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Urban Public Transit Systems Modeling Capabilities

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16. Abstract

Current national transportation policy places increasing emphasis on multi-modal solutions involving public transit and high-occupancy vehicle (HOV) facilities and services. Current traffic simulation/assignment models, however, have only limited capabilities for evaluating the fuel consumption, traffic, and environmental impacts of alternative transit and HOV facilities and services in a multi-modal transportation system. Therefore, a formal assessment of current transit and HOV modeling capabilities was conducted, with emphasis on CORFLO, which is uniquely suited among U.S. public-domain models for detailed evaluations of traffic conditions in urban corridors. Other models assessed include CONTRAM, INTEGRATION, JAM, LATM, MICRO-ASSIGNMENT, NETSIM, SATURN, TRAFFICQ, and TRANSYT. SATURN and CORFLO were the most highly rated with respect to their modeling approach, transit and HOV supply/demand modeling , and output measures of effectivenss. A detailed analysis of CORFLO's logic and code and a case study evaluation of transit and HOV alternatives using a CORFLO model of the North Central Expressway Corridor in Dallas, Texas, revealed several areas in which CORFLO should be enhanced to improve its urban public transit systems modeling capabilities. Recommended enhancements include increasing the number of bus stops that can be accommodated, refining the modeling of bus movements along links, and adding or improving fuel consumption and emissions algorithms. These enhancements are necessary in order to estimate with reasonable accuracy the fuel consumption, traffic, and environmental impacts of common transit and HOV alternatives.

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URBAN PUBLIC TRANSIT SYSTEMS MODELING CAPABILITIES

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TABLE OF CONTENTS

Page

LIST OF ILLUSTRATIONS

EXECUTIVE SUMMARY

Current national transportation policy places increasing emphasis on transit and HOV improvements as elements of multi-modal solutions to urban transportation problems. This report evaluates the capabilities of existing traffic simulation models to estimate the traffic and associated fuel consumption effects of transit and HOV improvements. Special attention is given to CORFLO, which is uniquely suited among public-domain models in the United States for evaluations of traffic conditions in urban corridors.

CORFLO compares favorably to other traffic simulation models with respect to its transit and HOV modeling capabilities. It can model transit and HOV supply improvements and it provides ample system, bus-related, and bus-route-related measures of effectiveness. It has limitations, however, in its transit and HOV demand modeling capabilities and in the size of bus transit system that can be modeled. Its fuel consumption estimation capabilities are also limited. Enhancements to the transit and HOV supply modeling and fuel consumption estimating capabilities of CORFLO that are feasible within its current structure are identified. Enhancements to overcome CORFLO's demand modeling limitations are not considered feasible within its current structure

For the citizens of Texas to realize energy savings based upon this study, it would be necessary for the Federal Highway Administration, which developed and continues to maintain CORFLO, to make the enhancements identified in this report and implement them in the publicly released version of CORFLO. Furthermore, it would be necessary for transportation agencies in Texas to utilize the enhanced CORFLO model in their transportation investment decision making process.

The potential benefits of applying the results of the research reported herein are significant. It is estimated—based upon average commute trip lengths, automobile fuel efficiency, and average vehicle occupancy—that a 1 percent improvement in fuel consumption benefits realized from better transportation investment decision making represents approximately 1.2 million gallons of fuel savings per year per million commuters affected by the investments implemented.

1. INTRODUCTION

Traffic congestion increases fuel consumption, air pollution, and travel times in urban areas. In the past, the most common approach for reducing traffic congestion was to construct additional traffic lanes. At present, however, growing social, environmental, and economic concerns limit this approach. Under current national transportation policy, as stated in the Intermodal Surface Transportation Efficiency Act of 1991, multi-modal solutions—in which public transit systems and high-occupancy vehicle (HOV) facilities are critical elements—play a more important role in plans to reduce traffic congestion, fuel consumption, and mobile source emissions.

PROBLEM STATEMENT

The growing emphasis on multi-modal solutions places increasing demands on the transportation modeling and analysis tools required to evaluate alternatives. Only limited modeling capabilities exist for evaluating the fuel consumption, environmental, and traffic impacts of alternative transit and HOV facilities and services (e.g., bus transit, HOV lanes, paratransit, and other transit-related strategies) in a multi-modal transportation system. Improved modeling capabilities are required for integrated evaluations of transit-related strategies. Therefore, a formal evaluation of transit and HOV modeling capabilities was warranted.

The modeling package CORFLO is uniquely suited among public-domain models for evaluations of traffic conditions in urban corridors. CORFLO, which was developed by the Federal Highway Administration of the U.S. Department of Transportation, is an integrated freeway and arterial street traffic assignment and simulation package. It has the capability to model bus routes, bus and HOV lanes, and bus stations; however, these capabilities have not been widely used or investigated.

SCOPE AND OBJECTIVES OF THE STUDY

The research study focused on the capabilities necessary to model urban public transit systems. A comparative evaluation of traffic simulation models was conducted based upon the review of previous research and literature. Actual model testing relative to transit and HOV systems was limited to the CORFLO model. The study identified feasible enhancements to the transit-related modeling capabilities of CORFLO. However, revising the CORFLO model to incorporate these enhancements was beyond the scope of the study.

The specific objectives of the study were as follows:

- Identify required transit and HOV modeling capabilities considering national transportation and environmental policy and Intelligent Transportation Systems developments.

- Evaluate the transit and HOV algorithms in CORFLO to determine how well they satisfy required modeling capabilities.
- Test the existing modeling capabilities by performing case study evaluations of alternative transit and HOV improvements using a CORFLO model previously developed at the Texas Transportation Institute for the US-75 North Central Expressway corridor in Dallas.
- Recommend enhancements to CORFLO's transit and HOV modeling capabilities.

ORGANIZATION OF THE REPORT

This report is organized into six chapters. Chapter 2 identifies requirements for effective transit and HOV modeling. A comparative evaluation of ten traffic simulation models with potential for modeling transit and HOV improvements is provided in Chapter 3. The transit and HOV modeling capabilities of the CORFLO model are assessed in Chapter 4. In Chapter 5 the lessons learned from a case study evaluation of the transit-related elements of CORFLO are documented. Chapter 6 concludes with recommended transit-related enhancements to CORFLO.

2. TRANSIT AND HOV MODELING REQUIREMENTS

A prerequisite for the evaluation of transit and HOV modeling capabilities is a good understanding of the characteristics of these strategies and their potentials effects on the transportation system. This chapter identifies available transit and HOV strategies, modeling requirements for evaluating these strategies, and needed performance measures.

TRANSIT AND HOV STRATEGIES

A number of strategies exist to improve the efficiency and attractiveness of transit and HOV modes, including HOV lanes, bus lanes, bus-only streets, traffic signal priority, HOV priority at metered entrance ramps, exemption from banned turns, and rideshare matching and marketing programs. These strategies influence both supply and demand. New facilities or operational changes to existing facilities improve system performance. These improvements, in turn, would be expected to influence transit and HOV demand and the modal split between single-occupant vehicles and transit and HOV alternatives. The principal transit and HOV strategies are briefly discussed in this section.

HOV Lanes

The HOV lane strategy provides special purpose lanes to transit vehicles and HOVs and gives them preferential routing treatment to bypass congestion. HOV lanes include exclusive facilities on existing right-of-way or separate right-of-way, concurrent flow lanes, and contraflow lanes.

Exclusive HOV facilities are roadways or lanes reserved for the exclusive use of HOVs. These facilities are built within an existing right-of-way but physically separated from other traffic lanes or built in an entirely separate right-of-way.

Concurrent flow bus/HOV lanes are traffic lanes within the existing right-of-way designated for use by buses and selected priority vehicles (e.g., carpools, vanpools, and emergency vehicles). These lanes operate in the peak direction of traffic flow and are not physically separated from other general traffic lanes. Concurrent bus/HOV lanes are aimed at minimizing delays for buses and HOVs during periods of heavy queuing for general traffic.

Contraflow HOV lanes operate on one or more lanes in a direction of travel opposite to the adjacent general traffic. Contraflow lanes are located in the off-peak direction of travel and designated for exclusive use by HOVs traveling in the peak direction. They are often aimed at maintaining or improving bus access to centers of employment or retailing. A typical location of a contraflow lane is a one-way arterial street system. Lengthy diversions that usually accompany one-way systems may be avoided. In addition, interference with right-turning vehicles is minimized, resulting in improved travel time for HOVs.

HOV lane strategies have the following benefits:

- Reduced travel time for buses and carpools passengers,
- Reduced waiting time at bus stops and improved service reliability,
- Reduced service costs and increase in revenue for bus operators,
- Reduced vehicle operating costs for carpool passengers,
- Increased person-carrying capacity of the existing roadway system,
- Reduced fuel consumption and mobile source emissions in accommodating a given person-travel demand.

The adverse impacts which need to be assessed include:

- A reduction in speed for the general traffic due to reduced capacity or reduced queuing capacity,
- Increased congestion on adjacent arterials due to traffic diversion,
- Possible increase in accident hazards for pedestrians, and
- The loss of capacity and queuing space for non-priority vehicles could cause queue spillbacks and traffic diversion.

Signal Priority for Public Transit

In an attempt to reduce delays and give priority to person movement (rather than vehicle movement) at signalized intersections, traffic signal control may be temporarily altered so that an approaching transit vehicle receives a green phase when it arrives. Priority for buses at traffic signals can be provided either by weighing the signal timings in favor of traffic streams containing buses (i.e., stream weighing or passive priority treatment) or by detecting buses individually and adjusting the signal timings accordingly to give them priority (i.e., selective detection, or active priority treatment).

The passive priority strategy can be implemented with isolated pretimed or actuated signals, coordinated fixed-time signal networks, or traffic-responsive control systems. At isolated signals, passive priority stream weighing is applied by increasing the maximum green time for selected streams, by time-of-day or day-of-week. In coordinated fixed-time signal networks, bus priority can be introduced by weighing delay or stops on selected traffic streams. In the optimization process of the signal timings, buses are modeled as a separate vehicle type so that the signal offsets can reflect the difference in performance between buses and other vehicles (e.g., speeds, and the effects of bus stops). In traffic-responsive systems, weighing may be applied to green splits and/or offsets may be fixed or biased to reflect bus performance. The main positive effect of passive priority is delay reduction for buses. Continuous priority, even when it is not needed, and increased delay for the cross street are the main disadvantages.

Active priority improves upon the basic weakness in passive priority by individually detecting buses in a mixed traffic stream some distance upstream of a signal controlled intersection. The signal is adjusted, if necessary, to give the bus priority. It is not designed to reduce congestion but rather to reduce the stopped delay buses experience at signals. Active priority has the following advantages: provides sufficient priority to allow the transit vehicle to clear the intersection, avoids providing priority when the transit vehicle is not there, and sensitive to the non-priority crossing street movements. The negative effect is the possible increase in delay for the cross street, despite compensation measures provided by advanced traffic signal control systems.

Bus Station Layout and Spacing

Bus stations layout and spacing can have significant impacts on both bus operations and general traffic. Impacts associated with different bus station layout and spacing that may need to be evaluated include: increased frequency of bus stations will increase access to the transit system but decrease the average speed of buses, and adequate station capacity and layout will reduce the interactions between buses and regular traffic during dwell times and improve traffic flow at the particular location.

Demand Impacts

Improved transit and HOV facilities and services will result, most of the time, in a change in the roadway system. This change, in turn, encourages shifts in transportation demand. These shifts will generally be in the following forms:

- Spatial diversion: The introduction of certain strategies (e.g., HOV lane) could have negative effects on non-priority vehicles. These negative effects (e.g., reduced speeds and reduced intersection capacities) may prompt some auto users to change their route to a given destination or change the destination of their trips to a less congested area.
- Modal diversion: Improved transit and HOV services with shorter travel times and better schedule reliability may attract more users to transit and HOVs from single occupant vehicle usage.
- Temporal diversion: Some travelers may change their departure time to avoid the period of heavy congestion.

Fuel Consumption Impacts

Reductions in fuel consumption are an important potential benefit of transit and HOV improvements. Reductions may result from both improvements in the supply of transit and HOV facilities and services as well as shifts in demand that result from supply improvements. The potential savings in fuel consumption for each commuter round trip diverted from a single-occupant vehicle to transit or HOV modes is approximately 0.6 gallon per person-trip, based upon average commute trip lengths (20 mi), new automobile fuel efficiency requirements (28.4 mi/gal), and average vehicle occupancy (1.2 persons per vehicle). Additional savings may result from improvements in traffic conditions associated with improvements in transit and HOV facilities and services. Since fuel consumption estimates are derived from estimates of system performance, the focus of this study is on the modeling of the effects of transit and HOV strategies on system performance.

TRANSIT AND HOV MODELING REQUIREMENTS

The characteristics and potential impacts of the strategies identified in the previous section suggest a set of modeling requirements for evaluating these strategies. Table 1 summarizes the modeling requirements for strategies that influence transit and HOV service supply. Table 2 summarizes the modeling requirements for evaluating the effects of strategies on transit and HOV demand.

TABLE 1. Requirements to Model Transit and HOV Supply

Ability to Model	Comment
Buses	To account for separate effects of buses
Carpools	To account for separate effects of carpools
Exclusive bus/HOV lane	To account for changes in capacities
Bus preemption	To determine effects on bus/auto delays
Station layout	To account for interaction with regular traffic
Station spacing	To determine effects on access/speeds
Station capacity	To account for interaction with regular traffic

TABLE 2. Requirements to Model Effects on Transit and HOV Demand

Ability to Model	Comment
Mode choice	To distinguish bus, carpool, and auto trips
Modal shift	To account for changes in auto/bus travel times
Route choice	Diversion due to increased congestion
Destination choice	Change of destination to a less congested area
Temporal diversion	Change of departure time to avoid congestion

REQUIRED PERFORMANCE MEASURES

The evaluation of a proposed transit or HOV strategy requires knowledge of the effects attributable to that strategy. If these effects can be measured or predicted accurately, then the associated impacts can be assessed. Table 3 summarizes the appropriate performance measures for evaluating transit and HOV strategies. The pertinent measures of effectiveness (MOEs) to consider when evaluating transit-related strategies are divided into system, bus-related, and bus-route-specific MOEs.

TABLE 3. MOEs for Evaluating Transit and HOV Strategies

Measure of Effectiveness	Units
System MOEs:	
Total travel time	Person-hours
Total travel	Person-hours
Total travel	Person-trips
Total travel	Vehicle-miles
Fuel consumption	Gallons
Mobile source emissions	Pounds
Bus-Related MOEs:	
Bus travel	Vehicle-miles
Bus travel	Person-miles
Bus travel	Person-trips
Bus travel	Bus-trips
Bus travel time	Bus-hours
Bus delay	Bus-hours
Bus speeds	Miles/hour
Bus stops	Number
Bus-Route-Specific MOEs:	
Bus travel	Bus-trips
Bus travel	Person-trips
Mean travel time on route	Minutes

System MOEs

System MOEs are network-aggregated statistics and may be either person-based or vehicle-based. Person-based MOEs include: total travel in person-miles and person-trips, total delay in person-hours, and total travel time in person-hours. Using these MOEs puts the emphasis on moving people rather than vehicles. Person-based MOEs are most appropriate in assessing bus transit and HOV strategies. For example, a decrease in person-delay and person travel time between a base case and a new scenario represents a desirable option.

Vehicle-based system MOEs include: total travel in vehicle-miles and vehicle-trips, total delay in vehicle-hours, and total travel time in vehicle-hours. These MOEs are of little help for evaluating the performance of a transit system, because they give no indication of the number of people that the system will carry after a proposed strategy is implemented. However, in the case of a "before-after" study where the effects are actually measured in the field before and after the strategy is implemented, vehicle-based system MOEs can provide a useful evaluation.

Fuel consumption and mobile source emissions reductions are potential benefits of transit and HOV improvements and, therefore, are important MOEs. In most traffic models, fuel consumption and mobile source emissions from derived from vehicle-based measures.

Bus-Related MOEs

MOEs specifically related to buses only isolate the impacts of strategies on bus operations. These MOEs include bus travel in vehicle- and person-miles, bus- and person-trips as well as bus travel time and delay. Impacts on regular traffic also should be assessed, however, to ascertain whether disbenefits to the regular traffic offset the benefits to bus operations.

Bus-Route-Specific MOEs

The provision of route-specific and station-specific MOEs expands the usefulness of a model to transit operators. A transit operator is more interested in the performance of individual bus routes and bus stations than in network links. These MOEs will provide information useful for adjusting schedules and assessing potential gains in service reliability.

3. ASSESSMENT OF TRAFFIC SIMULATION MODELS FOR TRANSIT AND HOV APPLICATIONS

Numerous existing traffic simulation models have some transit and HOV modeling capability. Although the objectives of this study were geared toward the evaluation of the CORFLO model's transit-related capabilities, an overall assessment of existing traffic simulation models was conducted. as a basis for comparison. This chapter presents a brief review of ten traffic simulation models and a comparative evaluation of five models selected for more detailed review.

REVIEW OF CANDIDATE TRAFFIC SIMULATION MODELS

This section presents an initial review of ten candidate network traffic simulation models with respect to modeling requirements and MOEs to evaluate transit and HOV strategies. Table 4 identifies the models.

TABLE 4. Candidate Traffic Simulation Models

Model	Application
CONTRAM	Arterial network traffic simulation-assignment
CORFLO	Integrated freeway/arterial simulation-assignment
INTEGRATION	Integrated freeway/arterial simulation-assignment
JAM	Arterial network traffic simulation-assignment
LATM	Local area network traffic simulation-assignment
MICRO-ASSIGNMENT	Local area network traffic simulation-assignment
NETSIM	Urban arterial network simulation
SATURN	Arterial network traffic simulation-assignment
TRAFFICQ	Local area network traffic simulation
TRANSYT	Network traffic signals optimization/simulation

Three major features are given special consideration due to their importance in assessing modeling capabilities for evaluating transit schemes:

- Ability to model buses as a separate vehicle type—Representing buses as a separate type of vehicle is the first step toward accounting for the effects of transit on the overall system performance. Therefore, this feature is essential for the purpose of this study.
- Representation of the roadway network—Transit and HOV alternatives generally require some special treatment of the roadway space such as bus lanes. Therefore, the model's approach to roadway modeling with respect to this requirement is critical.

- Bus measures of performance—Separate bus MOEs permit the proper accounting of the effects of bus-related measures on the performance of the transportation system.

CONTRAM

CONTRAM (*1, 2, 3*) is a traffic assignment model developed primarily for use in the design of traffic management schemes in urban areas. It is a capacity-restrained dynamic model that accounts for the interactive effects of intersection operations and the variation of traffic conditions over time. In particular, it models the build up and dissipation of queues. Traffic demand is expressed as origin-destination (O-D) trips for each time interval. Vehicles from each O-D pair are grouped into packages that are assigned to the minimum trip time route. An equilibrium traffic assignment is achieved through an iterative process. The model allows the representation of three types of vehicles: cars, buses, and trucks. The "banned vehicle" facility provides a method for examining bus lanes. Separate bus statistics are provided in the outputs.

CORFLO

CORFLO (*4*) is an integrated freeway/arterial network traffic simulation package that consists of three traffic simulation models and a traffic assignment model. It is designed such that the component models can be interfaced to form an integrated package. These models are: NETFLO urban model I, NETFLO urban model II, FREFLO freeway model, and TRAFFIC assignment model. The traffic assignment model assigns an O-D trip table to the network, and calculates the flows on each link, which are subsequently evaluated using one or more of the simulation models. Bus traffic is treated separately, and special purpose lanes to accommodate buses and carpools can be specified. CORFLO generates detailed bus-related MOEs.

INTEGRATION

INTEGRATION (*5*) was developed specifically to evaluate and optimize the operation of an integrated freeway/arterial network during periods of recurring and non-recurring congestion. The modeling approach considers the behavior of individual vehicle that have self-assignment capabilities. This capability serves the traffic assignment function. Consequently, continuously variable traffic demands and controls can be considered on both freeway and signalized arterials. INTEGRATION's main weaknesses with regard to this study are its lack of arterial HOV representation and its lack of explicit bus MOEs.

JAM

JAM (*6*) is a computer model developed for traffic assignment to urban networks in which intersection delays play a significant role in determining driver's route choice. Within the assignment process, trips are loaded onto the network incrementally within a single run of the program. In each increment, a fraction of the trips is assigned to a new set of path trees based upon the delays at each intersection node. Although the model represents buses and HOV lanes, it was not intended for the evaluation of public transportation schemes and the outputs do not provide bus-related statistics.

LATM

LATM (*7, 8*) is a traffic simulation-assignment model suitable for small-area short-duration studies. The model is a dynamic capacity-restraint assignment procedure which can approximate changes in travel demand, congestion levels, and network conditions over a finite time period. A probabilistic path selection mechanism is used to simulate the imperfect network knowledge and traffic information available to travelers. An important innovation of the model, which enhances its potential for local-area use, is that all trip generation occurs along the streets in the area, i.e., on the links of the network. Thus the problems caused by point generation in other assignment procedures are not present in LATM. The main weakness of LATM with regard to the purpose of this study is its inability to distinguish buses from other traffic.

MICRO-ASSIGNMENT

MICRO-ASSIGNMENT (*9*) is a microscopic adaptation of traditional transportation planning assignment techniques. Traffic is assigned in a conventional fashion, but the network is coded in considerably more detail, so that individual movements or lanes can be considered. Assignment is based on an iterative multipath procedure which assigns time-slice O-D trips to the links. MICRO-ASSIGNMENT's main weakness with regard to the purpose of this study is its inability to distinguish buses from other traffic.

NETSIM

NETSIM (*10*) is a microscopic, stochastic network simulation model. It treats the street network as a series of interconnected links and nodes, along which vehicles are processed in a time-scan format subject to the traffic control system. The model was primarily designed as a tool for testing alternative control strategies under conditions of heavy demand. Both buses and carpools are modeled as separate types of vehicles, and special purpose lanes for buses and carpools can be specified. The model produces detailed bus measures of performance.

SATURN

SATURN (*11, 12*) is a traffic assignment model based on a detailed simulation of intersection delays. Intersection delays are determined using cyclical flow profiles. Consequently the effects of signal coordination and platoon progression on delay can be accounted for. Traffic flows on each link are estimated using a combination of all-or-nothing assignments. These new estimates of link flows are then reevaluated with the cyclic profile approach until equilibrium is reached between the evaluation and the assignment. A travel mode choice model (SATCHMO) provides SATURN with extended capabilities for modeling public transportation, which include the modeling of bus trips, the ability to model exclusive bus/HOV lanes, and explicit bus-related outputs.

TRAFFICQ

TRAFFICQ is a simulation model of pedestrian delay, vehicle queuing, and platooning behavior (*13*). Each vehicle or pedestrian is modeled as an individual entity. The model is aimed at relatively small-scale systems. Routes taken by vehicles are specified by the user, and no internal assignment technique is present. The model provides the ability to model buses and exclusive bus/HOV lanes. Separate bus statistics are provided in the outputs.

TRANSYT

TRANSYT (*14*) is a signal optimization program for arterial networks, which can also simulate traffic conditions for the duration of a common cycle length. Buses and carpools can be explicitly modeled in TRANSYT. This is accomplished by assigning separate links to buses. Bus links may be entirely separate to simulate bus-only lanes, or they may "share" a stop-line with other traffic. The main weaknesses of TRANSYT with regard to the purpose of this study are its lack of separate bus statistics.

COMPARATIVE EVALUATION OF SELECTED MODELS

Five models whose characteristics most closely satisfy the requirements for modeling transit and HOV strategies were selected for further evaluation. The purpose of the evaluation is to assess the relative merits of each model with regard to the specific requirements set forth in this study. The five model are:

- CONTRAM,
- CORFLO,
- NETSIM,
- SATURN, and
- TRAFFICQ.

The comparative evaluation includes the following:

- An assessment of the models' performance based on selected criteria, and

- Highlights of the models' major strengths and weaknesses.

Evaluation Method

A quantitative method was developed for the comparative evaluation of each model. The models are evaluated with respect to three criteria:

- Modeling approach and logic,
- Transit supply and demand modeling capability, and
- Performance measures.

Specific features are itemized within each criteria. Each feature is assigned a relative importance. Table 5 summarizes the three categories of importance (A, B, and C) and the weighting coefficient assigned to each. Tables 6, 7, and 8 summarize the features evaluated within each of the three criteria and their relative importance.

TABLE 5. Relative Importance of Model Features

Category	Description	Weighting Coefficient
A	Necessary requirement or very important feature	3
B	Desirable requirement or important feature	2
C	Less important requirement or feature	1

The evaluation was performed using information gathered from published literature on the models. A model's performance with respect to each feature was rated as excellent, good, fair, or poor. Table 9 summarizes the weighting coefficients assigned to each rating level.

The models were scored based upon their performance with respect to each feature and the feature's relative importance. A score for each feature was calculated by multiplying the relative importance coefficient by the performance rating coefficient. For each criteria, a composite score was computed by summing the scores for the individual features within the criteria. A model's overall score was computed by summing the composite scores for the three criteria.

The scoring method has limitations. First, it only approximately represents the relative importance of features. Furthermore, it is difficult to assess precisely the models' performances because of the differences in the amount and quality of published documentation. Given the relatively large number of features considered in the evaluation, however, the results give a reasonable assessment of the relative performance of the five models.

TABLE 6. Modeling Approach and Logic: Features and Relative Importance

Feature	Importance Category
Arterial Representation	
Unidirectional/link	B
Traffic signals	A
Signal coordination	B
Yield intersection simulation	C
Uncontrolled intersection simulation	C
Separate turning movements	B
Platoon progression	B
Pretimed signal control simulation	B
Actuated signal simulation	B
Traffic Flow, Queueing, and Delay	
Macroscopic flow representation	A
Mesoscopic flow representation	A
Microscopic flow representation	A
Dynamic growth and dissipation of queues	A
Queue spillback	B
Assignment	
Equilibrium assignment	A
Dynamic (en-route) assignment	A

TABLE 7. **Transit Supply and Demand Modeling: Features and Relative Importance**

Feature	Importance Category
Transit and HOV Supply	
Bus class of vehicle	A
Carpool class of vehicle	B
Reserved lane modeling	A
Bus preemption simulation	A
Bus station layout modeling	C
Bus station spacing modeling	C
Bus station capacity modeling	B
Transit and HOV Demand	
Mode choice: separate auto, bus O-D trips	A
Synthetic O-D trips generation	B
Modal shift as function of travel times	A
Effects of congestion on route choice	A
Effects of congestion on destination choice	A
Effects of congestion on choice of time of departure	B

TABLE 8. Performance Measures: Features and Relative Importance

Feature	Importance Category
System MOEs	
Total travel time in person-hours	A
Total travel in person-miles	B
Total travel in person-trips	A
Total travel in vehicle-miles	B
Fuel consumption	A
Carbon monoxide emissions	B
Bus-Related MOEs	
Bus travel in vehicle-miles	B
Bus travel in person-miles	B
Bus travel in person-trips	B
Bus travel in bus-trips	B
Bus travel time	B
Bus delay	B
Bus speeds	B
Bus stops	C
Bus-Route-Specific MOEs	
Bus travel in bus-trips	B
Bus travel in person-trips	B
Mean travel time on route	B

TABLE 9. Model Performance Rating System

Performance Rating	Coefficient
Excellent	4
Good	3
Fair	2
Poor	0

Tabulation of Models' Capabilities

Table 10 summarizes the overall scores for the five models on the three criteria. Tables 11 through 13 provide details on the models' scores with respect to the features within the three criteria.

TABLE 10. Composite Scores of the Five Models

Criterion	CONTRAM	SATURN	CORFLO	NETSIM	TRAFFICQ
Modeling Approach	102	116	108	100	100
Transit Supply & Demand Modeling	56	92	64	60	68
Performance Measures	60	136	144	144	56
Overall Score	218	344	316	304	224

The results indicates that SATURN performed best, followed by CORFLO and NETSIM. SATURN had the highest scores in two of the three criteria (model approach and logic, and transit supply and demand modeling capability) and was second to CORFLO and NETSIM with respect to performance measures. CONTRAM and TRAFFICQ received much lower ratings than the other models.

CORFLO's capabilities are rated second to SATURN. The evaluation suggests that CORFLO has two fundamental deficiencies with regard to the purpose of this study. One is the inability of its traffic assignment model to deal with queuing, non-steady-state traffic conditions, and dynamic assignment. A dynamic traffic assignment model for CORFLO was recently developed and validated at the Texas Transportation Institute, but it has not been implemented in the public-release version of CORFLO (*16, 17*). The second is its inability to model the effects of congestion on mode, destination, and departure time choice. These capabilities would be difficult to incorporate within CORFLO's existing modeling framework.

NETSIM was rated slightly below CORFLO. It shares the disadvantages of CORFLO and, additionally, lacks an assignment model. Despite its high score, its potential use is limited to the evaluation of arterial street transit and HOV supply improvements.

CONTRAM has advanced traffic assignment capabilities that are valuable for transit and HOV evaluations, but its supply modeling capabilities are limited and it provides few bus-related performance measures. TRAFFICQ has good transit and HOV supply modeling capabilities, but it lacks demand modeling capabilities and provides only limited bus-related performance measures.

TABLE 11. **Modeling and Simulation Approach: Tabulation of Models' Characteristics**

Feature	CONTRAM	CORFLO	NETSIM	SATURN	TRAFFICQ
ARTERIAL REPRESENTATION					
Unidirectional link	Yes (8)	Yes (8)	Yes (8)	Yes (8)	Yes (8)
Traffic signals	Yes (12)	Yes (12)	Yes (12)	Yes (12)	Yes (12)
Signal coordination	Appr. (6)	Yes (8)	Yes (8)	Yes (8)	Yes (8)
Yield intersection simulation	Yes (4)	Yes (4)	Yes (4)	Yes (4)	Yes (4)
Uncontrolled intersection simulation	Yes (4)	Yes (4)	Yes (4)	Yes (4)	Yes (4)
Separate turning movements	Yes (8)	Yes (8)	Yes (8)	Yes (8)	Yes (8)
Platoon Progression	No (0)	Yes (8)	Yes (8)	Yes (8)	Yes (8)
Pretimed signal control simulation	Yes (8)	Yes (8)	Yes (8)	Yes (8)	Yes (8)
Actuated signal simulation	Appr. (8)	Yes (8)	Yes (8)	Yes (8)	Yes (8)
TRAFFIC FLOW, QUEUE, AND DELAY					
Macroscopic flow representation	No (0)	No (0)	No (0)	No (0)	No (0)
Mesoscopic flow representation	Yes (12)	Yes (12)	No (0)	Yes (12)	No (0)
Microscopic flow representation	No (0)	No (0)	Yes (12)	No (0)	Yes (12)
Dynamic growth and dissipation of queues	Yes (8)	Yes (12)	Yes (12)	Yes (8)	Yes (12)
Queue spillback	Yes (8)	Yes (8)	Yes (8)	Yes (8)	Yes (8)
ASSIGNMENT					
Equilibrium assignment	Yes (12)	Yes (8)	No (0)	Yes (12)	No (0)
Dynamic (en-route) assignment	Yes (8)	No (0)	No (0)	Yes (8)	No (0)
SCORE	102	108	100	116	100

TABLE 12. Transit and HOV Supply/Demand Modeling: Tabulation of Models' Characteristics

Feature	CONTRAM	CORFLO	NETSIM	SATURN	TRAFFICQ
TRANSIT & HOV SUPPLY					
Bus class of vehicle	Yes (12)	Yes (12)	Yes (12)	Yes (12)	Yes (12)
Carpool class of vehicle	No (0)	Yes (8)	Yes (8)	No (0)	Yes (8)
Reserved lane modelling	Yes (12)	Yes (12)	Yes (12)	Yes (12)	Yes (12)
Bus preemption simulation	No (0)	No (0)	Yes (12)	No (0)	Yes (12)
Bus station layout modelling	No (0)	Yes (4)	Yes (4)	No (0)	Yes (4)
Bus station spacing modelling	No (0)	Yes (8)	Yes (8)	Yes (8)	Yes (8)
Bus station capacity modelling	No (0)	Yes (4)	Yes (4)	No (0)	Yes (4)
TRANSIT & HOV DEMAND					
Mode choice: separate auto, bus O-D trips	Yes (12)	Appr. (8)	No (0)	Yes (12)	No (0)
Synthetic O-D trips generation	Yes (8)	No (0)	No (0)	Yes (12)	No (0)
Modal shift as function of travel times	No (0)	No (0)	No (0)	Yes (12)	No (0)
Effects of congestion on route choice	Yes (12)	Yes (8)	Yes (8)	Yes (8)	Yes (8)
Effects of congestion on destination choice	No (0)	No (0)	No (0)	Yes (8)	No (0)
Effects of congestion on choice of time of departure	No (0)	No (0)	No (0)	Yes (8)	No (0)
SCORE	56	64	60	92	68

TABLE 13. Performance Measures: Tabulation of Models' Characteristics

Feature	CONTRAM	CORFLO	NETSIM	SATURN	TRAFFICQ
<u>SYSTEM MOEs</u>					
Total travel time in person-hours	No (0)	Yes (12)	Yes (12)	Yes (12)	No (0)
Total travel in person-miles	No (0)	Yes (8)	Yes (8)	Yes (8)	No (0)
Total travel in person-trips	No (0)	Yes (12)	Yes (12)	Yes (12)	No (0)
Total travel in vehicle-miles	Yes (8)	Yes (8)	Yes (8)	Yes (8)	Yes (8)
Fuel consumption	Yes (12)	Yes (12)	Yes (12)	Yes (12)	Yes (12)
CO emissions	No (0)	Yes (8)	Yes (8)	No (0)	No (0)
<u>BUS RELATED MOEs</u>					
Bus travel in vehicle-miles	Yes (8)	Yes (8)	Yes (8)	Yes (8)	Yes (8)
Bus travel in person-miles	No (0)	Yes (8)	Yes (8)	Yes (8)	No (0)
Bus travel in person-trips	No (0)	Yes (8)	Yes (8)	Yes (8)	No (0)
Bus travel in bus-trips	No (0)	Yes (8)	Yes (8)	Yes (8)	No (0)
Bus travel time	Yes (8)	Yes (8)	Yes (8)	Yes (8)	Yes (8)
Bus delay	Yes (6)	Yes (8)	Yes (8)	Yes (8)	Yes (8)
Bus speeds	Yes (6)	Yes (8)	Yes (8)	Yes (8)	Yes (8)
Bus stops	No (0)	Yes (4)	Yes (4)	Yes (4)	Yes (4)
<u>BUS ROUTE-SPECIFIC MOEs</u>					
Bus travel in bus-trips	Yes (6)	Yes (8)	Yes (8)	Yes (8)	No (0)
Bus travel in person-trips	No (0)	Yes (8)	Yes (8)	Yes (8)	No (0)
Mean travel time on route	Yes (6)	Yes (8)	Yes (8)	Yes (8)	No (0)
SCORE	60	144	144	136	56

Models' Major Strengths and Weaknesses

The major strengths and weaknesses of the five models are summarized in Table 14. These characteristics are highlighted in this section.

CONTRAM

CONTRAM's main strength derives from its dynamic assignment technique. The assignment model recognizes the unique characteristics of bus routes by not assigning them to the shortest path route. Other strengths of the model include the ability to model buses as a separate type of vehicle and assign them to a reserved lane if necessary. CONTRAM's outputs include separate bus statistics, but it lacks person-movement measures.

CONTRAM's main weakness is its inability to model several important transit supply and demand options. Some of the supply options that cannot be modeled include carpool , bus stations, and bus preemption. On the demand side, CONTRAM does not model modal shift, change in destination choice, and temporal diversion.

CORFLO

CORFLO's major strengths are its ability to model all the major transit and HOV supply options and to provide detailed bus MOEs. Both buses and carpools are modeled as separate types of vehicles. Bus reserved lanes, bus stations, and bus routes can be specified when coding the network. CORFLO generates person-based MOEs, fuel consumption, and mobile emissions. Detailed bus route-specific and station-specific MOEs are also provided.

The main weakness of CORFLO is its limited representation of travel demand and mode choice. The model does not account for modal or temporal diversion, nor does it account for changes in destination choice. It does not simulate bus preemption systems.

NETSIM

NETSIM shares CORFLO's strength in modeling transit and HOV supply options. NETSIM models buses and carpools as well as bus/HOV lanes and bus stations on arterial streets. It generates person-based MOEs, bus route-specific, and station-specific MOEs. In addition a special version referred to as NETSIM/BPS provides the ability to model bus preemption.

NETSIM also shares CORFLO's weakness in demand modeling. Additionally, NETSIM lacks a traffic assignment procedure.

TABLE 14. Major Strengths and Weaknesses of the Reviewed Models

	Models' Strengths and Weaknesses	Traffic Simulation Models				
		CONTRAM	CORFLO	NETSIM	SATURN	TRAFFICQ
Strengths	Bus as a separate type of vehicle	●			●	●
	Bus preemption			●		
	Bus routes	●	●	●		
	Bus station capacity/layout/spacing		●	●		
	Bus stations					●
	Bus/HOV lanes	●	●	●	●	●
	Buses/carpools as separate types of vehicles		●	●		
	Changes in destination choice				●	
	Equilibrium dynamic assignment	●				
	Mobile emissions		●	●		
	Modal shifts				●	
	Person based MOEs		●	●		
	Route-specific station-specific MOEs		●	●		
	Separate bus MOEs					●
	Separate bus statistics	●			●	
	Separate Bus/Auto O-D trips	●				
	Synthetic O-D Matrices	●			●	
	Temporal diversion				●	
	Traffic assignments		●		●	
Weaknesses	Do not account for destination change	●	●	●		●
	Do not account for modal shift	●	●	●		●
	Do not account for temporal diversion	●	●	●		●
	Do not model bus preemption	●				
	No bus preemption		●		●	●
	No bus station representation	●				
	No carpool representation	●			●	●
	No mobile emissions	●				●
	No synthetic O-D trips generation/updating		●	●		●
	No traffic assignment			●		●

SATURN

SATURN has several important strengths. Buses can be modeled as a separate vehicle type, and bus-only links can be specified in the network coding. It also incorporates a traffic assignment routine. It provides separate performance measures for buses, which make it possible to study specific network effects of changes in bus routes. The travel mode choice routine accounts for changes in modal choice as a function of auto and bus travel times, suppression/generation of trips due to congestion effects, and variation in travel demand as a result of changes in departure times.

The limitations of SATURN are its inability to represent carpools and to simulate bus preemption. It was developed for use in England and would have to be adapted for use in the United States.

TRAFFICQ

Although TRAFFICQ has some transit and HOV modeling capabilities, it also has serious weaknesses. TRAFFICQ can model buses as a separate vehicle type, model bus/HOV lanes and bus stations, and provide separate bus MOEs.

TRAFFICQ's weaknesses include a lack of travel demand and traffic assignment modeling capabilities. Furthermore, it cannot model carpools or bus preemption strategies.

SUMMARY

On the basis of the evaluation process it appears that SATURN has the most extensive transit and HOV modeling capabilities. Important features are its ability to model incremental mode choice and elastic demand. Its public transportation module includes bus transit and other types of public transportation.

The evaluation results indicate that CORFLO compares favorably with other traffic simulation models with respect to transit and HOV strategies. It rates best among models developed in the United States. CORFLO appears to have excellent capabilities to model the transit supply side. Its modeling capabilities of the demand side, however, are limited. Further study of CORFLO's modeling capabilities and algorithms are provided in Chapter 4.

4. CORFLO'S TRANSIT AND HOV MODELING CAPABILITIES

The assessment of traffic simulation models documented in Chapter 3 indicated that the CORFLO model rated well compared to other similar models. This chapter further investigates the CORFLO model and describes its present transit modeling capabilities and limitations. Transit-related input data requirements and transit-related MOEs generated by the model are also discussed. The transit and HOV algorithms were assessed by reviewing CORFLO documentation and examining the related software code.

The transit-related simulation algorithms in FREFLO and NETFLO Level II are discussed first. A discussion of the input data and MOEs generated by the model follows.

TRANSIT AND HOV ALGORITHMS

Bus Treatment in FREFLO

FREFLO represents three distinct vehicle types: buses, carpools, and autos and trucks. Trucks are not a separate vehicle type, but are represented jointly with autos. Traffic variables including entry flow rate, exit flow rate, density, and space mean speed are also distinguished by vehicle type. To account for the influence of heavy vehicles on the traffic stream, a passenger car equivalent of 2 is assumed for buses and trucks.

The freeway subnetwork can have special purpose lanes and regular lanes. Special purpose lanes can be designated for use by buses and/or carpools, whereas regular lanes accommodate all types of traffic including buses and carpools. In calculating speeds and densities, vehicles are assumed to be distributed uniformly across all of the special purpose or regular lanes for which they are designated. This feature enables the model to calculate different speeds and densities for each vehicle type within a freeway section, which is useful in the evaluation of HOV strategies.

The flows of autos and trucks, buses, and carpools in the freeway links are represented by separate aggregate variables. In addition to these aggregate variables, buses are further distinguished in that they are separately transported to exit nodes for the purpose of computing transit times and placed at the entrance to other subnetworks, in order to maintain their identity. Buses are not allowed to stop on the freeway subnetwork.

Bus traffic is handled in two ways by FREFLO logic. First, a bus is introduced into the freeway subnetwork at an entry node or an entry interface node at the appropriate time. The time of entry at an entry node depends on bus headways for the routes originating at that entry node. At the entry interface node, buses are introduced into the freeway subnetwork based on the time they exited the arterial street subnetwork.

The introduction of vehicles, including buses, into the freeway subnetwork at an entry interface node may be delayed by a time interval, which is typically 1-2 minutes in duration. This delay results from the way freeway and arterial subnetworks are integrated in CORFLO. First, the freeway network and subsequently the arterial network are simulated for a duration equal to a time interval. But, the traffic in the two subnetworks moves simultaneously in time. Therefore, a vehicle, due to enter the freeway subnetwork at an interface node during a time interval, may not be able to enter until the beginning of the next time interval, because the freeway simulation for the time interval when the vehicle was actually scheduled to enter the subnetwork has already been completed.

Upon introduction, a bus is moved individually through the freeway subnetwork, along its route, until an exit interface node or an exit node is encountered. In contrast, other traffic is moved for one time interval at a time. During this process bus travel time is accumulated, and the bus is placed in the exit node with the appropriate time of arrival. Because buses are moved individually from the entry node to the exit node as soon they are introduced into the subnetwork, bus travel time is based on the traffic conditions in the freeway subnetwork at the time the bus enters the subnetwork. If the travel time on the freeway is long, then the error due to moving buses through the subnetwork immediately following introduction could be substantial, because traffic conditions on the freeway may change significantly during that time.

FREFLO adds buses to the bus entry flow rate so that proper accounting of the buses' impact on aggregate measures can be made. A passenger car equivalent of 2 is assumed. Density, space mean speed, and flow rates are maintained separately for each vehicle type. Aggregate measures for buses are maintained only to account for their influence on the other traffic. All bus-related MOEs are obtained from moving buses individually through the network.

When buses are moved individually through the network, they follow the specified route. However, when buses are merged into other traffic, the turn percentage specified for the general traffic is applied. As a result, the MOEs for freeway sections not traveled by buses may also reflect bus presence. Some links may show less than the actual bus effect, because some bus traffic may be diverted onto an exit ramp, based on the percentages, even though no buses exit at that ramp. Therefore, freeway sections downstream of the exit ramp would have fewer than the actual number of buses.

Bus Treatment in NETFLO Level II

The NETFLO Level II logic also treats buses as separate entities because their trajectories generally differ markedly from auto traffic and also separate bus statistics must be collected. The bus travel time along each link is computed by employing kinematic relations and includes the dwell time at stations. The sluggish acceleration (2 ft/s^2) and deceleration (4 ft/s^2) rates of buses are also considered. The interaction of buses with general traffic is explicitly treated.

A bus station on an arterial link can be modeled either in the left-most traffic lane or in a separate, protected bay. The longitudinal position of the bus station with respect to the stop line and the capacity of the bus station in terms of the number of buses that can be accommodated is specified by the user. The dwell time at each station has a statistical distribution, which is specified as a percentage of the mean dwell time. The percentage of buses on the routes serving each station that will bypass the section for lack of passenger demand can also be specified by the user.

Unlike in FREFLO, buses are not moved through the arterial subnetwork immediately after introduction. Within a link, however, buses are moved from the upstream end to the stop line in one step. Traffic other than buses is moved for the duration of a time interval. Another difference from FREFLO is that NETFLO Level II does not apply to buses the turn percentages used to simulate non-bus traffic. Buses travel only along the specified bus routes.

When a bus is moved to a stop line, the vehicles already queued at the stop line are not considered in computing the distance between the bus station and the stop line, which may lead to a small error in the estimated bus travel time. Queues are considered, however, for discharging buses from the link at the intersection.

Bus-Related Input Requirements

Bus-related input requirements for CORFLO are shown in Table 15. The table indicates the basis for the kind of information that must be procured to simulate a transit system.

PERFORMANCE MEASURES

MOEs for buses are provided on a route-specific basis. Buses are also included within the statistics generated by each of the component modules at different levels of detail.

FREFLO generates bus-related MOEs in its intermediate output. The MOEs include link-specific input volume, output volume, density, and space mean speed. No bus-related MOEs are provided in the cumulative output from FREFLO.

NETFLO Level II does not generate bus-related MOEs in its intermediate output. It does, however, provide link-specific bus statistics in its cumulative output. These statistics include bus trips, person trips, bus move time, bus delay time, and number of stops.

CORFLO generates route-specific bus MOEs, because bus routes may traverse both freeway and arterial subnetworks. MOEs include number of bus trips, total bus travel time (bus-min), mean travel time (sec/bus), person trips, person travel time (min) for each route.

TABLE 15. Input Data Required for Bus Simulation in CORFLO.

Data Type	Data Items	Comments
Load Factor	Auto/Truck/Bus/Carpool occupancies	A default of 25 persons/bus assumed.
Bus Station	Bus station number Upstream and downstream nodes of the link Bus station lane (left most or protected) Statistical distribution of dwell times Capacity of bus station (# of buses accommodated) Distance between the front end of station and stop line	6 built-in statistical distributions for dwell times. No bus stations on entry/exit links. No bus stations in the freeway subnetwork.
Dwell Time	Bus station number Mean dwell time Percentage of buses which bypass the section for the lack of demand	Dwell time $\leq$ 500 secs. Can be input each time period to reflect changes in conditions.
Bus Path	Route number Network node numbers from entry to exit along the bus route, in sequence	Interface nodes (if any) should be included in path. First time period only ie., routes cannot change during the period of simulation.
Bus Route	Route number Numbers of bus stations serviced by a bus traversing the route, in sequence	First time period only. Cannot add stations to a route during the period of simulation. A station may be serviced by more than one routes. A bus route can traverse through the network with servicing a single bus station in the network.
Bus Flow	Route number Mean bus headway along the route	Can change every time period. A headway < 30 seconds considered unreasonable.

5. CASE STUDY EVALUATION OF CORFLO

SITE AND MODEL DESCRIPTION

A CORFLO model of the US-75 North Central Expressway corridor in Dallas, Texas was developed during previous studies at the Texas Transportation Institute to evaluate the impacts of construction and improvement activities in the corridor. Figure 1 illustrates the Dallas area. The limits of the model are Lyndon B. Johnson Freeway to the north, Harry Hines Boulevard-Woodall Rogers Freeway-R. L. Thornton Freeway to the south, Dallas North Tollway to the west, and Garland-Buckner-Audelia to the east. The model was developed for the morning peak period from 6:00 a.m. to 9:00 a.m.

The North Central Expressway corridor model was developed and calibrated using CORFLO version 3.0. After version 4.0 was released in June 1993, the source code was obtained from the Federal Highway Administration in order to make modifications to the internal model parameters so that a network as large as the North Central Expressway corridor could be simulated. The modified version 4.0 of CORFLO was used in this study to evaluate its transit and HOV modeling capabilities.

TRANSIT AND HOV SCENARIOS

In formulating transit and HOV scenarios, the main focus was directed at evaluating the impact of transit operations on traffic in the network, and not at evaluating alternative transit operational strategies. CORFLO could also be used to evaluate certain transit operational strategies such as skipping stops, reducing dwell times at stops, and increasing the capacity of bus stops; but, evaluation of these strategies would be more meaningful, if first it could be established that CORFLO is capable of reasonably simulating bus and auto interactions in the traffic stream.

Six scenarios were selected to evaluate the transit and HOV modeling capabilities of CORFLO:

1. The network was simulated without either buses or HOV lanes.
2. The Dallas Area Rapid Transit (DART) system map and several individual route maps and other information were obtained from DART office in Dallas. Route 001, shown in Figure 1, which operates entirely on the surface streets, and mainly on Greenville, was coded into the network. All information including the location of bus stops, number of bus stops along the route and the bus headway were extracted from the route map.
3. In order to evaluate the impact of adding a bus-lane on the bus and auto traffic, an exclusive bus lane was added to the network links traversed by buses on Route 001.

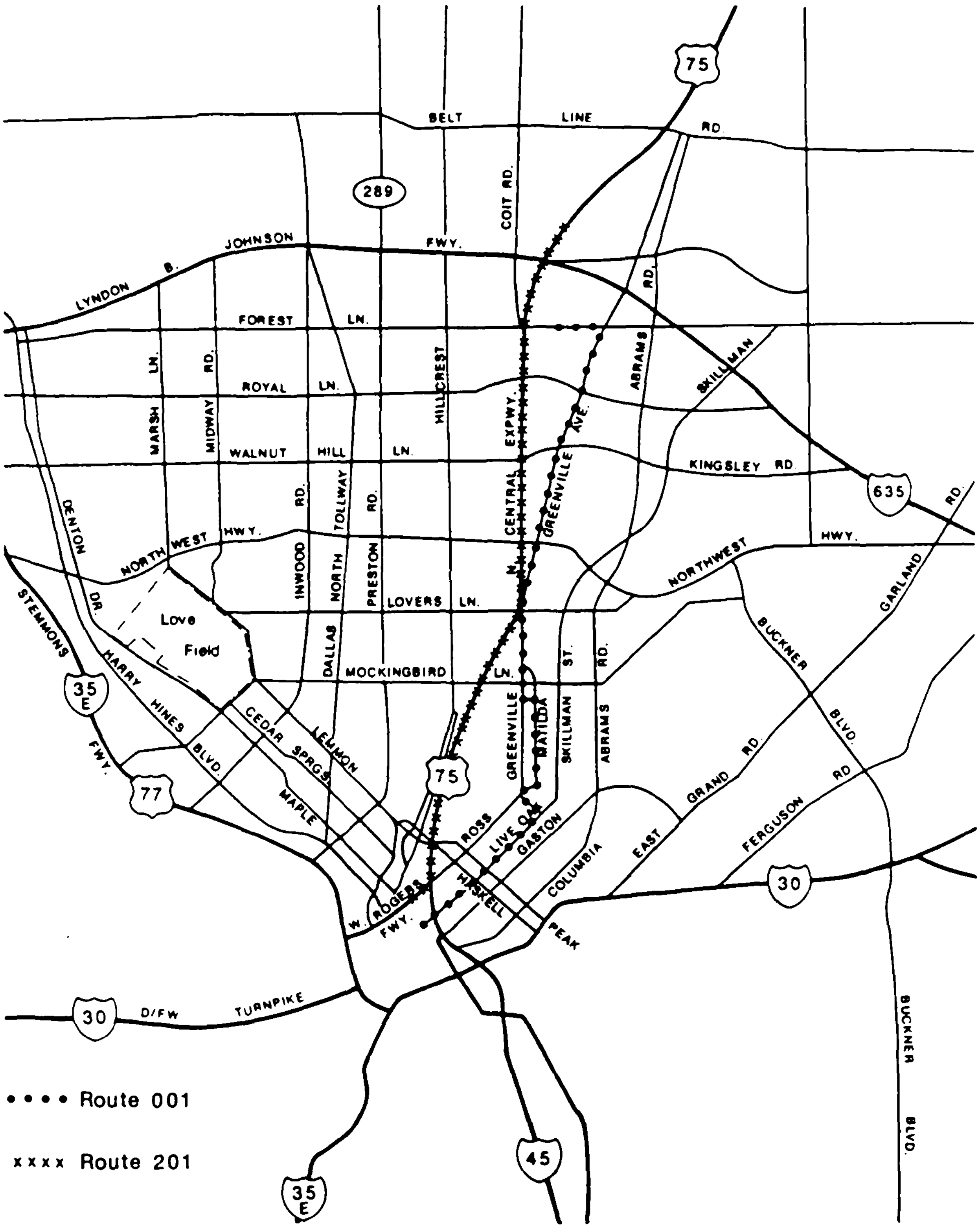

FIGURE 1. North Central Expressway Corridor in Dallas

4. Route 201 which begins north of LBJ Freeway and traverses North Central Expressway to downtown was also added to the model. The purpose of adding this route was to evaluate the treatment of buses by FREFLO and to determine the interaction, if any, between the two bus routes (001 and 201).
5. To evaluate the treatment of HOV lanes in FREFLO, an HOV lane was added to the freeway links traversed by buses on Route 201.
6. Finally, to study the impact of a mode shift from autos to buses, the auto traffic originating along Route 001 was reduced by approximately 5 percent, assuming that those trips would now be made by bus. This shift would result in a reduction in auto traffic on Route 001. It was assumed that traffic originating at other nodes would be unaffected. Also, since the headway between successive buses is 15 minutes, at 25 passengers per bus, buses would not be able to attract more than 100 person-trips made by auto along the route. This would amount to approximately 85 auto-trips, assuming an occupancy rate of 1.2 persons/vehicle. Therefore, the reduction in auto traffic did not exceed 85 vehicles on any link. When the number of trips reduced on a link exceeds 85, those trips were assigned to the nearest exit node. In order to code this shift, traffic assignment results were converted into turning movement data and included in the CORFLO input data.

While coding the bus routes in the above scenarios several problems were encountered that would affect the applicability of CORFLO to transit simulation. One of the primary drawbacks is the level of network detail coded into the model. Because North Central Expressway corridor model was developed to evaluate alternative traffic management strategies in the corridor during North Central Expressway reconstruction activity, only the more heavily traveled arterial and collector were included in the model. Local streets were excluded because of constraints on the number of links and nodes that can be modeled. Most bus routes, however, travel on local streets through residential areas to pick up passengers. For a network of reasonable size, the need to represent all streets on which buses operate is likely to involve more links and nodes than CORFLO parameters permit. In this case study, for example, Route 001 operates on several streets not included in the network. In order to simulate it, therefore, the actual route was slightly modified so that it could be represented in the model.

Buses operate on several routes in the corridor. It would be interesting to study the impact of buses on all routes in the corridor. In CORFLO, however, a maximum of only 99 bus stations can be coded. When a large network such as the North Central Expressway corridor is simulated, the total number of bus stations can far exceed this limit. For example, buses on Route 001 stop at 75 stations allowing only 24 stations for other routes. Owing to this limitation, only one arterial route could be coded in this case study.

The location of a bus station is coded in CORFLO in terms of its distance from the downstream stop line. Bus station information was obtained from DART. The geometry, traffic, and control information for the CORFLO model was obtained from other sources. While coding the bus station information, inconsistencies were found in the data from these different sources, and some adjustments were made.

CASE STUDY EVALUATIONS

Buses primarily impact traffic operations on the links they traverse. Sometimes, due to the traffic conditions in the network, the presence of buses may also affect traffic on other routes in the network through queue spillback. Therefore, to evaluate the scenarios discussed in the previous sections, both network-wide and route-specific delay statistics were examined for each scenario. Fuel consumption and emissions estimates are estimated strictly as a function of traffic condition estimates; as a result, the former estimates can be reasonable only if the latter estimates are reasonable. Therefore, this evaluation focused on delay as a primary measure of traffic conditions.

Corridor-Wide Statistics

Table 16 shows the network-wide cumulative delay statistics for each scenario. Since the number of vehicle miles traveled and the number of vehicle-trips also vary in each scenario, delay per vehicle-trip, and delay per vehicle-mile are also tabulated.

TABLE 16. Network-Wide Cumulative Delay Statistics

Delay (Vehicle-Hours)						
Subnetwork	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Freeway	8147	9048	8297	8489	8738	7951
Arterial	95599	95889	95390	95155	95556	96349
Total	103746	104937	103687	103644	104294	104300
Delay (Minutes/Vehicle-Trip)						
Freeway	3	3	3	3	3	3
Arterial	40.86	41.50	40.78	40.50	41.07	28.68
Total	-	-	-	-	-	-
Delay (Minutes/Vehicle-Mile)						
Freeway	0.89	1.00	0.91	0.93	0.95	0.86
Arterial	17.14	17.29	17.08	17.01	17.50	17.00
Total	7.04	7.21	7.03	7.03	7.06	7.01

It is apparent from Table 16 that the variation in delays among the six scenarios is small. The maximum difference in vehicle hours of delay between any two scenarios is slightly greater than 1 percent. This small variation is reasonable considering the large bus headways used in these scenarios. The pattern of variation in delays is further analyzed, however, to gain a better understanding of the bus and HOV treatment in CORFLO.

In Scenario 1, the corridor was simulated without any buses or HOV lanes. It can be observed from Table 16 that the presence of buses on the arterial (Route 001) in scenario 2 caused a substantial increase in delay in the freeway subnetwork. On the other hand, the delay increase in the arterial subnetwork is relatively small, although buses travel exclusively on the arterial subnetwork. Conditions were very congested even without bus traffic on Route 001. Also, the southbound North Central Expressway frontage road was operating with speeds less than 2 mph on most links. Conditions on most on-ramps along southbound North Central Expressway deteriorated, while the off-ramp conditions remained the same between Scenario 1 and Scenario 2. Hence, the deterioration in the conditions on North Central Expressway, which had nearly free flow conditions on most links in Scenario 1, may be due either to the internal dynamics of FREFLO or to spillback conditions.

In Scenario 3, the addition of an exclusive bus lane resulted in a decrease in delay in both the freeway and arterial subnetworks with respect to Scenario 2. The freeway subnetwork delay in Scenario 3 is still slightly higher than in Scenario 1, even though there is no variation in the traffic demand pattern or composition on the freeway subnetwork. The delay on the arterial subnetwork in Scenario 3 is slightly less than in Scenario 1 although there is no difference in the traffic volumes in the regular lanes in either scenario.

In Scenario 4, the introduction of buses on the freeway subnetwork along Route 201 at a headway of 6 minutes resulted in an increase in delay as compared to Scenario 1 and Scenario 3. The arterial subnetwork delay, however, decreased despite identical demand patterns in all scenarios.

In Scenario 5, in which an HOV lane was introduced on the freeway links traversed by buses, there is an increase in the overall freeway delay, as compared to Scenario 4, in which there was no HOV lane although buses were present on the freeway subnetwork. Inspection of the individual link delays indicated that most of the increased delay was due to one freeway link, although no obvious traffic demand or queue spillback related cause could be identified for this increase. It can also be observed that there is an increase in the arterial subnetwork delay as compared to Scenario 4, in which the freeway network had bus traffic without HOV lanes.

In Scenario 6, approximately 5 percent of the demand originating along Route 001, but not exceeding the capacity of the buses, was assumed to have switched mode from auto to bus. Inherent in this scenario is the assumption that the trips that moved from auto to bus originally traversed the same path as the buses. It should be noted that if trips that shifted to buses have a different path than the buses, then the impact of the modal shift would be scattered across the corridor and would not be limited to the bus route. Due to the lack of a mode split capability in CORFLO, it is not possible to determine the impact of corridor-wide changes in demand patterns due to mode shift.

Assuming all the changes in traffic demand are localized to the links along the bus route, Scenario 6 exhibited a slight drop in the overall delay in the freeway subnetwork in comparison with Scenario 1, in which no buses were present on the network. The drop in delay on the freeway subnetwork is substantial when compared with Scenario 2 where the buses were in addition to the regular traffic demand. The cumulative delay on the arterial subnetwork increased from the levels in Scenarios 1 and 2 due to an increased amount of travel, as is reflected in the delay per vehicle-trip and delay per vehicle-mile, which are lowest in Scenario 6.

Route-Specific Statistics

Table 17 shows the route-specific delay statistics. The delay shown in the table is the cumulative delay for all network links along the route at the end of simulation time period. The delay statistics for both bus routes are tabulated for each scenario irrespective of the presence or absence of bus traffic on the routes in order to understand the interaction between the bus routes. Since part of Route 201 traverses the arterial subnetwork, separate delay statistics are shown in Table 17 for the arterial and freeway portions of Route 201.

TABLE 17. Route Specific Cumulative Delay Statistics

	Delay (Vehicle-Hours)					
Route	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Route 001	4444	4425	4495	4462	4476	4194
Route 201						
Freeway	266	705	279	304	459	279
Arterial	58	58	58	58	57	58
Total	324	763	337	362	516	337
	Delay (Minutes/Vehicle-Mile)					
Route 001	24.79	24.59	23.40	23.15	23.20	23.62
Route 201						
Freeway	0.25	0.76	0.27	0.29	0.44	0.27
Arterial	49.20	49.10	49.28	42.48	41.04	40.02
Total	0.31	0.82	0.32	0.34	0.49	0.32

A review of the delay statistics in Table 17 indicates that delay decreases on Route 001 and increases on Route 201 moving from Scenario 1 to Scenario 2, although buses are introduced on Route 001 in Scenario 2. The freeway portion of Route 201 is entirely on southbound North Central Expressway, which parallels Route 001 on Greenville Avenue. On further examination of delays on North Central Expressway it was found that the northbound North Central Expressway also shows a similar increase in delay.

Adding an exclusive bus lane on Route 001 in Scenario 3 resulted in an increase in delay on Route 001 and a reduction in delay on Route 201 as compared to Scenario 2. Delay on Route 201 in Scenario 3 is slightly higher than in Scenario 1.

The introduction of buses on Route 201 in Scenario 4 resulted in a reduction in delay on Route 001 as compared to Scenario 3. It should be noted that there is no difference between Scenario 3 and Scenario 4 apart from the bus traffic on Route 201. On Route 201, however, there is an increase in the cumulative delay as would be expected.

With the addition of an HOV lane to the freeway portion of Route 201 in Scenario 5, the cumulative delay on both routes showed a marked increase as compared to Scenario 4, where there was no HOV lane on Route 201. As mentioned earlier, it was found that much of the delay increase on Route 201 was on one link. An inspection of the traffic pattern did not reveal any obvious cause for such a marked increase in delay on the link.

In Scenario 6, with the removal of some auto trips from Route 001 to account for mode shift, the overall delay on Route 001 dropped as compared to Scenarios 1 and 2. On Route 201, however, the delay is slightly higher than in Scenario 1 and much lower than in Scenario 2.

Interaction of Bus and Auto Traffic

In order to understand the interaction of buses and other traffic in CORFLO, a comparison of the bus and auto travel times was made. No bus-related MOEs are generated in FREFLO's cumulative output. FREFLO generates link-specific bus volume, speed, density, and number of buses discharged in its intermediate output. Owing to the size of the network, it is impractical to print frequent intermediate output. In this case study, intermediate output was generated at 30-minute intervals in order to obtain data for evaluating bus treatment in FREFLO. In NETFLO Level II, bus-related cumulative MOEs including number of bus trips and passenger trips, travel time, delay time, and number of stops are generated for each arterial link bus routes.

A comparison of the bus and auto travel times in NETFLO Level II links showed that even in the absence of an exclusive bus lane, bus travel time was lower than auto travel time in most links despite the stops that buses are required to make along its route. This difference may be because Level II moves buses separately, accounting for acceleration and deceleration times at bus stops, dwell time and time to move from one bus stop to the next as described earlier. Since bus speeds are not limited by the speed of the auto traffic in the link, if sufficient distance for acceleration is available, then buses can accelerate to speeds higher than the autos.

On the freeways, however, the interaction of the bus and other traffic is more difficult to understand because FREFLO does not generate bus-related cumulative MOEs. The speed and density generated in the intermediate output are instantaneous values during the time interval when the output is generated. For the North Central Expressway model, the time interval duration is 90 seconds. Traffic on each subnetwork is simulated alternately for a period equivalent to one time period (1 hour).

Inspection of the instantaneous bus speeds in Scenario 4 (no HOV lane) after 150 minutes from the start of simulation showed that southbound North Central Expressway was operating at nearly free flow conditions except in one link. After 180 minutes from the start of simulation, the freeway was operating at jam density, with speeds in almost all the links being zero. Assuming a continuous deterioration in conditions during the intervening 30 minutes, it was found that FREFLO estimates more trips on Route 201 than is actually possible considering the traffic conditions on southbound North Central Expressway. Because FREFLO logic moves a bus from entry node to the exit node in the freeway subnetwork as soon as it is introduced and computes the travel time and the exit time based on the traffic conditions at the time of entry, the number of bus trips is overestimated.

SUMMARY

Alternative transit and HOV scenarios were developed to evaluate CORFLO's modeling capabilities. The output MOEs generated by CORFLO for each of the scenarios were used for the evaluation. In all scenarios, the traffic demand patterns, the traffic controls, and the geometry were identical (except for HOV lanes in some scenarios). CORFLO has some transit and HOV-related simulation capabilities that make it a useful tool for evaluating certain transit and HOV strategies. Several problems exist, however, that limit its applicability.

When the network is operating under congested conditions, CORFLO estimates of the corridor-wide impact of buses could be disproportionately large. For example, bus operations at the rate of 4 buses per hour on a surface street resulted in a substantial increase in delays on the freeway without a corresponding increase on the off-ramps. These results imply that the increased delay on the freeway subnetwork is not due to queue spillback from the surface streets.

When a large network such as the North Central Expressway corridor is simulated using CORFLO, it would be impractical to represent all streets in the model. Most bus routes, however, cover minor streets in order to reach residential and commercial areas for passenger pickup. Hence, most bus routes cannot be coded without modifications the CORFLO model.

Only a small number of bus routes can be simultaneously modeled in CORFLO because of a maximum limit of 99 bus stops throughout the network. In a large network, where bus routes are long, this limitation is significant because each route would have a large number of stops.

In order to maintain the identity of buses, they are moved individually in CORFLO and their travel time and speed are recorded. Because of such treatment of buses, bus MOEs may not match the MOEs for the other traffic, although buses operate within the same environment as the remaining traffic. This discrepancy makes CORFLO unsuitable for detailed evaluation of transit operational strategies.

Improvements to transit and HOV facilities and services might lead to mode shifts from single-occupant vehicles to transit or HOV modes. In the absence of a capability to predict the mode shift in CORFLO, it would be necessary to independently estimate the network-wide impact of mode shift. If the CORFLO input data (i.e., turning movement and entry node volumes) are adjusted to reflect these mode shift estimates, however, then the resulting traffic conditions can be simulated using CORFLO.

In its current form, CORFLO cannot provide reliable estimates of fuel consumption savings associated with transit and HOV improvements. Fuel consumption estimates are provided for the arterial subnetwork but not for the freeway subnetwork. The fuel consumption of buses on the arterial subnetwork is assumed to equal 2.5 times the corresponding values for autos. These values are approximations for link speeds exceeding 20 mph. During previous research, researchers at the Texas Transportation Institute developed a auto fuel consumption algorithm for FREFLO (*18*). This algorithm has not yet been implemented by the Federal Highway Administration in the public-release version of CORFLO. Furthermore, due to the lack of data on bus fuel consumption under various traffic conditions, the algorithm does not provide fuel consumption estimates for buses.

6. RECOMMENDED TRANSIT-RELATED ENHANCEMENTS TO CORFLO

With some modifications to increase the maximum limit on the number of stops, treat bus movements along links, and improve emissions and fuel consumption models, CORFLO could be a useful tool to estimate the effect of buses on the other traffic, and to estimate fuel consumption savings and other impacts of transit and HOV improvements. Several enhancements to the transit and HOV supply modeling capabilities of CORFLO are identified in this section that appear to be feasible without the need to significantly alter CORFLO's basic structure. It is recommended that the Federal Highway Administration make these enhancements and implement them in the public-release version of CORFLO. Significant enhancements to transit and HOV demand modeling capabilities within CORFLO's existing structure are not considered feasible and, therefore, such enhancements are not recommended in this report.

As noted earlier, the maximum number of bus stations that CORFLO allows in a network is only 99. Most urban networks of reasonable size, such as the North Central Expressway corridor network used in this study, have more than 99 bus stations. Because of this limitation only one arterial bus route could be simulated in this study. Increasing the maximum limit on the number of bus stations in the network would permit more realistic simulation of the multiple bus routes in a typical urban corridor.

In NETFLO Level II, buses are moved along the link in one step from the upstream end to the back of the queue at the downstream stop line (if any) or to the stop line. During this movement only bus acceleration rates, stops, dwell times, and speed limits are considered. In a congested network, this method of modeling bus movements leads to lower travel time estimates for buses than for autos, because the effect of auto traffic on buses is not considered. In contrast, the effect of buses on autos is considered. Enhancing the method of modeling bus movements so that the effect of auto traffic on buses is also considered would result in more reasonable travel time estimates for buses.

In FREFLO, buses are moved from the entry node to the exit node in one step. Because of this treatment, only the effect of traffic existing in the freeway network at the time of bus entry is taken into account. When the distance traveled by the bus on the freeway is large, this treatment could lead to considerable error in bus travel times and speeds. In the duration between the entry time and exit time, the traffic conditions on the freeway network could change significantly. FREFLO logic should be enhanced to move buses in increments of one time interval, like other traffic, so that the travel times are properly estimated. FREFLO's method of accounting for the effect of buses on auto traffic also needs to be enhanced to permit separate turning percentages for buses, in lieu of the current assumption that all vehicle types have the same turning percentages.

Several enhancements are recommended to improve CORFLO's estimation of fuel consumption. First, the enhancements described earlier to improve the representation of bus movements are needed to obtain more reasonable estimates of bus speeds. Second, the component models methods for using traffic measures to estimate fuel consumption need to be improved. NETFLO Level II approximates the fuel consumption of buses as 2.5 times the fuel consumption for autos under the same traffic conditions. Original data on bus fuel consumption as a function of traffic conditions are necessary to verify and, as necessary, refine the method for estimating bus fuel consumption. A fuel consumption algorithm needs to be added to the publicly released version of FREFLO in order to evaluate the system-wide energy benefits from transit operations. The fuel consumption algorithm previously developed for FREFLO by the Texas Transportation Institute needs to be enhanced to estimate fuel consumption for buses and then incorporated into FREFLO.

Implementing these enhancements would improve the accuracy of CORFLO's transit and HOV supply modeling and provide CORFLO the capabilities to estimate the fuel consumption savings from transit and HOV improvements. Enhanced modeling capabilities to more accurately evaluate alternative improvements, if used to improve the effectiveness of urban transportation investment decisions, should increase both the likelihood and magnitude of fuel consumption savings actually realized. Considering the potential savings in fuel consumption per person-trip diverted from a single-occupant vehicle to transit or HOV modes, a 1 percent improvement in fuel savings realized from better investment decision making represents approximately 1.2 million gallons of fuel savings per year per million commuters affected by the investments.

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