumes were constrained in the "before" condition and because this is where TxDOT made the primary bottleneck improvement by adding a lane to the ramp. Figure 14 illustrates this comparison with a legend identifying each of the volume profiles.

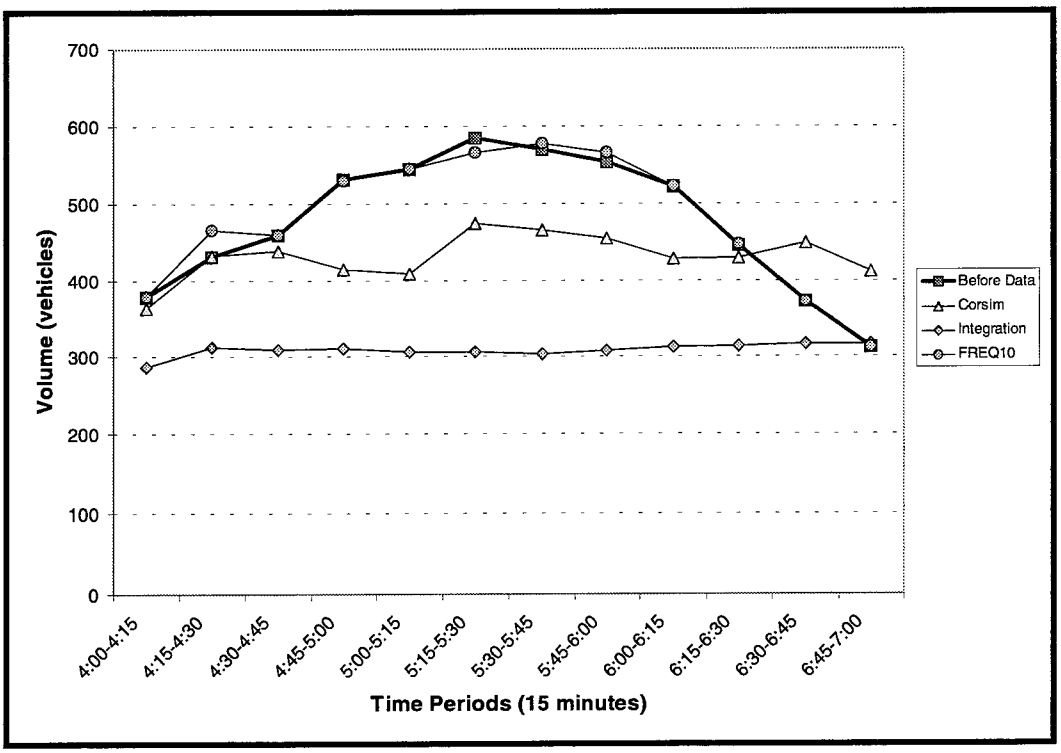


Figure 14. Site 1: SB SP 408 Ramp to WB IH 20: Default Volumes (4:00–7:00 PM).

The volumes produced by the FREQ model on the SB Spur 408 connector ramp to WB IH 20 closely resemble the "before" data throughout the evening peak period. This result is expected based on the results shown in Figure 13 where the speeds reflected almost free-flow conditions. The INTEGRATION volume output is lower than the "before" data and appears constrained due to the flatness of the profile at approximately 300 vehicles per 15 minute time period. Researchers expected this result because the speed profile in Figure 13 showed severe congestion. Finally, the volumes produced by CORSIM track the before profile well during the first three time periods; however, it then levels off similar to the INTEGRATION volume but at approximately 450 vehicles per time period. The lack of congestion might explain this performance during the first three time periods. It is also apparent that the CORSIM volumes are higher during the last two time periods. This is expected because the model is discharging volumes that have accumulated in queue during previous time periods.

4.1.2 Site 2: IH 635/US 75 Base Case Results

The base case results for Site 2, EB IH 635 to NB US 75, are presented in this section. The output from the three models is compared with the data collected during field studies before the implementation of the bottleneck improvement. The first item compared is the speed profiles. The speed profiles produced by the models for the 5:00 to 5:15 PM time period are compared to the profile obtained via a travel time run that occurred approximately the same time of day.

This time period was selected because a significant level of congestion existed. Figure 15 shows this comparison with a legend identifying each speed profile. The profile labeled as "before" corresponds to the speeds gathered during the field studies. Ramp locations along this freeway section are designated with text just above the x-axis. The speed profiles produced by the models and the "before" data start (just prior to Hillcrest on IH 635) and end (at the Midpark exit on US 75) at the same location. As in Site 1, it should be noted is that the FREQ model does not provide speed output for ramps; therefore, no speed value is shown in the FREQ profile between the NB US 75 exit and the US 75 merge.

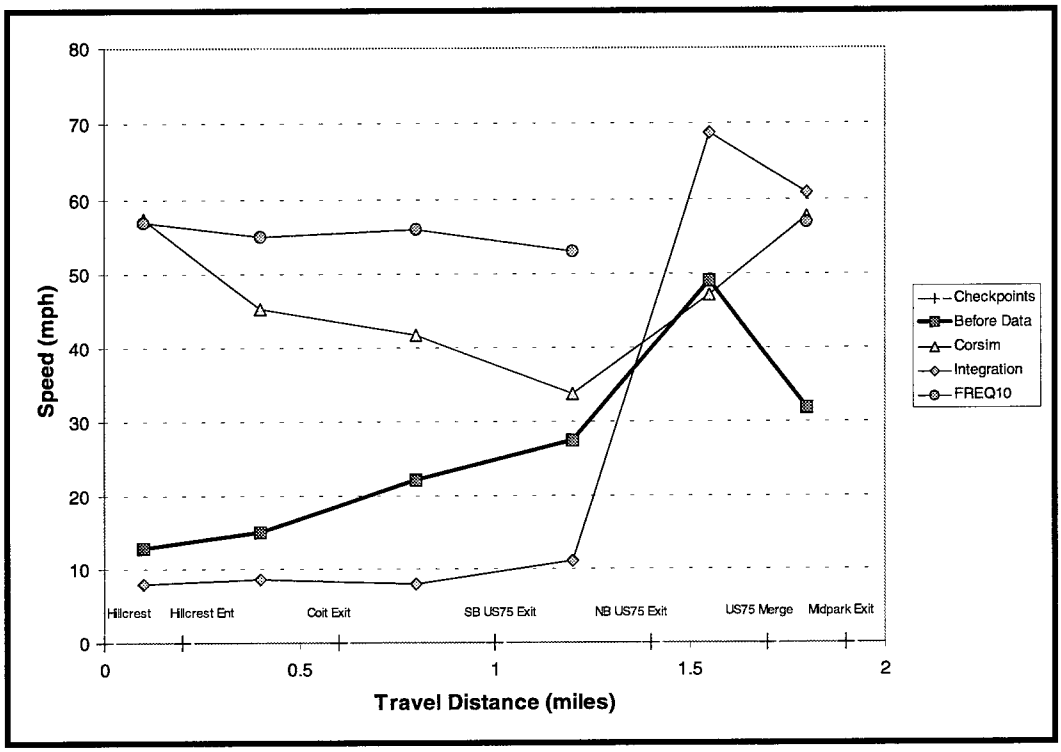


Figure 15. Site 2: EB IH 635 to NB 75: Default Speeds (5:00–5:15 PM).

In Figure 15, the lack of upstream and downstream travel time data is readily apparent. The high values at the beginning and end of the speed profiles compared to the "before" data reflects the lack of available input data. Similar to Site 1, the FREQ speed profile does not capture the effect of the bottleneck during the 5:00 to 5:15 PM time period. The INTEGRATION model captures the effect of the bottleneck; however, the speed profile is lower than what was observed. Finally, the CORSIM speed profile captures the effect of the bottleneck at the NB US 75 exit from IH 635; however, congested conditions upstream on IH 635 and downstream on US 75 are not reflected in the speed profile. This indicates that there are additional bottlenecks upstream and downstream of where data were collected.

The second comparison item in the evaluation of the Site 2 base case is the volume level at a key location within the project section. Researchers compared the volumes produced by the models for the evening peak period (i.e., 4:00–6:30 PM) on the EB IH 635 to NB US 75 connector to the volumes obtained from field studies (automatic count using a pneumatic road tube) at the same location. The research team selected the connector ramp between IH 635 and US 75 for the comparison because the volumes were constrained in the before condition and because this is where TxDOT made the primary bottleneck improvement by adding a lane to the ramp. Figure 16 illustrates this comparison with a legend identifying each of the volume profiles.

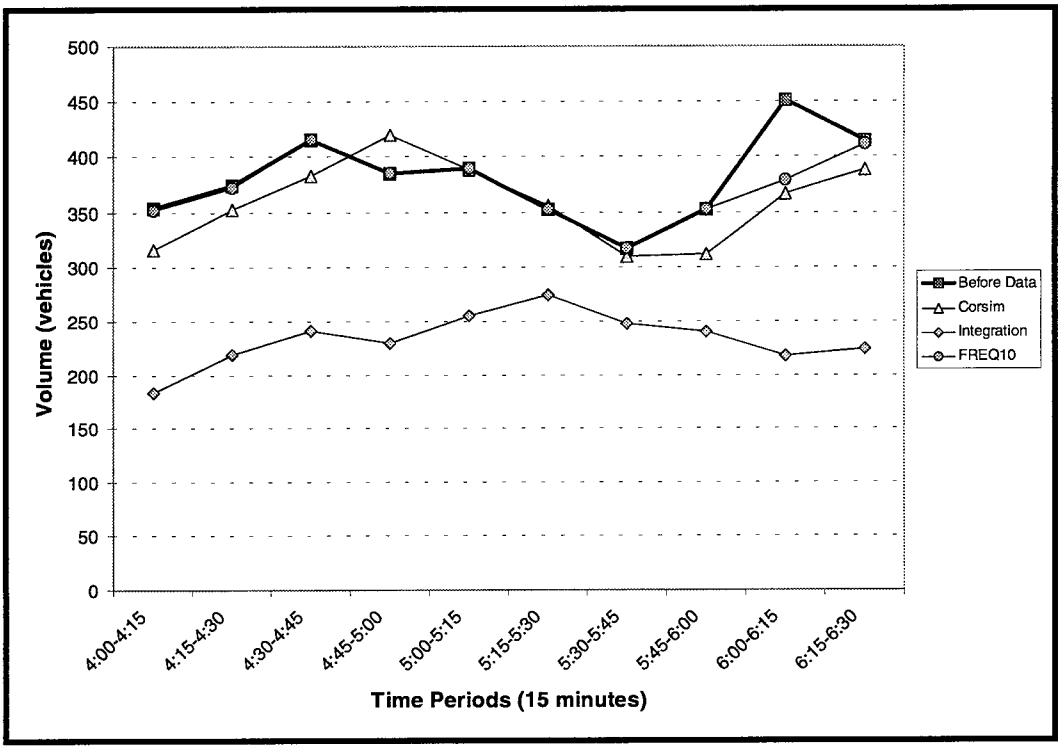


Figure 16. Site 2: EB 635 Ramp to NB 75: Default Volumes (4:00–6:30 PM).

The volumes produced by the FREQ model on the EB IH 635 connector ramp to NB US 75 closely resemble the "before" data throughout the evening peak period. This result is expected based on the results shown in Figure 15 where the speeds reflected almost free-flow conditions. The INTEGRATION volume output is lower than the "before" data and appears constrained due to the flatness of the profile at approximately 250 vehicles per 15 minute time period. This result is expected because the speed profile in Figure 15 showed severe congestion. Finally, the volume profile produced by CORSIM tracks the "before" profile well for the most part during the entire time period modeled.

4.1.3 Site 3: SH 360 Base Case Results

The base case results for Site 3, NB SH 360, are presented in this section. The output from the three models is compared with the data collected during field studies before the implementation of the bottleneck improvement. The first item compared is the speed profiles. The speed profiles produced by the models for the 7:30 to 7:45 AM time period are compared to the profile obtained via a travel time run that occurred approximately the same time of day. This time period was selected for the comparison because of the presence of congestion. Figure 17 shows this comparison with a legend identifying each speed profile. The profile labeled as "before" corresponds to the speeds gathered during the field studies. Ramp locations along this freeway section are designated with text just above the x-axis. The speed profiles produced by the models and the "before" data start (just prior to the Mayfield entrance ramp) and end (just after the Randol Mill exit ramp) at the same location.

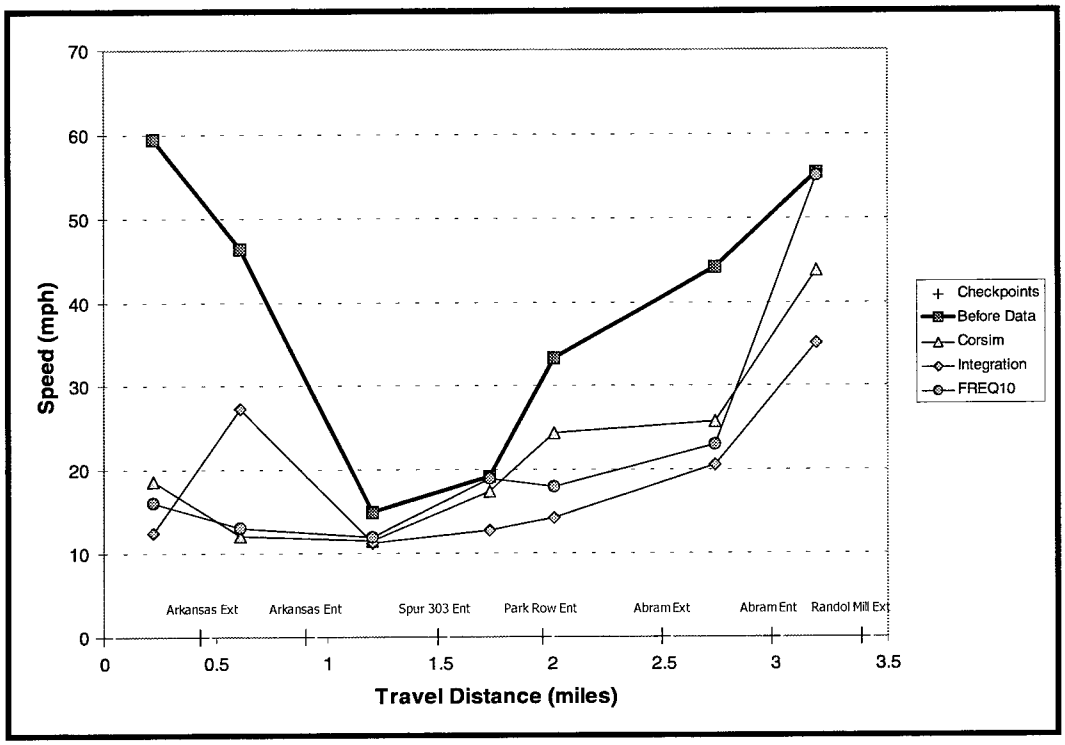


Figure 17. Site 3: NB SH 360: Default Speeds (7:30–7:45 AM).

In Figure 17, all of the speed profiles produced by the models are below the before data speed profile. This result is different than what was observed in the Site 1 and Site 2 default cases. All of the models appear to capture the congestion observed during the 7:30 to 7:45 AM time period, and they appear to be overestimating the severity of the congestion due to the low speeds at the start of the profile.

The second comparison item in the evaluation of the Site 3 base case is the volume level at a key location within the project section. The volumes produced by the models for the morning peak period (i.e., 6:00 to 9:00 AM) on the NB SH 360 main lanes just past the Randol Mill exit ramp are compared to the volumes calculated from field studies (manual count on main lanes and automatic counts using a pneumatic road tube) at the same location. Researchers selected this location for the comparison because it is just past the bottleneck area at Division. Figure 18 illustrates this comparison with a legend identifying each of the volume profiles.

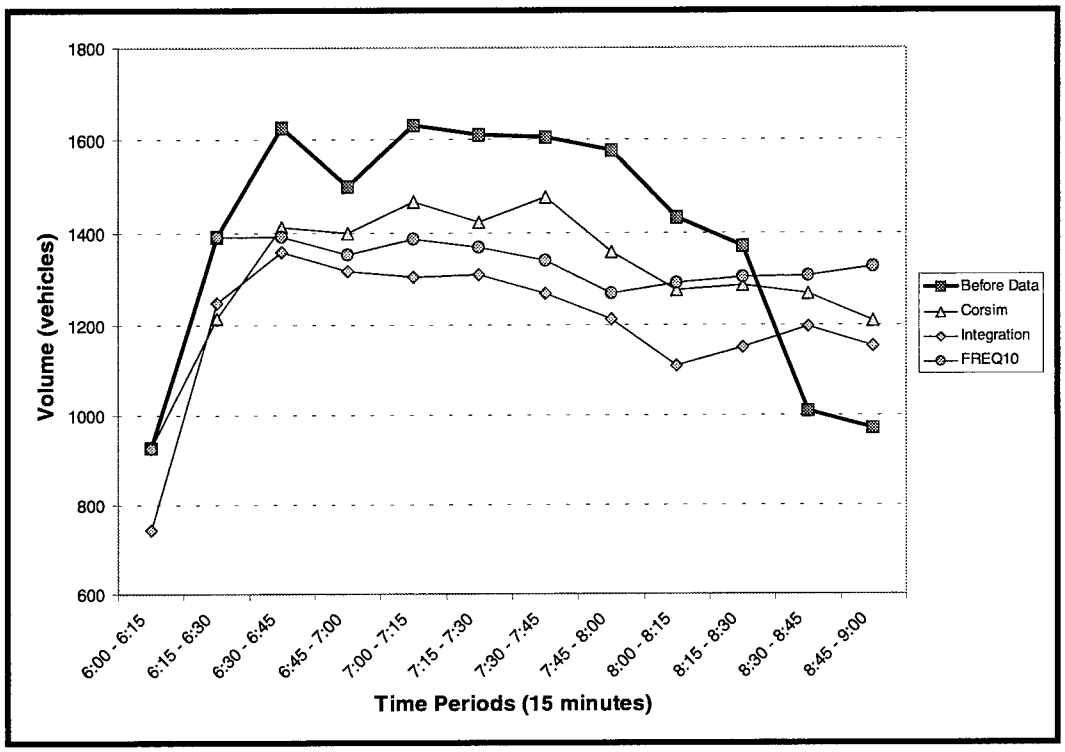


Figure 18. Site 3: NB SH 360: Default Volumes After Randol Mill Exit (6:00–9:00 AM).

In Figure 18, all of the volume profiles produced by the models are below the "before" data volume profile. Researchers expected this result based on the low speeds shown in Figure 17. All of the models appear to capture the congestion observed during the morning peak period, but the volumes are lower because of default values. The other point that should be made is that volumes in the last two time periods (i.e., 8:30 to 9:00 AM) are higher because of the volumes accumulated in queue by the models in previous time periods.

4.2 MODEL CALIBRATION RESULTS

This section provides the results of the model calibration efforts for the CORSIM, FREQ, and INTEGRATION simulation models at each of the project sites. The physical freeway network

within the models for each site remained the same as in the base case. The following subsections discuss the calibration efforts (i.e., what model parameters were changed from the base case evaluation) that were undertaken on the models for the three project sites and the subsequent results.

4.2.1 Site 1: Spur 408/IH 20 Calibration Results

The calibration results for Site 1, SB Spur 408 to WB IH 20, are presented in this section. The researchers felt that adding two links (subsections in FREQ) in each of the models at the beginning of the network would help in the calibration process. These two links (i.e., from prior to Grady Niblo exit to Grady Niblo entrance) were only added to help calibrate the speed profiles. The research team neglected the volumes on the Grady Niblo ramps due to the very low ramp volumes. The following list provides an explanation of the measures attempted to calibrate each of the simulation models:

FREQ: The researchers modified several of the parameters to calibrate the model. The design (i.e., free-flow) speed on the Spur 408 main lanes was changed from 65 mph to 60 mph. The research team changed main lane capacities for each of the five subsections in the coded Spur 408 network.

INTEGRATION: The researchers made numerous adjustments to the jam density and speed-at-capacity values within the model. The free-flow speed was changed from 105 kph (65 mph) to 113 kph (70 mph). The ramp capacity was increased from 2,000 vphpl to 2,100 vphpl. The main lane capacity for IH 20 was increased from 2,200 vphpl to 2,300 vphpl based on the recommended values in the HCM for three or more lane sections.

CORSIM: The researchers varied several of the CORSIM parameters during the calibration process. Specifically, the research team lowered default values contained in record type 68 (Table 4) to include more aggressive driver behavior. The researchers modified several of the default parameters in record type 70 (Table 5). They lowered the time to execute a lane change from 3.0 to 2.0 seconds. The minimum separation for generation of vehicles was changed from 1.8 to 1.5 seconds. Finally, the percentage of drivers desiring to yield the right-of-way was changed to 50 percent. The only other parameters that were modified were the free-flow speeds on the Spur 408 main lanes (changed to 60 mph) and Spur 408 ramps (changed to 55 mph).

The output from the three calibrated models is compared with the data collected during field studies before the implementation of the bottleneck improvement. The first item compared is the speed profiles for Site 1. The speed profiles produced by the calibrated models for the 5:45 to 6:00 PM time period are compared to the speeds obtained via a travel time run that occurred approximately the same time of day. Figure 19 shows this comparison with a legend identifying each speed profile.

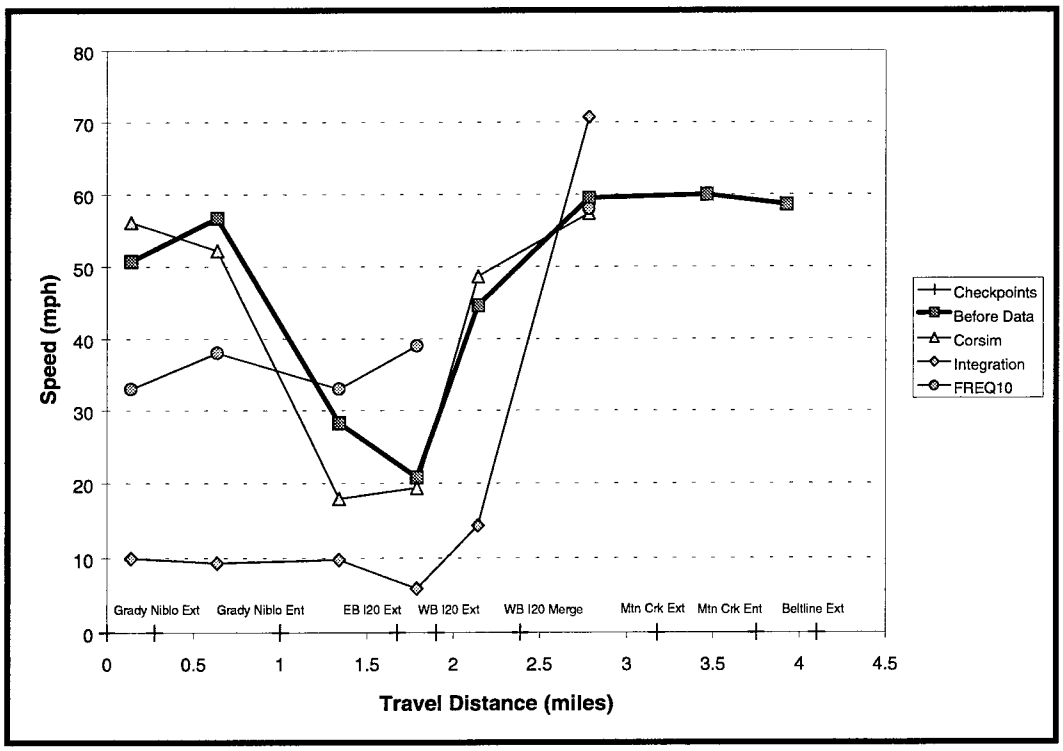


Figure 19. Site 1: SB Sp 408 to WB IH 20: Calibration Speeds (5:45–6:00 PM).

In Figure 19, the FREQ speed profile now shows the effect of the bottleneck during the 5:45 to 6:00 PM time period because the speed values are in the 30–40 mph range. FREQ does not accurately follow the portion of the speed profile along Spur 408. The INTEGRATION model still captures the effect of the bottleneck and still overestimates the severity of the congestion that was observed. The calibration efforts did not substantially improve the performance of the model from the default run. Finally, the researcher's calibration efforts on CORSIM improved the speed profile to more closely replicate the "before" data.

The second comparison item in the evaluation of the Site 1 calibration is the volume level on the SB Spur 408 to WB IH 20 connector. The volumes produced by the models for the entire evening peak period (i.e., 4:00 to 7:00 PM) are compared to the volumes obtained from field studies at this same location. Figure 20 shows this comparison with a legend identifying each of the volume profiles.

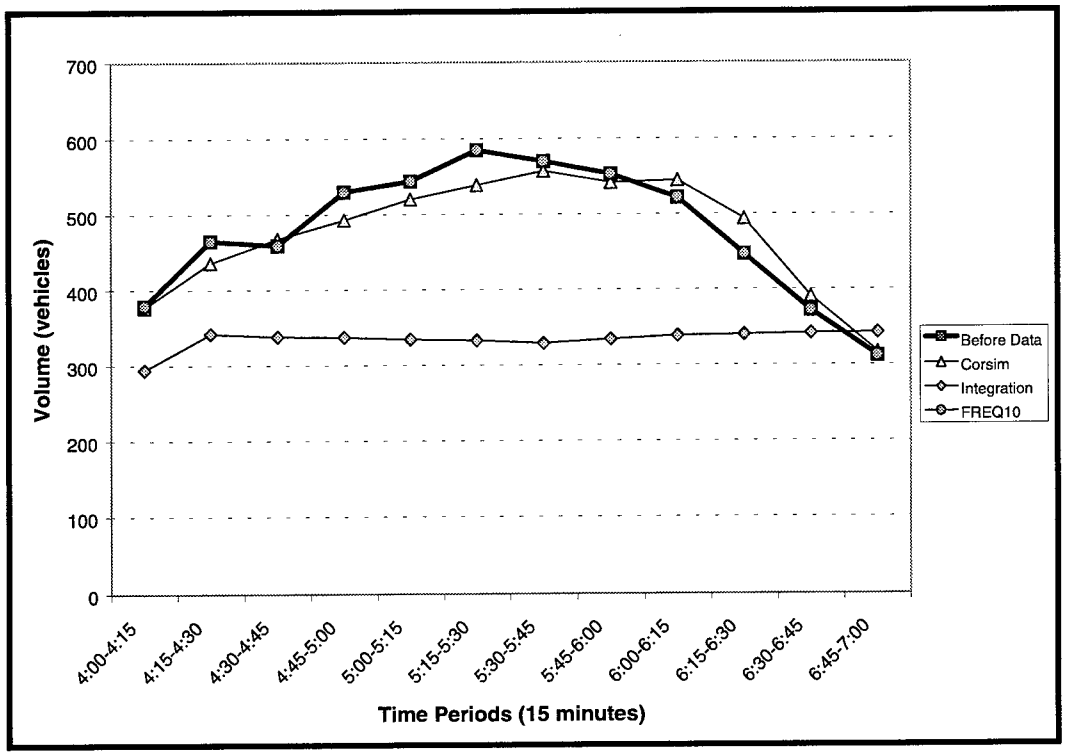


Figure 20. Site 1: SB SP 408 Ramp to WB IH 20: Calibration Volumes (4:00–7:00 PM).

The volumes produced by the FREQ model on the SB Spur 408 connector ramp to WB IH 20 match the before data throughout the evening peak period. This means that FREQ had the capacity available to let all assigned vehicles use the connector ramp based on the increases given during calibration. The INTEGRATION volume output is still lower than the "before" data and appears constrained due to the flatness of the profile at approximately 350 vehicles per 15 minute time period. The calibration efforts did not improve the speeds. It is now apparent that the INTEGRATION model was not calibrated because the volumes were also unimproved. Finally, the volumes produced by the CORSIM calibration effort improved from the default case. The volume difference for each time period is no more than 50 vehicles from observed volumes.

4.2.2 Site 2: IH 635/US 75 Calibration Results

The calibration results for Site 2, EB IH 635 to NB US 75, are presented in this section. The following list provides an explanation of the measures attempted to calibrate each of the simulation models for Site 2:

FREQ: The researchers modified several of the parameters to calibrate the model. The design (i.e., free-flow) speed on the IH 635 main lanes was changed from 65 mph to 60 mph. The main lane capacities were reduced to 1,750 vphpl for each of the seven subsections in the coded IH

635 network. The final adjustment was changing the capacity of the NB US 75 exit ramp from the default to 1,000 vphpl.

INTEGRATION: The researchers made adjustments similar to Site 1 to the jam density and speed-at-capacity values within the model. They increased the ramp capacity from 2,000 vphpl to 2,100 vphpl and increased the main lane capacities from 2,200 vphpl to 2,300 vphpl based on the recommended values in the Highway Capacity Manual for three or more lanes.

CORSIM: The researchers varied several of the CORSIM parameters during the calibration process. Specifically, the research team lowered default values contained in record type 68 (Table 4) to include more aggressive driver behavior. The researchers modified several of the default parameters in record type 70 (Table 5). The time to execute a lane change was lowered from 3.0 to 2.0 seconds. The minimum separation for generation of vehicles was changed from 1.8 to 1.5 seconds. Because OD data was available for this corridor, record type 74 was added to see if it would improve the model performance. In the absence of record type 74, CORSIM uses an internal OD distribution that is calculated from turning movement percentages input on record type 25. The input volumes entering the network on the IH 635 main lanes were raised in order to better reflect the true or latent demand. The only other parameter that was modified was the free-flow speed on the IH 635 ramps (changed to 55 mph).

The output from the three calibrated models is compared with the data collected during field studies before the implementation of the bottleneck improvement. The first item compared is the speed profiles. The speed profiles produced by the calibrated models for the 5:00 to 5:15 PM time period are compared to the speeds obtained via a travel time run that occurred approximately the same time of day. Figure 21 shows this comparison with a legend identifying each speed profile.

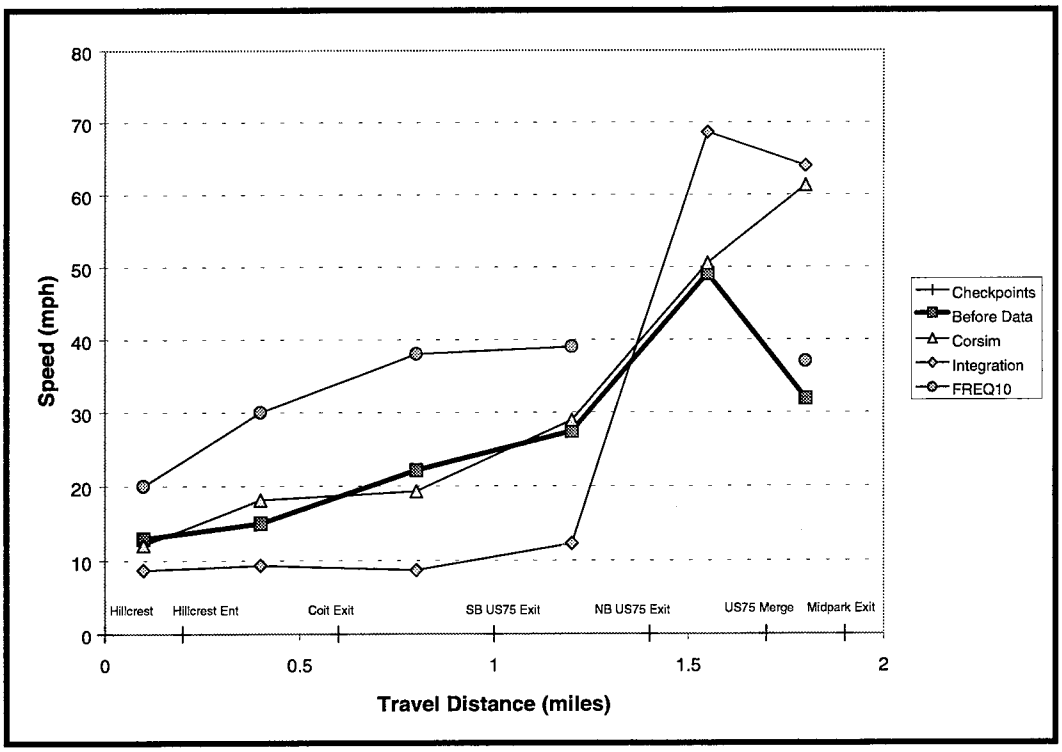


Figure 21. Site 2: EB IH 635 to NB US 75: Calibration Speeds (5:00–5:15 PM).

In Figure 21, the lack of downstream travel time data is again readily apparent. The high values at the end of the speed profiles compared to the "before" data indicate that there is additional congestion downstream that is not being modeled. The FREQ speed profile seems to be capturing some of the expected congestion, though the profile is not close to the "before" data. The INTEGRATION model captures the effect of the bottleneck; however, despite calibration efforts the speed profile is lower than what was observed. Finally, the CORSIM speed profile closely captures the effect of the bottleneck at the NB US 75 exit and the effect of the congestion along IH 635.

The second comparison item in the evaluation of the calibration of Site 2 is the volume level on the EB IH 635 to NB US 75 connector. The volumes produced by the models for the evening peak period (i.e., 4:00 to 6:30 PM) are compared to the volumes obtained from field studies at this same location. Figure 22 gives this comparison with a legend identifying each of the volume profiles.

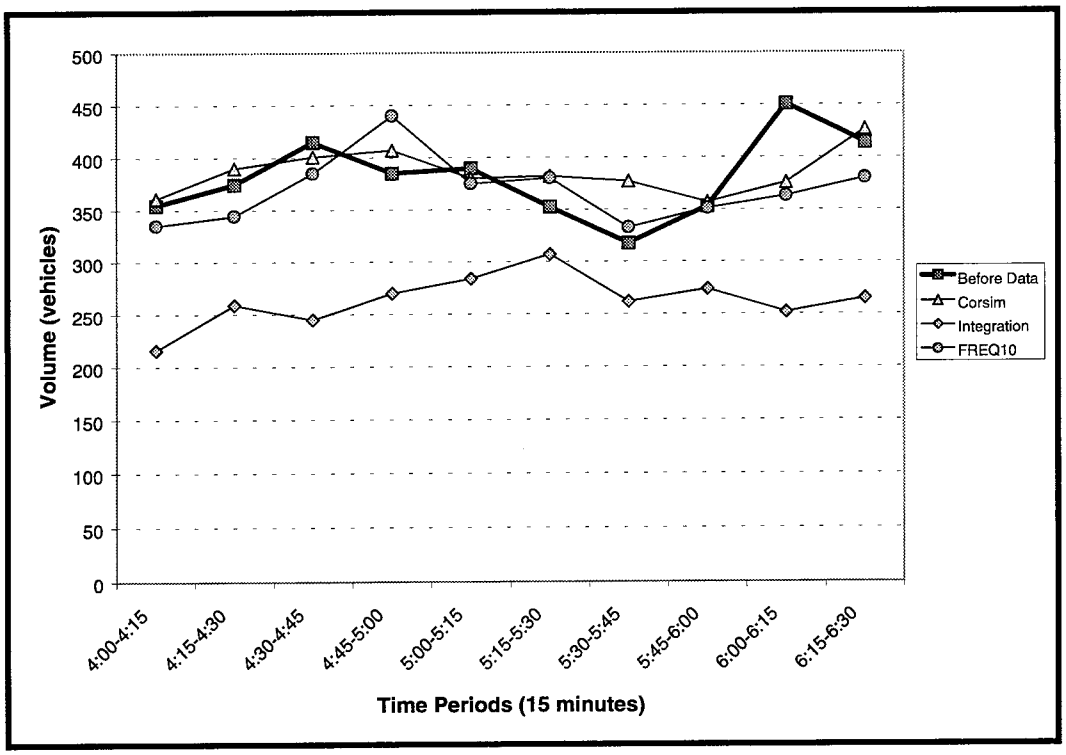


Figure 22. Site 2: EB 635 Ramp to NB 75: Calibration Volumes (4:00–6:30 PM).

The FREQ calibration effort did not change the volumes much from the base case, and the volumes remain close to the "before" data throughout the evening peak period. This means that FREQ had the capacity available to let all assigned vehicles use the connector ramp based on the increases given during calibration. The INTEGRATION volume output is still lower than the "before" data and the calibration efforts only slightly increased the volumes by about 50 vehicles per each 15 minute time period. The CORSIM calibration effort also did not change the volumes much from the base case; however, the volumes are closer to the "before" data.

4.2.3 Site 3: SH 360 Calibration Results

The calibration results for Site 3, NB SH 360, are presented in this section. The following list provides an explanation of the measures attempted to calibrate each of the simulation models:

FREQ: The researchers modified several of the parameters to calibrate the model. They changed the design (i.e., free-flow) speed on the SH 360 main lanes from 65 mph to 55 mph and increased the main lane capacities to 2,200 vphpl for each of the 12 subsections in the coded network.

INTEGRATION: The researchers made adjustments similar to Site 1 to the jam density and speed-at-capacity values within the model. They increased the ramp capacity from 2,000 vphpl to 2,100 vphpl and increased the main lane capacities from 2,200 vphpl to 2,300 vphpl based on the recommended values in the HCM for three or more lanes.

CORSIM: The researchers varied several of the CORSIM parameters during the calibration process. Specifically, the research team lowered default values contained in record type 68 (Table 4) to include more aggressive driver behavior. The researchers modified several of the default parameters in record type 70 (Table 5). They lowered the time to execute a lane change from 3.0 to 2.5 seconds. The minimum separation for generation of vehicles was changed from 1.8 to 1.6 seconds, and the percentage of drivers desiring to yield the right-of-way was changed to 40 percent.

The output from the three calibrated models is compared with the data collected during field studies before the implementation of the bottleneck improvement. The first item compared is the speed profiles. The speed profiles produced by the calibrated models for the 7:30 to 7:45 AM time period are compared to the speeds obtained via a travel time run that occurred approximately the same time of day. Figure 23 shows this comparison with a legend identifying each speed profile.

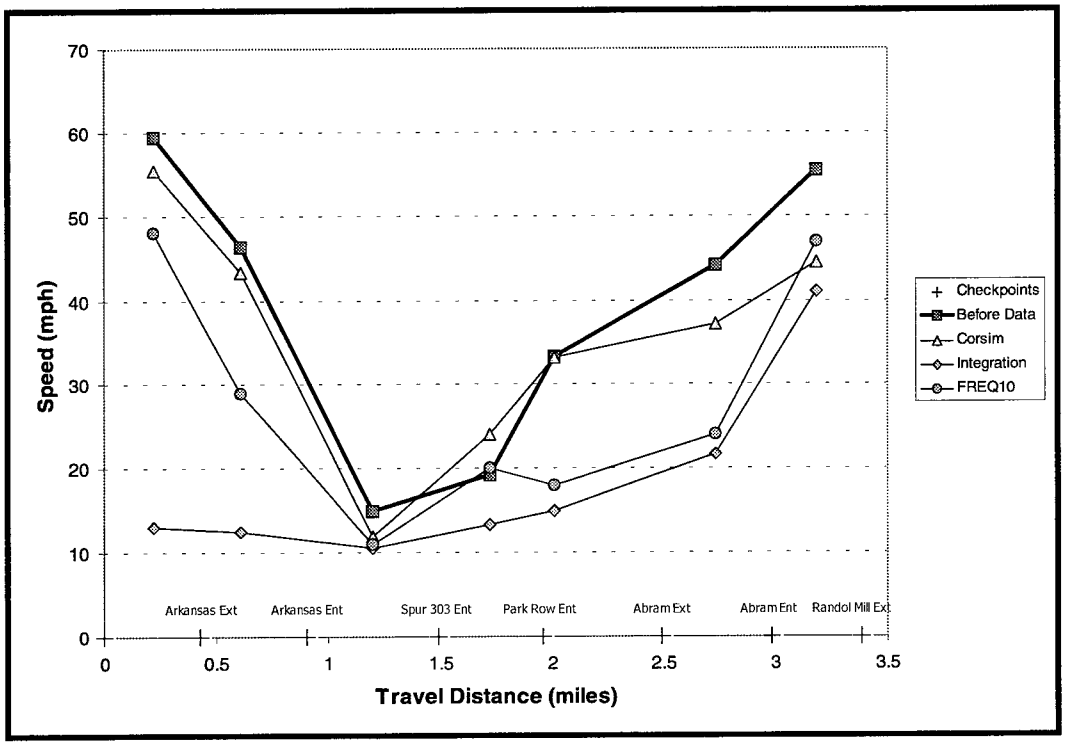


Figure 23. Site 3: NB SH 360: Calibration Speeds (7:30–7:45 AM).

The calibration efforts for FREQ appear to capture the effects of the bottleneck, though the level of congestion from the Park Row entrance to the Abram entrance ramp is more severe than observed in the field. The calibration efforts for the INTEGRATION model appear to estimate more congestion than the base case. For CORSIM the calibration produced speeds that closely follow the "before" data except at the end of the network. The addition of OD data to the

CORSIM and INTEGRATION models may have further improved the calibration results; however, that data was not collected during field studies for the original bottleneck analysis.

The second comparison item in the evaluation of the calibration of Site 3 is the volume level on the main lanes just after the Randol Mill exit ramp. The volumes produced by the models for the morning peak period (i.e., 6:00 to 9:00 AM) are compared to the volumes obtained from field studies at this same location. Figure 24 gives this comparison with a legend identifying each of the volume profiles.

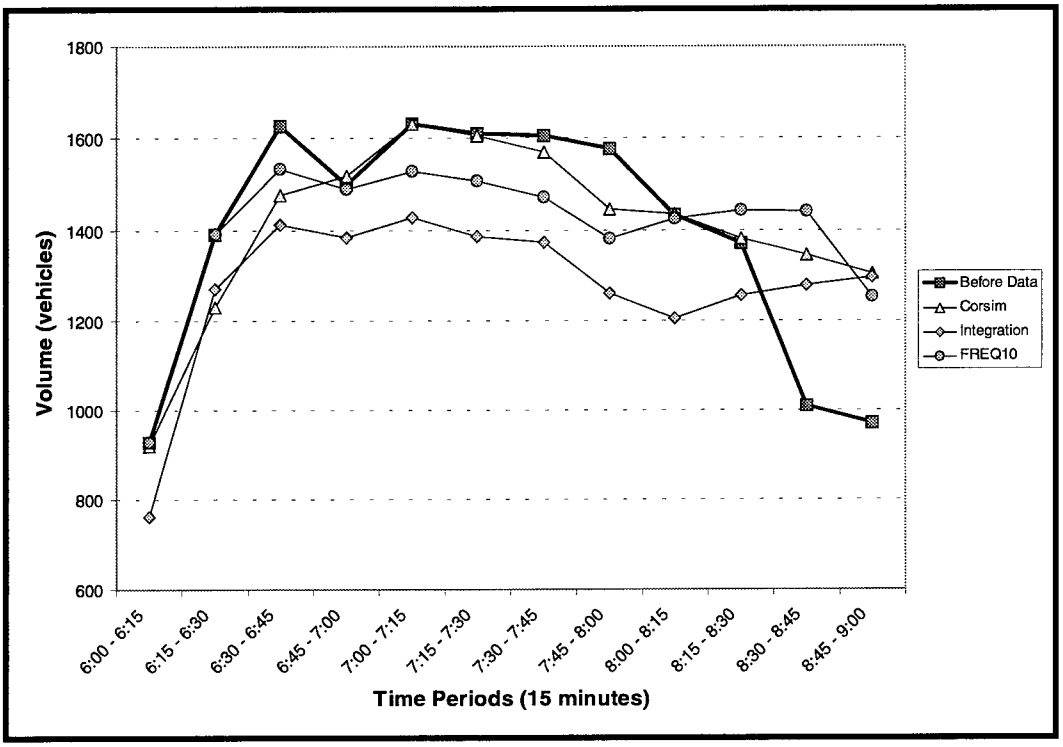


Figure 24. Site 3: NB SH 360: Calibration Volumes After Randol Mill Exit (6:00–9:00 AM).

In Figure 24, all of the volume profiles produced by the models after the calibration efforts are still below the "before" data volume profile. However, the FREQ and CORSIM model output is closer. The low volumes for the INTEGRATION model were expected based on the low speeds shown in Figure 23. All of the models appear to capture the congestion observed during the morning peak period. The other point that should be made is that volumes in the last two time periods (i.e., 8:30 to 9:00 AM) are higher because of the volumes accumulated in queue by the models in previous time periods.

4.3 MODEL VALIDATION RESULTS

This section provides the results of the model validation efforts for the CORSIM, FREQ, and INTEGRATION simulation models at each of the project sites. The physical freeway networks within the calibrated models for each of the project sites were modified to reflect the geometry after TxDOT constructed the bottleneck improvement. The following subsections present the model validation results.

4.3.1 Site 1: Spur 408/IH 20 Validation Results

The validation results for Site 1, SB Spur 408 to WB IH 20, are presented in this section. The researchers only changed the input volumes and the link or section geometry to reflect after bottleneck improvement for each model network.

The output from the three validated models is compared with the data collected during field studies after the implementation of the bottleneck improvement. The first item compared is the speed profiles. The speed profiles produced by the validated models for the 5:45 to 6:00 PM time period are compared to the speeds obtained via a travel time run that occurred approximately the same time of day. Figure 25 shows this comparison with a legend identifying each speed profile.

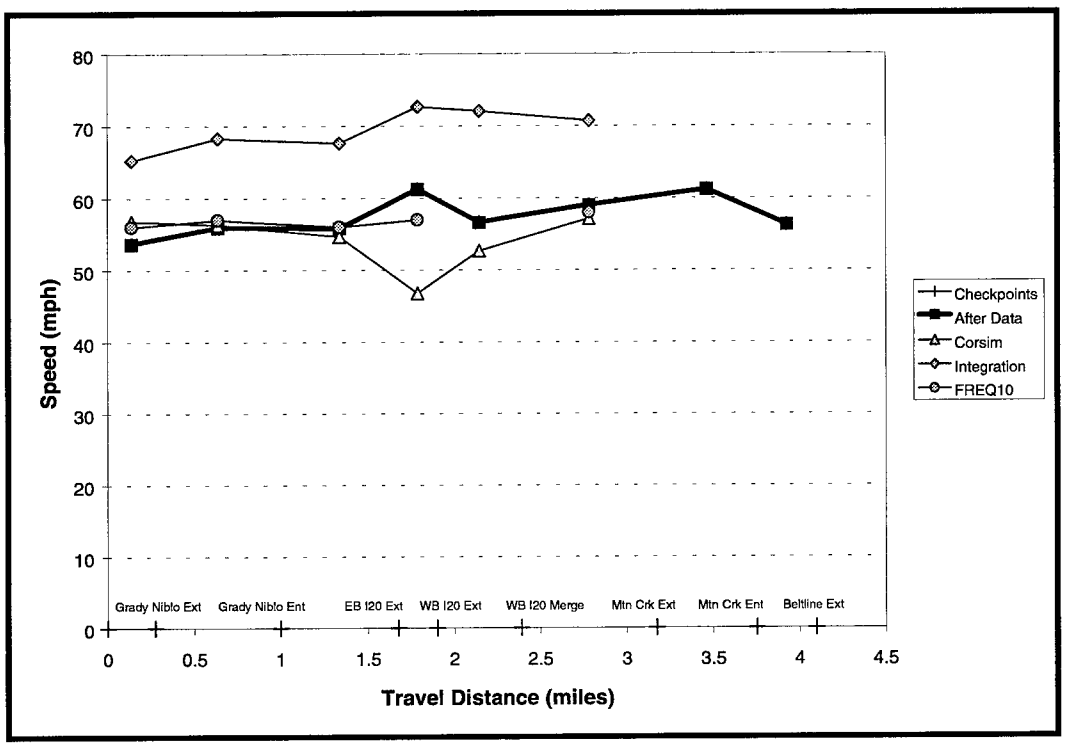


Figure 25. Site 1: SB SP 408 to WB IH 20: Validation Speeds (5:45–6:00 PM).

In Figure 25, each speed profile shows free-flow conditions that were expected since the bottleneck improvements eliminated the congestion. The INTEGRATION model shows the vehicles in free-flow; however, the speeds are overestimated because the free-flow speed was set at 113 kph (70 mph) during the attempted calibration of the model.

The second comparison item in the evaluation of the Site 1 validation is the volume level on the SB Spur 408 to WB IH 20 connector. The volumes produced by the models for the entire evening peak period (i.e., 4:00 to 7:00 PM) are compared to the volumes obtained from field studies at this same location. Figure 26 shows this comparison with a legend identifying each of the volume profiles.

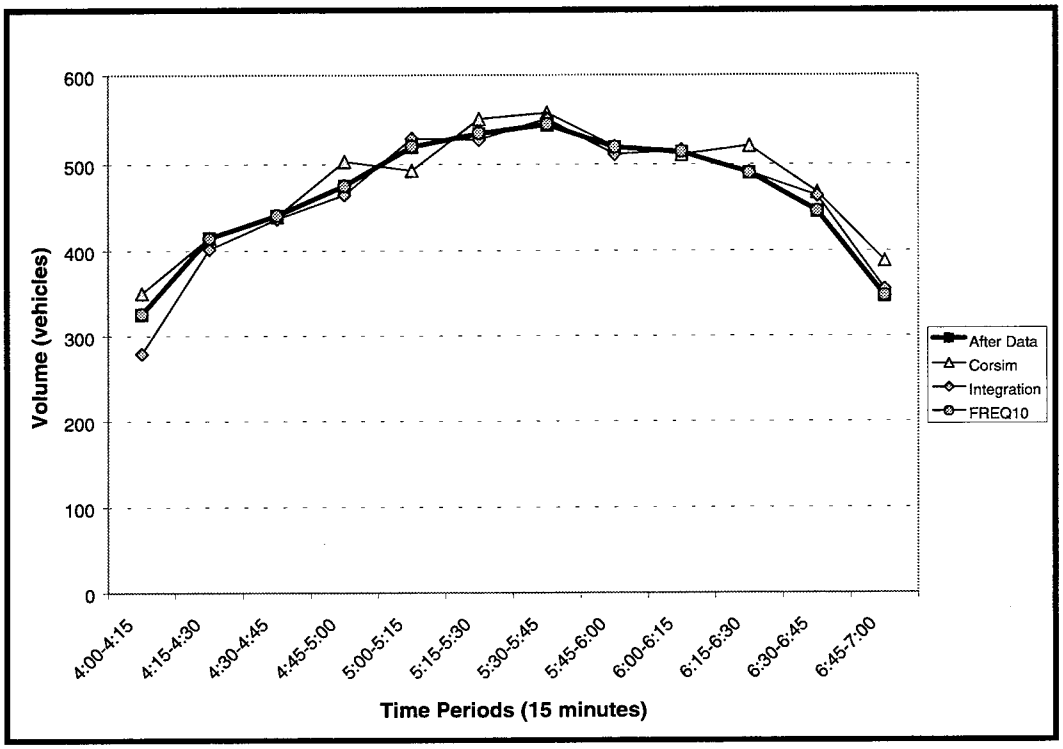


Figure 26. Site 1: SB SP 408 Ramp to WB IH 20: Validation Volumes (4:00–7:00 PM).

In Figure 26, each of the volume profiles produced by the simulation models closely follow the "after" data volume profile. Again, this result was expected because the bottleneck improvements eliminated the congestion on SB Spur 408.

4.3.2 Site 2: Interstate 635/US 75 Validation Results

The validation results for Site 2, EB IH 635 to NB US 75, are presented in this section. The researchers only changed the input volumes and the link or section geometry to reflect after bottleneck improvement for each model network.

The output from the three validated models is compared with the data collected during field studies after the implementation of the bottleneck improvement. The first item compared is the speed profiles. The speed profiles produced by the validated models for the 5:00 to 5:15 PM time period are compared to the speeds obtained via a travel time run that occurred at the same time of day. Figure 27 shows this comparison with a legend identifying each speed profile.

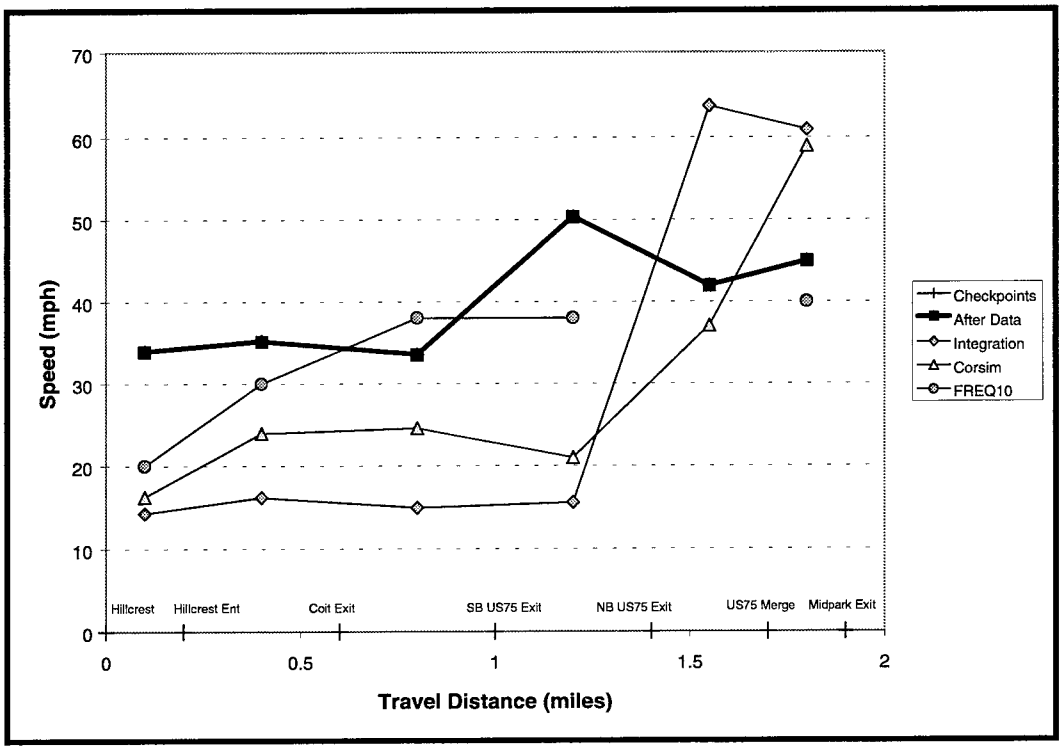


Figure 27. Site 2: EB IH 635 to NB US 75: Validation Speeds (5:00–5:15 PM).

In Figure 27, the speed profiles produced during the model validation runs did not show the expected increase in speeds due to the bottleneck improvement. The FREQ model validation output is the closest to replicating the speeds observed; however, the predicted speeds are essentially the same as in the calibration profile (Figure 21). This likely means that FREQ is not recognizing the benefits of the bottleneck improvements. The other models speed profiles did increase slightly from the values in the calibration profiles; however, both are still well below the observed speed conditions. It appears that these models (CORSIM and INTEGRATION) also did not capture the benefits of the bottleneck improvements.

The second comparison item in the evaluation of the validation of Site 2 is the volume level on the EB IH 635 to NB US 75 connector. The volumes produced by the models for the evening peak period (i.e., 4:00 to 6:30 PM) are compared to the volumes obtained from field studies at this same location. Figure 28 gives this comparison with a legend identifying each of the volume profiles.

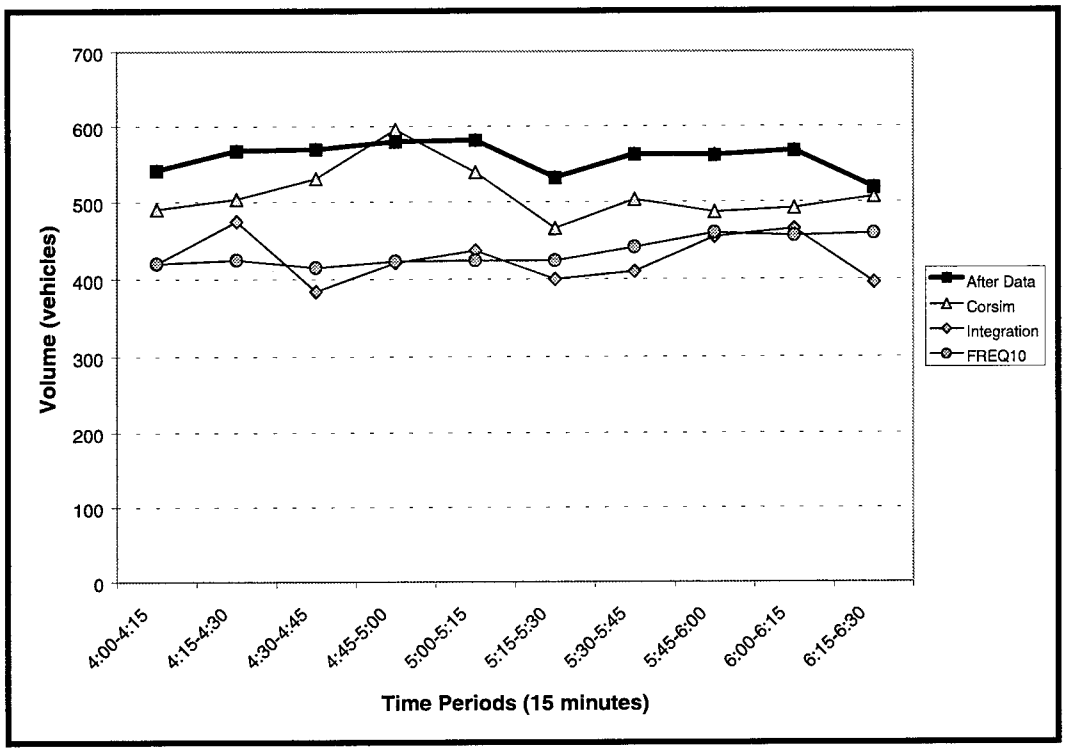


Figure 28. Site 2: EB 635 Ramp to NB 75: Validation Volumes (4:00–6:30 PM).

In Figure 28, it appears that all of the validation volume profiles are constrained because they fall below the "after" volume data. Each of the models did increase the volume level on the EB IH 635 to NB US 75 connection; however, they did not capture the full benefit of the increase in capacity.

4.3.3 Site 3: SH 360 Validation Results

The validation results for Site 3, NB SH 360, are presented in this section. The researchers only changed the input volumes and the link or section geometry to reflect after bottleneck improvement for each model network.

The output from the three validated models is compared with the data collected during field studies after the implementation of the bottleneck improvement. The first item compared is the speed profiles. The speed profiles produced by the validated models for the 7:30 to 7:45 AM time period are compared to the profile obtained via a travel time run that occurred

approximately the same time of day. Figure 29 shows this comparison with a legend identifying each speed profile.

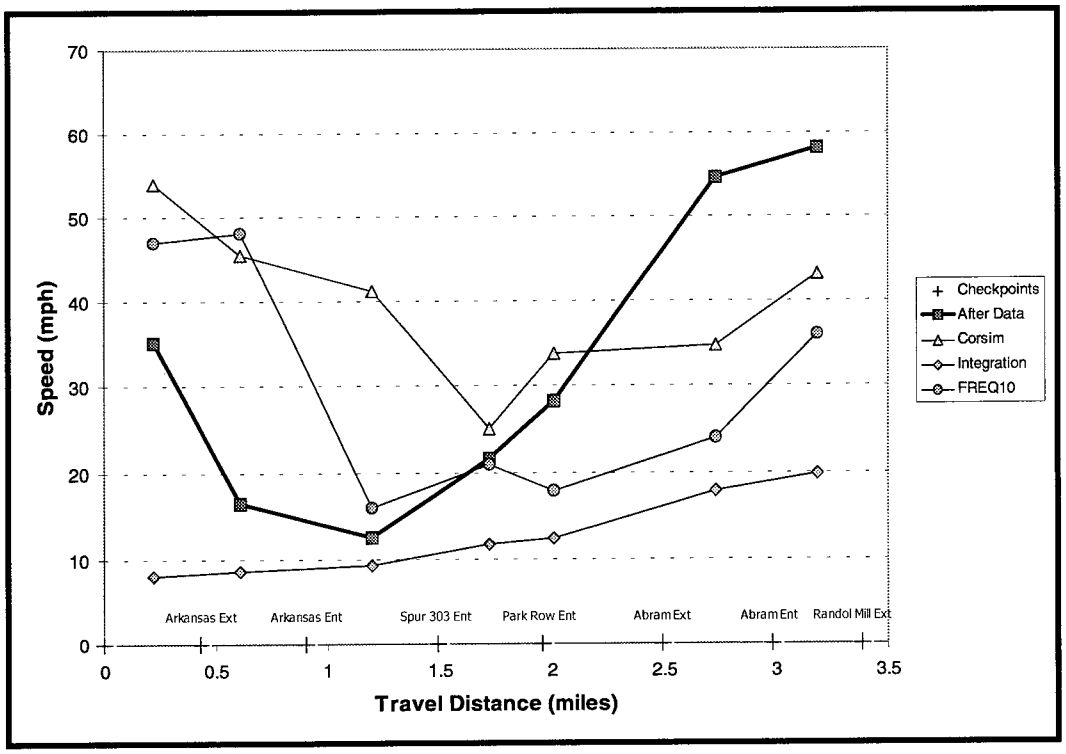


Figure 29. Site 3: NB SH 360: Validation Speeds (7:30–7:45 AM).

In Figure 29, none of the speed profiles produced by the simulation models resemble the observed "after" data speed profile. The promising results shown in calibration (Figure 23) by CORSIM and FREQ at this site did not translate into good results in the validation comparison. Both models underestimate the congestion in the first mile of the project section and then overestimate it in the last mile. INTEGRATION still appears to be overestimating the congestion level throughout the entire project section.

The second comparison item in the evaluation of the validation of Site 3 is the volume level on the main lanes just after the Randol Mill exit ramp. The volumes produced by the models for the morning peak period (i.e., 6:00 to 9:00 AM) are compared to the volumes obtained from field studies at this same location. Figure 30 gives this comparison with a legend identifying each of the volume profiles.

In Figure 30, despite the differences in the speed profiles shown in Figure 29 the models more closely match the observed volumes. The CORSIM and FREQ output is still slightly below the "after" data; however, they do show a large portion of the volume increase from the before conditions. The volume profile produced by the INTEGRATION model is essentially the same

as during the calibration which suggests that it does not recognize the geometric changes of the bottleneck improvement.

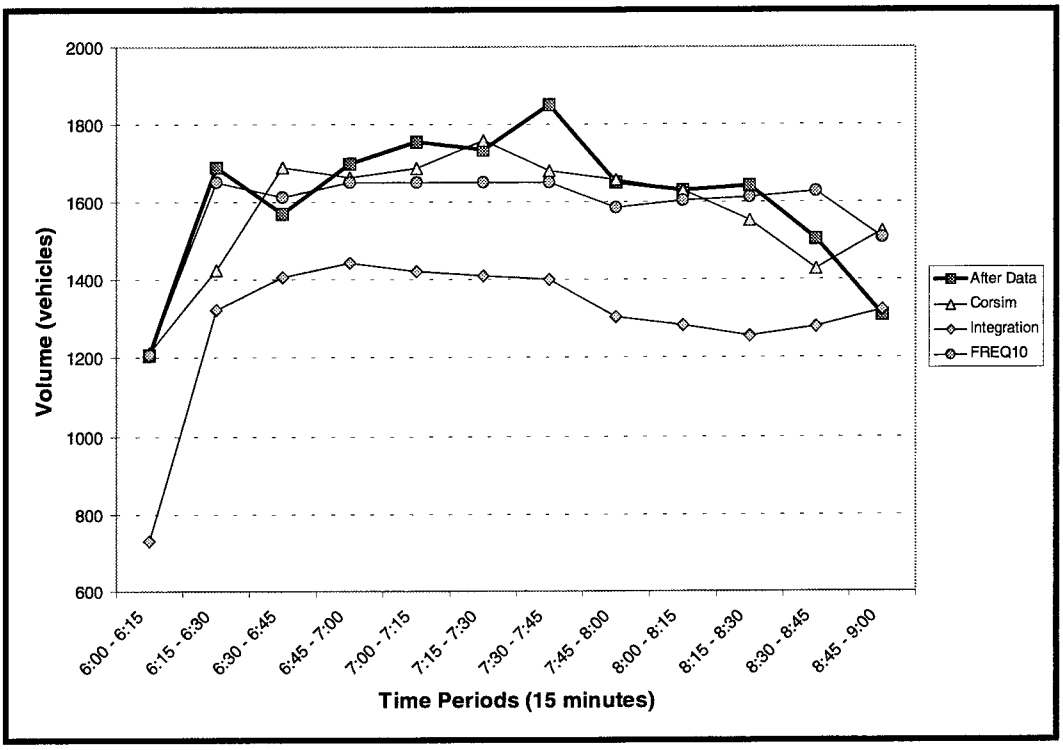


Figure 30. Site 3: NB SH 360: Validation Volumes After Randol Mill Exit (6:00–9:00 AM).

CHAPTER 5

PROJECT CONCLUSIONS AND RECOMMENDATIONS

This chapter presents the conclusions and recommendations of this research which evaluated the use of simulation models for evaluating congested freeway facilities. Researchers selected three simulation models for project including: CORSIM (FRESIM component), FREQ, and INTEGRATION. They tested these models on three different freeway sites in the Dallas/Fort Worth area. The evaluation of model performance was done in three separate phases. In the first phase, the models were executed using the default parameters. This phase was referred to as the "base case" simulation. The second phase, model calibration, involved making adjustments to each model so that they would more closely replicate known field conditions. The final phase, model validation, used the calibrated models to evaluate how they performed with the new volumes and geometrics after the bottlenecks at each site were removed.

5.1 CONCLUSIONS

The following list provides a summary of the broad-based conclusions that can be drawn from this project:

- The models all perform relatively well for uncongested conditions; however, the performance becomes sporadic and mostly unreliable for congested conditions.

- It appears that the models function better when allowed to begin simulation prior to the onset of congestion. Having data upstream and downstream of a freeway bottleneck (each of the three sites in this project had congestion caused by geometric bottlenecks) or location of recurrent congestion helps the models perform better. Having data for several time periods before congestion starts (e.g., having data for 6:00 to 6:30 AM when congestion begins at approximately 6:30 AM) is also helpful.

- It is apparent that people drive differently in congested versus uncongested conditions. None of the models tested allowed the user to dynamically change key model parameters (e.g., headway, lane-changing, and driver behavior) to account for this driving difference based on the volume-to-capacity ratio.

- Much of the theory of flow in congested conditions is relatively new and therefore is still evolving (see Section 2.1.2). This means that many of the findings of the research that is occurring internationally have not been incorporated into the logic of any of the simulation models evaluated in this project.

- None of the models fared particularly well in the validation phase, even when the model calibration results were promising. This result could be because the volumes used in the

validation phase are higher and the model does not fully recognize the benefit of the capacity provided by the bottleneck improvement.

- The unpredictable and less than desirable performance of the models in congested conditions leads to the conclusion that the members of the research team would trust their own judgment over the simulation model output in most cases. This is because each of the sites selected was, in fact, a success story for bottleneck removals, and the models did not predict that.

Some of the more model-specific conclusions are presented in the following subsections.

5.1.1 Conclusions Regarding the Performance of FREQ

- The inability of the FREQ program to model vehicle speeds on freeway-to-freeway ramps is a significant detriment. This inability caused the evaluation of Sites 1 (SB Spur 408 to WB IH 20) and 2 (EB IH 635 to NB US 75) to not be as complete as when the other two models were used. The FREQ model seemed to perform its best on Site 3 (SH 360) because it involved simulation on only one freeway facility whereas the other sites required simulation on two facilities.

- The FREQ program is the most user-friendly in terms of ease of use and application. The creation of a FREQ input file is a straightforward process that takes very little time. The program requires the least amount of input data and also executes in a matter of seconds which makes the evaluation of multiple alternatives much more convenient. The ability to specify capacity on a link-by-link and ramp-by-ramp basis is also a feature that makes the model attractive for freeway operations applications.

- In most cases, researchers were unable to calibrate FREQ to replicate known field conditions (especially link speeds) within a reasonable accuracy level (+/– 5 mph).

5.1.2 Conclusions Regarding the Performance of CORSIM

- The CORSIM simulation model is the most robust in terms of input and output capabilities. The animation program is an invaluable source of information to the user when attempting to determine if the model is performing as expected and for verifying that the network is coded properly.

- The research team identified several limitations during the use of the FRESIM component of the CORSIM software. One of the limitations that is most frustrating is that capacity is not an input or an output variable. This distinction makes the model hard to calibrate because capacity is never known to the user. The generic per-lane capacity, while not known explicitly, is the same for all of the links contained in the freeway network. Capacity cannot be adjusted on a link-by-link basis as with the other two

models included in this project. Another frustration encountered while using this model was the fact that output values were reported on a cumulative basis over the time periods included in the project. This made it difficult to examine each time slice separately.

- The calibration of CORSIM was most easily done by modifying the parameters in record types 68 and 70. These record types control the parameters such as car-following sensitivity, lane-changing, driver aggressiveness, etc., which are all very important in evaluating operations in a congested environment. The calibration adjustments suggest that drivers in the Dallas/Fort Worth area are more aggressive than the default driver distribution in the model.

- CORSIM still seems to have a problem with a significant number of vehicles missing their assigned destination (i.e., exit ramp). The high number of vehicles missing their destination was evident from the output reports (list the number of vehicles) and by watching the animation where vehicles are color-coded (yellow) if they are supposed to exit on a link. In fact, there a few instances where a vehicle became "hung" (i.e., stopped in a freeway main lane) when it missed the final exit ramp destination in one of the networks. It is believed that this does not replicate what happens in the "real-world."

- The CORSIM program had the best overall performance in this project, and it shows promise for future application for the operational evaluation of congested freeway facilities. CORSIM has dramatically improved in the past several years and is continuing to be refined and updated under the direction of the FHWA. Because of the ongoing development and readily available technical support, it is believed that CORSIM's performance will continue to improve and get closer to being able to reliably predict operations on congested freeway sections.

5.1.3 Conclusions Regarding the Performance of INTEGRATION

- The INTEGRATION model required the most effort in terms of network coding and executing the model. The requirement that input volumes be specified in terms of origin-destination data makes it more difficult to use than either CORSIM or FREQ. INTEGRATION also was difficult to run (i.e., long execution times) and even failed to run for the Site 3 network because it was too large and complex. Researchers divided this site into two separate input files (one for the 6:00 to 7:45 AM time period and the other for 7:15 to 9:00 AM time period).

- INTEGRATION exhibited the worst overall performance in terms of being able to replicate known speed and volume profiles. The model consistently predicted lower volumes and speeds than those observed in the before and after conditions from field studies. A variety of measures were attempted to improve the model; however, none of the adjustments were able to significantly improve the overall performance of the model.

- One of the explanations for the previous conclusion is that the version of INTEGRATION used in this project (purchased from McTRANS in September of 1998) is not the best version available. An updated version of the INTEGRATION program (Windows-based, August 1999) became available too late to be used within the scope of this project.

5.2 RECOMMENDATIONS

The research team intended this project to provide guidance in analyzing congested freeway conditions. There is an ever-increasing demand for travel on urban freeways, and many freeways are operating under congested conditions throughout most of the day. Proposed improvements for congested freeways are difficult to evaluate because of complex vehicle interactions and the impact of various design elements on traffic flow. The researchers had several objectives to address the problem of analyzing congestion with the final objective or goal being to provide recommendations to TxDOT employees or consultants on the use of the best model to simulate congested freeway operations in Texas.

- Of the models available to the research team the CORSIM model, which is part of the *Traffic Software Integrated System Version 4.2* (TSIS 4.2) from the FHWA, showed promise in simulating congested freeway operations.

- The researchers recommend that CORSIM be used at locations that are fairly simple geometrically such as single freeway-to-freeway direct connection ramps similar to the direct connection studied at the SB Spur 408 to WB IH 20. More complex interchanges where ramps connect to other ramps such as the EB and WB ramp connection to NB US 75 are difficult to code and may not be effectively simulated by the model.

- The proper and effective calibration of CORSIM for a congested site requires that the user have good and extensive volume and travel time data, as well as origin and destination data. The user must collect data over a time period that begins prior to the onset of congestion and ends after the congestion has dissipated. Also, the data collection effort must extend over an area that covers the length of the traffic queues formed by the congestion. If the user cannot provide existing data or project future conditions, then the calibration and results of the CORSIM model cannot be expected to be reliable.

The FHWA continues to improve the CORSIM model, and future versions should be more user-friendly and should provide more reliable simulation of congested conditions. Improved versions of INTEGRATION as well as other models being developed may also provide effective and reliable simulations of congested freeways.

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