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TEXAS TRANSPORTATION INSTITUTE

ANALYSIS OF ACCIDENTS AT LONG-TERM CONSTRUCTION PROJECTS IN TEXAS

RESEARCH REPORT 1108

COOPERATIVE RESEARCH PROGRAM

TEXAS TRANSPORTATION INSTITUTE
THE TEXAS A&M UNIVERSITY SYSTEM
COLLEGE STATION, TEXAS

TEXAS DEPARTMENT OF TRANSPORTATION

in cooperation with the
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16. Abstract

This report summarizes related experiences, existing computer models, and other research that should be incorporated into a comprehensive data base and sound analytical approach for estimating the changes in traffic patterns and road user costs resulting from freeway construction options.

The traffic management and impact mitigation strategies and actual travel impacts were reviewed for major urban freeway reconstruction projects in Chicago, Pittsburgh, Boston, Seattle, Philadelphia, and Detroit.

Nine existing computer models were evaluated including QUEWZ, FREWAY, PASSER IV, CORQ-CORCON, HEEM-II, FREQ, FREFLO, INTRAS, AND CARHOP. It was concluded that none of the models satisfy all of the requirements of Study 2-8-87-1108, but that QUEWZ comes closest and is the best candidate for further development. PASSER IV, CORQ-CORCON, HEEM-II, and CARHOP have important traffic assignment capabilities that may be useful in estimating changes in traffic patterns. FREWAY, FREQ, FREFLO, and INTRAS have traffic simulation capabilities that may be useful in estimating traffic flow characteristics.

Research on traffic flow characteristics through work zones, the response of drivers to work-zone-related delays, and road user costs was also reviewed.

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TRAVEL IMPACTS OF FREEWAY RECONSTRUCTION: SYNTHESIS OF PREVIOUS RESEARCH AND EXPERIENCES

by

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Research Report 1108-1

Research Study No. 2-8-87-1108
Traffic Pattern Assessment and Road User Delay Costs
Resulting from Roadway Construction Options

Sponsored by
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TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas

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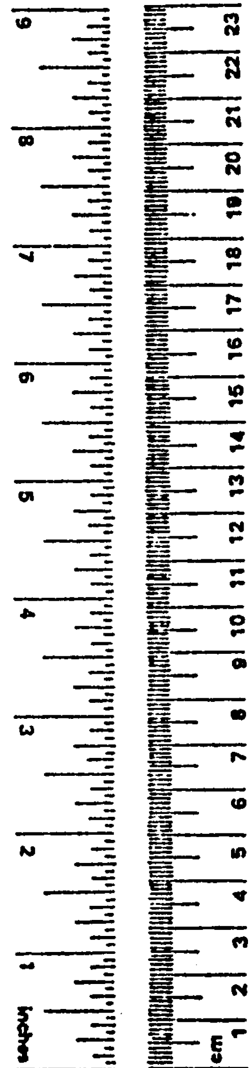
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
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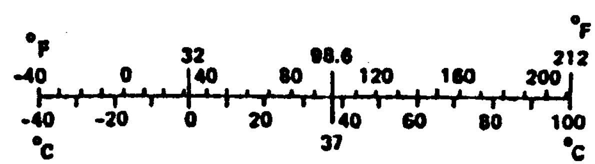

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

SUMMARY

The goal of Study 1108 is to develop a comprehensive data base and sound analytical approach for estimating the changes in traffic patterns and road user costs resulting from freeway construction options. The objective of this report was to review and summarize related experiences, existing computer models, and other research that should be incorporated into the data base and analytical approach.

Major urban freeway reconstruction projects in Chicago, Pittsburgh, Boston, Seattle, Philadelphia, and Detroit were reviewed. The review focused on the traffic management strategies employed and travel impacts experienced. Freeway capacity was reduced during all of the projects. Several actions were taken to mitigate the adverse impacts of the projects including (1) improvements on alternative routes, (2) improvements in high-occupancy vehicle services, (3) motorist assistance services, and (4) public information programs. Many motorists responded to the projects by diverting to alternative routes and by adjusting their departure times to compensate for reconstruction-related delays. The experiences from these projects suggest that well-planned, coordinated, and implemented traffic management and impact mitigation strategies can effectively minimize the disruption in corridor traffic flow during major freeway reconstruction projects.

The capabilities of nine existing computer models (QUEWZ, FREWAY, PASSER IV, CORQ-CORCON, HEEM-II, FREQ, FREFLO, INTRAS, and CARHOP) were evaluated with respect to: (1) the types of work zone traffic management strategies that can be analyzed, (2) the theoretical basis for the analytical techniques, (3) the assumptions implicit in the model, (4) the input data requirements, and (5) the model output. It was concluded that none of the models satisfies all of the requirements of Study 1108, but that QUEWZ comes closest and is the best candidate for modification during the next (second) year of the study. The other models reviewed have important capabilities that might be incorporated into QUEWZ to enhance its usefulness and accuracy. PASSER IV, CORQ-CORCON, HEEM-II, and CARHOP have traffic assignment capabilities that may be useful in modeling changes in traffic patterns. FREWAY, FREQ, FREFLO, and INTRAS have important freeway simulation capabilities that may be valuable in estimating traffic flow characteristics before and during construction activities. The feasibility and desirability of incorporating these capabilities into QUEWZ will be evaluated in the second year of Study 1108.

The magnitude of changes in traffic flow characteristics resulting from freeway construction options is influenced primarily by the capacity and the demand volume at the affected freeway segment. A limited amount of data on work zone capacity was collected during previous studies at TTI, but additional data will be required to quantify the effects of the work zone configuration and geometry, intensity of work activity, and traffic stream characteristics. Traffic diverting away from a freeway segment in response to work-zone-related delays significantly affects the traffic volumes actually passing through the work zone and, hence, actual traffic flow characteristics. Only a limited amount of information is available on how much and under what conditions traffic diversion occurs. Two techniques (equilibrium traffic assignment and delay tolerance) appear to have potential for modeling diversion, but further analysis of the soundness of these techniques is required.

IMPLEMENTATION STATEMENT

The review of six major urban freeway reconstruction projects outside Texas identifies traffic management and impact mitigation strategies that have proven effective in other parts of the United States and that may be implementable in Texas. Additional research should be conducted to determine the applicability and cost effectiveness of these strategies for conditions prevalent in Texas.

The review of the nine computer models identifies existing capabilities and limitations for estimating the changes in traffic patterns and road user costs resulting from freeway construction options. QUEWZ was identified as the best candidate for modifications to satisfy Study 1108 requirements. Those modifications will be made during the next (second) year of Study 1108. A more detailed evaluation of the traffic assignment capabilities of PASSER IV, CORQ-CORCON, HEEM-II, and CARHOP, and of the traffic simulation capabilities of FREWAY, FREQ, FREFLO, and INTRAS should be conducted to determine the feasibility and desirability of incorporating those capabilities into QUEWZ.

The review of research on work-zone-related travel impacts indicates that a very limited amount of data are available for estimating work zone capacity, speed-volume relationships in work zones, queueing characteristics upstream of a work zone, the response of drivers to work-zone-related delays, and the changes in accident rates during freeway construction activities. Additional data need to be collected on each of these impacts.

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DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration or the State Department of Highways and Public Transportation. This report does not constitute a standard, specification, or regulation.

ABSTRACT

This report summarizes related experiences, existing computer models, and other research that should be incorporated into a comprehensive data base and sound analytical approach for estimating the changes in traffic patterns and road user costs resulting from freeway construction options.

The traffic management and impact mitigation strategies and actual travel impacts were reviewed for major urban freeway reconstruction projects in Chicago, Pittsburgh, Boston, Seattle, Philadelphia, and Detroit.

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1. INTRODUCTION

Reconstruction activities are either underway or being planned on major urban freeways throughout Texas and, indeed, throughout the United States. In planning a major freeway reconstruction project, a balance must be reached between (1) maximizing the efficiency of the work activity and (2) minimizing the adverse impacts on motorists and others (businesses, residents). In order to achieve the optimal balance, highway officials must be able to estimate the travel impacts of roadway construction options.

Study 1108 was undertaken to provide the Texas State Department of Highways and Public Transportation (SDHPT) with a comprehensive data base and sound analytical approach for estimating the changes in traffic patterns and road user costs resulting from roadway construction options.

This report documents a review of related experiences, existing computer models, and other research and analytical techniques that might be incorporated into the data base and analytical approach.

The objectives of this report are to:

1. Summarize the experiences gained and lessons learned from major urban freeway reconstruction projects in other parts of the country

2. Evaluate the capabilities of existing computer models for estimating changes in traffic patterns and road user costs resulting from freeway construction options

3. Review the information and techniques available for estimating work-zone-related travel impacts

The report is divided into three chapters. In Chapter 2, major urban freeway reconstruction projects in Chicago, Pittsburgh, Boston, Seattle, Philadelphia, and Detroit are reviewed, with emphasis on the traffic management and impact mitigation strategies employed and the actual travel impacts experienced. Chapter 3 provides an evaluation of the capabilities and limitations of nine existing computer models: QUEWZ, FREWAY, PASSER IV, CORQ-CORCON, HEEM-II, FREQ, INTRAS, and CARHOP. Chapter 4 is a summary of the information and techniques available for estimating work-zone-related travel impacts including traffic flow characteristics, driver response to work-zone-related delays, and road user costs.

2. REVIEW OF PREVIOUS EXPERIENCES

Major reconstruction projects have been completed or are currently underway on a number of important urban freeways throughout the country. Table 1 lists some of the more important projects outside the state of Texas (1, 2).

This chapter reviews the traffic management and impact mitigation strategies employed during several of those projects and summarizes the experiences gained and lessons learned. The information in this chapter was drawn primarily from reports and articles documenting the projects and secondarily from telephone interviews with persons involved with each project. The projects reviewed, in chronological order, are:

1. IH-94, Edens Expressway, in Chicago
2. IH-376, Penn-Lincoln Parkway East, in Pittsburgh
3. IH-93, Southeast Expressway, in Boston
4. IH-5, Ship Canal Bridge, in Seattle
5. IH-76, Schuylkill Expressway, in Philadelphia
6. US 10, John C. Lodge Freeway, in Detroit

Although each of the above projects was conducted under a unique set of conditions, many of the strategies employed and results experienced were similar. Therefore, before reviewing the individual projects in detail, the common strategies and experiences will be discussed.

Summary

Table 2 summarizes the characteristics of the six projects, including the dates of reconstruction, length of freeway that was reconstructed, the number of lanes before and during reconstruction, the average annual daily traffic (AADT) on the freeway before reconstruction, and percentage reduction in AADT on the freeway during reconstruction.

Even though state highway agencies had the primary responsibility for planning and executing the reconstruction projects, the traffic management and impact mitigation strategies were planned and executed through the coordinated effort of local government agencies; transit and ridesharing agencies; police, fire, and emergency medical services; business and citizens groups; and others.

One of the first steps in the planning process was the selection of the basic traffic management strategy. Roadway space is a scarce resource that must be allocated between the required work activities and the motorists. In each project, a compromise had to be reached between expediting the reconstruction activity and accommodating traffic demands. All of the projects involved significant reductions in freeway capacity during reconstruction.

TABLE 1. SOME MAJOR HIGHWAY RECONSTRUCTION PROJECTS IN THE UNITED STATES (EXCLUDING TEXAS)

Allentown (IH-78)
Atlanta (IH 75, IH-85, and IH-285)
Boston (IH-90 and IH-93)
Chicago (IH-90, IH-94, and IH-290)
Detroit (US-10)
Hartford (IH-91)
Los Angeles (IH-5)
Madison (IH-90 and IH-95)
Maryland (IH-95 and IH-495)
Miami/ Ft. Lauderdale (IH-95)
Minneapolis (IH-394)
New Jersey (IH-287)
Philadelphia (IH-76)
Pittsburgh (IH-376)
Seattle (IH-5)
Syracuse (IH-81)
Washington, DC (IH-395)

Source: Anderson and Janson (2)

TABLE 2. SUMMARY OF RECONSTRUCTION PROJECT CHARACTERISTICS

Project	Dates of Reconstruction	Length (mi)	No. of Lanes in Each Direction Before	No. of Lanes in Each Direction During	Freeway AADT Before Reconstruction (1000 vpd)	% Reduction in Freeway AADT
Chicago, Edens Expressway	1978-80	15	3	2	57-135	30
Pittsburgh, Parkway East	1981-82	6.5	2	1	55- 80	60
Boston, Southeast Expressway	1984-85	8.5	3(4)[a]	2(4)[b]	160	6 (in 1984) 0 (in 1985)
Seattle, Ship Canal Bridge	1984-85	2[c]	4	2	210	38 (in 1984) 40 (in 1985)
Philadelphia, Schuylkill Expressway	1985-88	18	2[d]	1	80-143	50
Detroit, Lodge Freeway	1986-87	7.8	3	2[e]	130-150	20 (in 1986)

[a] 3 travel lanes with a 4th (breakdown) lane used as a travel lane during peak periods.
[b] 2 travel lanes in off-peak direction, 4 travel lanes in peak direction.
[c] 1 mi. northbound in 1984, 2 mi. southbound in 1985.
[d] Some sections have 3 or 4 lanes in each direction.
[e] Off-peak only.

Several special traffic-handling techniques were used in order to maximize available capacity on the freeway during reconstruction:

1. Reconstruction was performed in phases to minimize the number of lanes closed at one time

2. Shoulders were widened and upgraded prior to the actual reconstruction project for use as travel lanes during the project

3. Some or all of the ramps within the reconstruction zone were either completely closed or restricted to high-occupancy vehicles (HOVs)

4. Screens were installed on the sides of the work area to minimize the reduction in traffic capacity due to motorist rubbernecking

Special contracting strategies were also used to minimize the time to complete the projects. The contracts for five of the six projects included incentive/disincentive clauses to encourage early completion.

Corridor-wide impact mitigation strategies were implemented to compensate for the reductions in freeway capacity. The mitigation strategies can be divided into four categories:

1. Improvements on alternative routes

2. Improvements in HOV services

3. Motorist assistance services

4. Public information programs

Most of the improvements on alternative routes and in HOV services could be considered transportation systems management (TSM) type actions. Improvements on alternative routes were undertaken to accommodate additional traffic on those routes. Improvements in HOV services were designed to reduce the number of vehicles in the affected corridor. Motorist assistance services were implemented to minimize the impacts of incidents within the reconstruction zone by reducing incident detection and removal time. Extensive public information programs were designed to advise motorists of work activities and traffic conditions and to encourage motorists to use alternative routes and modes of travel. The types of actions in each category and the projects at which those actions were funded are summarized in Tables 3 through 6. It should be noted that the Edens Expressway in Chicago was reconstructed before the Federal Highway Administration (FHWA) authorized the use of federal funds for impact mitigation actions off the Interstate and therefore improvements on alternative routes and in HOV services were not funded as part of the project.

TABLE 3. IMPROVEMENTS ON ALTERNATIVE ROUTES

	Chicago	Pittsburgh	Boston	Seattle	Philadelphia	Detroit
Signal Operations Improvements		X	X	X	X	X
Coordination						
Retiming						
New Signals						
Modernized Signals						
Temporary Signals						
Other Operational Improvements		X	X	X	X	X
Left-Turn Restrictions						
On-Street Parking Restrictions						
Reversible Lanes						
Signing/Lighting/Marking Improvements						
Police Control at Key Locations		X	X	X	X	X
Maintenance Operations	X			X	X	X
Accelerated Maintenance Before						
Emergency Maintenance Only During						
Roadway Construction		X	X	X	X	
Minor Widening						
Addition of Turning Lanes						
Improved Connectors						

TABLE 4. IMPROVEMENTS IN HIGH-OCCUPANCY VEHICLE SERVICES

	Chicago	Pittsburgh	Boston	Seattle	Philadelphia	Detroit
New or Expanded Rail Service		X	X		X	
New Commuter Train						
Additional Cars on Existing Trains						
Extension of Rail Service Beyond Existing Terminus						
Additional Trains to Increase Service Frequency						
Additional Police for Security						
Expanded Bus Service	X	X	X	X	X	X
New Express Bus Routes						
Additional Feeder Service to Commuter Train						
Additional Buses to Maintain/Increase Pre-Reconstruction Headways						
Backup Buses On-Call in Case of Delays						
Expanded Commuter Boat Service			X			
New or Expanded Park-and-Ride Lots	X	X	X	X	X	
New or Expanded Ridesharing Programs	X	X	X	X	X	
Restricting Ramps to High-Occupancy Vehicles Only		X		X		

TABLE 5. MOTORIST ASSISTANCE SERVICES

	Chicago	Pittsburgh	Seattle	Boston	Philadelphia	Detroit
Additional Police/Courtesy Patrols on the Freeway and Alternative Routes	X	X	X	X	X	X
New or Expanded Free Tow Truck Services	X	X	X	X	X	X

TABLE 6. PUBLIC INFORMATION PROGRAMS

	Chicago	Pittsburgh	Boston	Seattle	Philadelphia	Detroit
Traditional Public Relations Tools Press Conferences Public Meetings News Releases Interviews Media Events Public Service Announcements	X	X	X		X	X
Special Posters, Pamphlets, Newsletters, Maps, and/or Mailings		X	X		X	X
Toll-Free Hotlines		X	X		X	X
Coordination with Freeway Surveillance and Control Center	X			X		
Special Informational Signing	X	X	X	X	X	X
Highway Advisory Radio	X			X		
Coordination with Public/Private Agencies	X	X	X	X	X	X

Findings

The experiences from the projects reviewed in this chapter demonstrate that major urban freeway reconstruction can be conducted without intolerable disruptions in corridor traffic flow in spite of 50 percent reductions in the number of freeway lanes open to traffic during reconstruction. The traffic management and impact mitigation strategies deserve much of the credit for these successes. Latent capacity in the corridor and the ingenuity of motorists in selecting optimal routes also contributed to the fact that the regional transportation network was able to accommodate the freeway capacity reductions with less congestion and delay than had been predicted.

Motorists have five basic options for responding to the impacts of reconstruction projects: (1) cancellation of trips in the corridor; (2) spatial diversion, i.e., continue to travel in the corridor by automobile but on a different route; (3) temporal diversion, i.e., continue to travel in the corridor by automobile but at a different time; (4) modal diversion, i.e., continue to travel in the corridor but by a different mode; and (5) continuation of normal travel patterns.

The majority of drivers that changed their travel patterns continued to drive their automobiles in the corridor but either diverted to another route or changed their departure times. Traffic diverted to many different routes. In Pittsburgh, where local traffic was forced to divert because entrance ramps were closed, diverting traffic was traced to many alternative routes but most was concentrated on the parallel arterial routes closest to the freeway. In Chicago, two-thirds of the diverting traffic, particularly long distance truckers and other drivers, used a parallel alternative freeway and the rest used a variety of alternative arterial routes. The experiences in Boston, Seattle, and Philadelphia were similar; diverted traffic could be traced to a number of alternative routes.

At several projects where traffic was closely monitored, it appeared that motorists shifted back and forth between the freeway and alternative routes. It took several weeks after the start of the projects for traffic patterns to stabilize. The fluctuations in traffic patterns early in a project can be attributed to motorists experimenting with alternative routes before selecting the best. In some cases, predictions of chaos by the press may have scared motorists away, but when the chaos failed to materialize the motorists returned to the freeway. After several weeks, an equilibrium was established. However, fluctuations continued. Throughout the projects, motorists shifted back and forth between the freeway and their alternative route as traffic conditions changed.

Temporal diversion was also observed. Motorists adjusted their departure times, especially in the morning, to compensate for the increased travel times in the corridor. In Pittsburgh, for example, morning departure times during reconstruction averaged 20 min earlier than before reconstruction.

Some modal diversion to HOV modes occurred, but the magnitude was much less than project planners had anticipated. In Pittsburgh, for example, only 5 percent of the traffic that left the freeway was attributed to modal diversion. Officials in Chicago and Boston also reported only small changes in transit ridership.

Importantly, at all of the projects it appeared that the reconstruction project caused little, if any, reduction in the total corridor daily traffic volumes. Except for indications at several projects, including Chicago and Boston, that some discretionary, midday, non-work trips were eliminated from the corridor, it appears that few vehicle trips in the corridor were actually cancelled.

In light of the motorist impacts that were observed, it is apparent that the improvements on alternative routes were the most important component of the impact mitigation strategies. The improvements in HOV services were less effective, in terms of the cost per trip diverted. However, some investment in alternative modes was generally considered necessary in order to provide flexibility to the motorist. The evidence suggests that improvements to existing service were more effective than the provision of new services, such as the new commuter train in Pittsburgh which was discontinued near the end of the first year of reconstruction.

The public information programs were considered vital to the success of the projects. They helped prevent strong negative public reaction. More than that, they helped promote reasonably positive reactions that (1) the work was necessary for the long term good and (2) the agencies involved were doing their best to complete the project with the least inconvenience possible to motorists, businesses, and residents. Three important elements of the programs were the efforts to (1) keep the public informed about the conditions through the reconstruction zone and about the availability of travel alternatives, (2) coordinate the actions of all public agencies directly involved in the project, and (3) maintain communications with major public and private groups affected by the project.

Overall, past experiences suggest that a well planned, coordinated, and implemented set of traffic management and impact mitigation strategies can work effectively to limit the disruption in corridor traffic flow during major freeway reconstruction projects. Good information and sound analysis are vital to the design of an effective strategy. Also vital are (1) the ability to evaluate unexpected impacts quickly and (2) the flexibility to alter strategies accordingly. The lessons that can be learned from successfully completed projects are valuable and merit careful study. Summaries of each of the six projects follow.

IH-94, Edens Expressway, in Chicago

The Edens Expressway, opened to traffic in 1951, is a six-lane freeway which serves as the principal arterial through the north shore suburbs of Chicago. The AADT before reconstruction ranged from 57,000 vehicles per day (vpd) at the Lake-Cook county line to 135,000 vpd at the southern terminus with the Kennedy Expressway (IH-90). In 1977, it was determined that extensive rehabilitation was required. A three-year reconstruction project was undertaken by the Illinois Department of Transportation (IDOT) on a 15-mi segment of the Expressway to (1) remove the existing pavement and replace it with a 10-in continuously reinforced concrete pavement, (2) reconstruct the shoulders, (3) reconstruct the drainage system, (4) widen and redeck all bridges, (5) replace the median guardrail with a concrete median barrier, (6) lengthen the ramp speed change lanes, and (7) modernize signing, lighting, and traffic surveillance equipment. The project was performed during the construction seasons of 1978 - 1980. Several articles have documented the project (3-6).

The work was performed under six contracts. Each contract stipulated a completion date and included an incentive/disincentive clause. The clause assessed the contractor a liquidated damage of $15,000 for each day late. The incentive had two levels: the contractor would be paid $7,500 for each day the contract was completed in advance of a 31-day hiatus and an additional $7,500 per day if all six contracts were completed prior to the 31-day hiatus. However, incentives would be paid only if a contract was completed at least 31 days before the stipulated completion date.

A variety of traffic management strategies, ranging from full closure of the entire freeway to lane closures only in active work areas were considered during project planning. The option selected was to close one direction of the Expressway at a time and to maintain four-lane two-way traffic in the other direction. This was accomplished by upgrading the right shoulder to serve as a temporary lane. A continuous, temporary concrete barrier separated two-way traffic.

The traffic management plan during reconstruction had three stages. In the first stage, the southbound right lane was closed, while the southbound right shoulder was upgraded to handle traffic. In the second stage, four-lane, two-way traffic was maintained in the southbound lanes and upgraded shoulder, while the northbound direction was closed to reconstruct the main-lanes, median, and shoulders . In the third stage, four-lane two-way traffic was maintained in the new northbound lanes and right shoulder, while the southbound lanes were closed for reconstruction.

A 35 mph speed limit was established during four-lane, two-way operation due to the reduced lane widths, restricted lateral clearances to the median barrier, proximity of reconstruction operations, low-speed temporary ramp connections, and frequent changes in ramp closures.

The Edens Expressway was reconstructed before the FHWA authorized the use of federal funds for impact mitigation actions off the Interstate. Therefore, the IDOT was not able to fund improvements on alternative routes and in HOV services. The IDOT did provide project information to the Regional Transportation Authority which increased transit and park-and-ride lot capacity in the corridor. Signing on the Expressway encouraged carpool and transit usage. The IDOT also worked with municipal and county highway and public works agencies to coordinate highway maintenance schedules on alternative routes.

Traffic management and monitoring during reconstruction was handled by the following three units with operational responsibility for the Chicago Metropolitan Area Expressway System: the Highway Communications Center, the Emergency Traffic Patrol, and the Traffic Systems Center.

The Highway Communications Center monitors and disseminates expressway congestion information and coordinates all traffic, maintenance, and construction operations, including the Emergency Traffic Patrol fleet. During the reconstruction project, the Communications Center took several special actions: (1) a direct telephone line was installed to the prime contractor's office, (2) portable two-way radios were issued to the state construction engineers for the project, (3) live broadcasts about special activities or incidents were provided to the news media, (4) municipal enforcement agencies were notified 24 hours in advance of any ramp closures, and (5) a Highway Advisory Radio system was operated.

The Emergency Traffic Patrol travels the Chicago expressways to identify incidents and to initiate appropriate response actions. The normal patrol of one unit on the Edens Expressway was intensified during the reconstruction to two units off-peak and three units during peak periods. Also, a heavy duty tow truck was made available in addition to the wrecker already in use.

The changes in traffic patterns during reconstruction were monitored using data from the electronic surveillance system operated by the Traffic Systems Center. It took several weeks after the start of the project for traffic patterns to stabilize. The AADT on the Edens Expressway decreased by approximately 30 percent during reconstruction. Volumes during peak periods decreased by as much as 35 percent, with the highest levels of peak-period diversion occurring during the first several weeks of the project. Officials attributed 20 of the 30 percent decrease in AADT to diversion to the Tri-State Tollway, a parallel facility approximately 6 mi west of the Edens. The remainder of the decrease in traffic volumes was attributed to: (1) diversion to arterial streets, (2) diversion by long-haul truckers and interstate drivers to other freeways, (3) elimination or diversion of discretionary, non-work trips from the Edens, and (4) reduction in trips due to the energy crisis which began in April 1979. No significant diversion to mass transit was observed. Transit ridership in the corridor increased during the first few days of the project but soon returned to pre-reconstruction levels. Diversion occurred without excessive deterioration in service quality on the alternative routes.

A comparison of Edens Expressway accident data before and during reconstruction suggested that although the frequency of accidents on the Expressway was lower during reconstruction, the accident rate was higher since Expressway traffic volumes were also lower during reconstruction. In addition, the data indicated that both the percentage of accidents involving trucks and the percentage of accidents involving non-local drivers was higher during reconstruction.

Ziejewski (3) concluded "The Edens reconstruction project illustrates that proper traffic planning will help establish public awareness of the project and the expected impacts. The fact that the predicted traffic chaos never resulted demonstrates that the planning and implementation of the overall traffic program was most effective."

IH-376, Penn-Lincoln Parkway East, in Pittsburgh

The Parkway East was the first urban freeway reconstruction project in which FHWA approved the use of Interstate funds to mitigate the off-system impacts of Interstate reconstruction. Because of this innovation, the Pennsylvania Department of Transportation (PennDOT) and FHWA sponsored a study to monitor and evaluate the traffic characteristics, the responses and attitudes of travelers in the affected corridor, and the usage of the impact mitigation strategies. The findings of the study have been thoroughly documented in an extensive report and in several related articles (7-9).

The Parkway East is the only major east-west freeway connecting the Pennsylvania Turnpike (IH-76) and eastern suburban communities with downtown Pittsburgh. The facility is a four-lane freeway, including the 0.8-mi double-bore Squirrel Hill Tunnel. A total of 132,000 vpd enter the section being reconstructed. A $62 million reconstruction and safety update project was undertaken on a 6.5-mi section of the Parkway during the 1981 and 1982 construction seasons (March through October). Work included (1) placement of an 8-in concrete pavement overlay, (2) rehabilitation of 21 bridges, (3) installation of new lighting and ventilation in the tunnel, and (4) installation of new signing and high mast lighting. Work was concentrated on the inbound (westbound) lanes in 1981 and on the outbound (eastbound) lanes in 1982.

The basic traffic management strategy during most of the project was to close both lanes in the affected direction (inbound in 1981 and outbound in 1982) and to maintain two-lane, two-way traffic in the other direction. The entrance ramps within the reconstruction zone were closed and the entrance ramp nearest each end of the reconstruction zone was restricted to HOVs. Individual exit ramps within the reconstruction zone were closed when directly affected by work activity.

The closure of one direction of the freeway reduced the number of travel lanes from four to two and the closure of entrance ramps restricted access. As a result, many motorists were forced to divert from the Parkway. The only alternative routes were arterial streets, many of which were congested even before the restrictions were imposed on the Parkway. Therefore, a plan of people-moving strategies was implemented both to improve alternative routes and to provide alternative modes of travel.

The people-moving strategies, referred to as the "Pittsburgh Experiment," included:

1. Instituting a new commuter train that operated between Pittsburgh's eastern suburbs and central business district

2. Contracting with a third-party vanpool coordinator to organize vanpooling in the eastern suburbs

3. Contracting with the local transit authority to add several express bus routes in the corridor

4. Arranging with several property owners in the eastern suburbs to use existing parking lots as new park-and-ride lots for express bus passengers, carpoolers, and vanpoolers

5. Restricting entrance ramps to the Parkway at both ends of the reconstruction zone to high-occupancy vehicles

6. Making traffic operations improvements on several alternative routes in the corridor

The traffic operations improvements on alternative routes in the corridor were intended to increase capacity and reduce congestion. The improvements included signal installation, coordination, and other improvements; left-turn prohibitions; parking restrictions; pavement widening; signing and pavement marking; and the stationing of traffic control officers at critical intersections during peak periods.

The Parkway East project was the first in which FHWA approved 90 percent Interstate matching funds for strategies, such as those described above, to mitigate the travel impacts off the Interstate. The initial approved cost for the alternative transportation strategies was more than $11 million, although only $4.8 million were actually expended.

An extensive data collection program was implemented to measure the changes in traffic patterns, the impacts on motorists, and the effectiveness of the alternative transportation strategies. The data collected included:

1. Hourly and daily traffic counts at forty locations along one full and three partial screenlines before, during, and after the first reconstruction phase in 1981 and at six locations during and after the second reconstruction season in 1982

2. Morning peak period vehicle occupancy and classification counts before, during, and after the first reconstruction season

3. Morning peak, off-peak, and evening peak period travel times on the Parkway and five alternative routes before, during, and after the first reconstruction season

4. Travelers' responses to questionnaires with information including trip origins and destinations, and changes in departure time, route, and mode of travel

5. Ridership or user counts on the new commuter train, vanpools, express buses, and park-and-ride lots

In response to the traffic restrictions, the total volume of traffic entering the Parkway East reconstruction zone decreased by 60 percent from 132,000 vpd before reconstruction to 52,000 vpd during. The percentage reduction in volumes during morning and evening peaks was even greater: through the Squirrel Hill Tunnel, for example, the morning peak hour volume dropped by almost 70 percent from 3500 vph to 1100 vph in the peak direction. However, the counts along the complete screenline, which included all major highways in the corridor and which cut through the center of the reconstruction zone, were only slightly less during reconstruction than before. These counts, in conjunction with other data, indicated that the most common response by motorists was to continue to drive their automobiles but to use alternative routes in the corridor.

The complete screenline included counts on the Parkway as well as on 16 other major highways in the corridor. The diverted traffic was concentrated on the arterial streets closest to the Parkway; increased volumes on the six arterial streets closest to the Parkway accounted for more than 60 percent of the decrease in volume on the Parkway.

Average vehicle occupancy in the corridor changed very little during reconstruction, remaining at approximately 1.4 persons per vehicle. However, average vehicle occupancy on the Parkway itself increased during reconstruction from 1.4 to almost 1.7 persons per vehicle. These statistics, along with the screenline traffic counts, suggest that, overall, there was little diversion to HOV modes. However, those using carpools or vanpools apparently found the use of the Parkway advantageous because of the HOV-only ramps.

During the first reconstruction season, average travel times on the Parkway increased by about 9 min (30 percent) inbound during the morning peak and 20 min (154 percent) outbound during the evening peak. Average travel times throughout the whole corridor increased by 16 percent inbound during the morning peak and by 57 percent outbound during the evening peak. Travelers accommodated these increases with departure times that averaged 20 min earlier during reconstruction.

The effectiveness of the alternative transportation strategies varied. The new commuter train carried far fewer passengers than had been anticipated. Suburban community officials had predicted 2,800 to 7,600 riders per day. However, the actual average daily ridership which was more than 600 at the beginning of the project declined to less than 400 by the end of the first reconstruction season. As a result, the commuter train service was discontinued in November 1981 and was replaced by express bus service. The average of 500 passengers per weekday using the commuter train during the first reconstruction season was estimated to represent a reduction of 200 weekday vehicle trips on the Parkway East.

Six new express bus routes operated during the first reconstruction season and a seventh was added during the second season to replace the commuter train. The routes were changed several times in response to demand. The average weekday ridership was about 1400 during the first season and 1500 during the second season which represented a diversion of about 500 weekday vehicle trips from the entire corridor and more than 300 weekday vehicle trips from the Parkway East.

The vanpool program operated 18 vanpools during the first season, representing more than 600 weekday passenger trips and the diversion of 165 weekday vehicle trips from the corridor and almost 100 weekday vehicle trips from the Parkway. During the second season, as many as 34 vanpools operated in the corridor.

The park-and-ride lots were coordinated with the express bus service and vanpool program. Initially, twelve existing parking lots were designated as new park-and-ride lots to supplement the 10 lots that had been in use before reconstruction. Five of the twelve new lots were discontinued during the first reconstruction season due to low usage.

The HOV-only ramps were intended to promote ridesharing by reducing travel times for authorized users. It was estimated that use of the ramps reduced average total travel times by 8 minutes.

In summary, despite a reduction in the number of lanes on the Parkway East from four to two, the negative impact on motorists was deemed small (7). Significant traffic diversion away from the Parkway did occur during the reconstruction project; 60 percent fewer vehicles per day entered the Parkway reconstruction zone. However, the total traffic on all routes in the corridor decreased only slightly. The most common motorist response to the reconstruction was to change to alternative routes and to depart earlier. The ridesharing options accounted for only about 5 percent of the vehicles diverted from the Parkway during the peak hour. Therefore, the traffic operations improvements to alternative routes were deemed the most effective means of accommodating the traffic diverted from the reconstruction zone.

IH-93, Southeast Expressway, in Boston

The Southeast Expressway is the only major highway facility connecting Boston with southeastern Massachusetts. The freeway facility has six lanes, with a discontinuous breakdown lane in each direction used as a travel lane during peak hours. It carried more than 160,000 vpd before reconstruction. A $63.7 million reconstruction project was undertaken by the Massachusetts Department of Public Works (MDPW) on an 8.5-mi section of the Expressway during the 1984 and 1985 construction seasons (March through November) to (1) replace bridge decks and resurface the roadway, (2) widen and lengthen merge areas at ramps, (3) improve lighting and signing, and (4) alleviate drainage problems. The contract included a $10,000 per day incentive/ disincentive clause. The experiences from this project have been documented in an extensive report (10) and in related articles (11, 12).

The basic traffic management strategy was to retain as much capacity as possible on the Expressway during reconstruction. This was accomplished by (1) using concrete median barriers to divide the Expressway into four two-lane segments and (2) working on only one two-lane segment at a time. One segment was provided for each direction at all times and the remaining segment was reversible. This provided four lanes in the peak direction, the same number as before reconstruction, and two lanes in the off-peak direction. In addition, screens were installed on the sides of the work area to minimize potential reductions in capacity resulting from motorist rubbernecking.

Numerous actions were taken by the MDPW to mitigate the impacts of the reconstruction both on Expressway users and on residents and businesses in affected communities. The philosophy was to provide as many travel options as possible to Expressway users. The actions included:

1. Providing increased commuter rail, boat, and bus service

2. Adding park-and-ride lot spaces

3. Supporting an employer-based ridesharing program and an information brokering program

4. Encouraging large employers to implement variable work hour or flex-time programs

5. Making traffic signal and pavement marking improvements at key intersections on alternative highway routes

6. Placing police officers at certain intersections for traffic control

7. Funding proposals from 15 communities to mitigate local traffic control problems resulting from the reconstruction

8. Providing an extensive public information and community liaison program

The cost of these mitigating actions was $9 million. A key to implemention was maintaining the flexibility to modify or discontinue actions that were ineffective. For example, much of the additional bus service was discontinued because it did not attract sufficient riders.

In order to evaluate the effectiveness of the mitigating actions, an extensive travel monitoring program was implemented. This program included travel time measurements and volume counts on the expressway and alternative routes, and motorist/transit rider surveys before, during, and after reconstruction.

The results of the travel monitoring program indicated that it took several weeks for commuters to experiment with alternative routes and decide how to alter their tripmaking in response to the reconstruction project. This was evidenced by fluctuations in traffic patterns during the first several weeks of the project.

During the first year of reconstruction, between 5,000 and 9,000 vpd (3-6 percent of pre-reconstruction volumes) diverted from the Expressway; but during the second year, volumes returned to pre-reconstruction levels. Morning peak volumes were actually higher than pre-reconstruction levels. The distribution of morning peak period volumes indicated a shift to earlier departure times during reconstruction than before. The reductions in first year volumes were due to lower midday and afternoon peak volumes. Officials in Boston speculated that the reason for these lower volumes was the absence of discretionary midday trips.

Data from the traffic monitoring program suggested that most of the diverting traffic used the alternative highway routes in the corridor. The increase in volumes on the alternative routes was actually greater than the decrease in volumes on the Expressway during the first year. In addition, the use of the park-and-ride lots, commuter boat, and commuter rail service increased; however, some of these increases were attributed to improvements in service and not to the negative impact of reconstruction. Ridership on the rapid transit system was stable during the first year but declined during the second year, while use of the express bus service varied from route-to-route but, overall, declined slightly during reconstruction.

IH-5, Ship Canal Bridge, in Seattle

IH-5 is the major north-south freeway running through Seattle. It includes an eight-lane freeway and a separate two-lane reversible roadway. The reversible roadway runs north from the central business district for 8 mi and serves as express lanes. A project was undertaken by the Washington State Department of Transportation to resurface the mainlanes of the Ship Canal

Bridge and the Lakeview/Galer Viaduct on IH-5. The average weekday traffic on this section of IH-5 before resurfacing was 210,000 vpd. Two articles have documented this project (13, 14).

A 1-mi section of the northbound (outbound) mainlanes was resurfaced during the summer of 1984 and a 2-mi section of the southbound (inbound) mainlanes was resurfaced during the summer of 1985. The contract for the northbound lanes included a $10,000 per day incentive/discentive clause, and the contract for the southbound lanes included a $20,000 per day incentive/disincentive clause.

The resurfacing project on the northbound lanes in 1984 had three phases. In the first phase, preparatory work (repairing joints and grinding the surface) was performed in two-lane segments on weeknights during off-peak hours (8 p.m. until 6:30 a.m.) and on weekends. This required the installation and removal of lane closures nightly. During the day, all lanes were open, but traffic was slowed by the rough surface. In the second phase, two lanes at a time were closed for placing and curing the 1.5-in concrete overlay. Traffic was maintained on two 11-ft lanes with a 1-ft left shoulder and a 1.5 ft right shoulder. In the third phase, lanes were closed during weeknights and weekends for final cleanup operations.

After the completion of the northbound resurfacing project, officials reviewed the traffic management strategy that was employed. They concluded that the daily traffic control setup not only caused the project to take longer than expected but also confused the driving public because of the frequent changes in traffic patterns. Therefore, during the resurfacing of the southbound lanes in 1985, a temporary median barrier was used to close two lanes at a time through the length of the project while all preparatory work and paving were completed in those lanes. This traffic control plan was considered superior because it allowed the contractor to work more efficiently (evidenced by the fact that the southbound work was completed in less time than the northbound even though the length resurfaced southbound was greater) and it provided a more stable driving environment.

During the project planning process, it was determined that it would not be possible to accommodate normal traffic volumes with two lanes closed. Therefore, a coordinated effort was undertaken to reduce the volumes on IH-5 and to minimize the adverse impact on motorists. The strategy was to take advantage of the express lanes as an alternative route and of the strong mass transit and carpool/vanpool organizations in Seattle.

The use of alternative routes, including the express lanes, was encouraged by:

1. Restricting the use of two downtown entrance ramps to HOV only

2. Constructing cross-over ramps from the mainlanes to the express lanes

3. Expanding the hours of operation of the express lanes in the direction being resurfaced

4. Retiming traffic signals on alternative routes

5. Restricting maintenance work on alternative routes to emergency operations only

6. Using off-duty police officers for traffic control at critical locations on alternative routes

Bus transit and carpool/vanpool usage was encouraged in several ways:

1. Restricting two downtown ramps to HOV only

2. Adding several new bus routes

3. Making backup buses available for service in the event of delays to regular buses in route

4. Disseminating carpooling information

Traffic operations on IH-5 were monitored using the Surveillance, Control, and Driver Information System operated by the state's Traffic Systems Management Center. The center was also able to dispatch state patrol cars and the tow trucks provided by the contractor; it also provided up-to-date traffic reports to the metropolitan transit agency and to local radio stations.

A public information plan was also implemented. Information was disseminated through news conferences and public hearings; brochures, posters, letters, and flyers; a 24-hour Resurfacing Hotline; a Highway Advisory Radio station; and variable message signs.

The project was completed without serious congestion either on IH-5 or on the alternative routes. Average weekday traffic decreased by 38 percent on the northbound mainlanes in 1984 and by 40 percent on the southbound mainlanes in 1985. Much of the diversion of traffic was either to the express lanes (40 percent) or to one of the five parallel alternative routes that cross the Ship Canal (40 percent). The remaining diverted trips used other routes, changed modes, or were not made. Some diversion to high occupancy vehicles also occurred: requests for ridematching increased 56 percent in August 1985 compared to August 1983 and bus ridership in the summer of 1985 was 10 percent higher than the usual summer.

IH-76, Schuylkill Expressway, in Philadelphia

The Schuylkill Expressway is the major east-west freeway connecting the Pennsylvania Turnpike (IH-76) and western suburbs with downtown Philadelphia. The 21-mi long freeway is predominantly four-lane, although several segments near downtown have six or eight lanes. Traffic volumes ranged from 80,000 vpd near the Turnpike to 143,000 vpd near downtown. The Expressway was completed in 1961 and the deteriorating condition of both the pavement and bridge decks necessitated a three-year, $175 million reconstruction project to (1) rehabilitate 18 mi of pavement with a structural bituminous overlay, (2) rehabilitate 50 bridges by redecking 38 and overlaying 12, (3) widen shoulders, and (4) replace the existing metal guardrail in the median with concrete median barrier.

The reconstruction project began in 1985, when a 5-mi segment near the Turnpike and a 1.5-mi segment at the downtown end of the Expressway were reconstructed. In 1986, 12 continuous mi were rehabilitated. The remaining work, reconstruction of a major downtown interchange, was originally scheduled for completion in 1987. However, design and construction problems were encountered and, as a result, the remaining work has been delayed to 1988. The reconstruction work in 1985 and 1986 was performed under five separate contracts. Each contract included an incentive/disincentive clause which varied from $21,875 to $30,000 per day. The project has been described in several articles (15-17), but the actual travel impacts have not been thoroughly documented since the project is not yet complete.

To assist in project planning, PennDOT retained a traffic engineering consultant to (1) establish and analyze the existing transportation situation, (2) develop reconstruction strategies, (3) evaluate the impact of recommended strategies on the local transportation network, (4) develop and design the traffic management plan, and (5) monitor the effectiveness of the plan.

The evaluation of the existing transportation situation included travel time studies on 15 parallel alternative routes to the Expressway, automatic and manual volume counts, vehicle classification counts, on-street parking studies, capacity analysis, a traffic signal inventory, and an origin-destination survey. Predictions were made of the volume increases on alternative routes during reconstruction.

Officials decided to stage the project over three construction seasons (March to November). The traffic management plan had three goals: (1) maintain at least one lane of traffic on the Expressway in each direction at all times, (2) encourage truck drivers, tourists, and other long-distance travelers to remain on the Expressway during reconstruction, and (3) reopen all lanes of traffic between reconstruction seasons.

In general, two-lane two-way traffic was maintained in one direction while work was performed in the other direction. Shoulders were upgraded prior to reconstruction. This enabled traffic to operate on the shoulder and on the median lane with a buffer lane in between the two lanes of traffic. Most of the entrance ramps and some of the exit ramps within or leading to the reconstruction zone were closed, in order to limit access to the Expressway by local drivers.

The alternative routes and the public transportation system in the Schuylkill Expressway corridor were not considered capable of handling the traffic that would have to divert from the Expressway due to the reduction in Expressway capacity. Therefore, a program of mitigation measures was undertaken to increase the capacity of alternative routes and to improve public transportation facilities and services. The program was budgeted at $12 million.

Improvements on alternative routes included:

1. Modernizing, coordinating, and retiming existing traffic signals

2. Installing additional signals (some permanent and some temporary)

3. Widening and constructing intersection turning lanes

4. Eliminating on-street parking

5. Accelerating maintenance and pavement patching schedules on key routes

6. Assigning traffic control officers to key intersections and school bus stops

Improvements to public transportation facilities and HOV services included:

1. Expanding park-and-ride lots

2. Extending commuter rail service farther west

3. Adding rail cars on existing trains in the corridor

4. Adding buses to maintain pre-reconstruction headways on existing routes

5. Increasing ridesharing programs

An extensive public information program was also undertaken. The program included:

1. Traditional public relations tools (press conferences, news releases, interviews, media events, and public service announcements)

2. A Visitor's Guide, which provided information and encouragement for truckers, tourists, and long-distance travelers to stay on the Expressway

3. A Commuter's Guide, which provided information and encouragement for local drivers to take alternative routes

4. A toll-free hotline to identify alternative routes, answer questions, take and respond to complaints, and distribute information.

A traffic monitoring program during reconstruction included volume counts both on the Expressway and on alternative routes, and speed and delay runs on the Expressway. Data from the monitoring program were used in the early stages of reconstruction to adjust signal phasing and timing and to reassign traffic control officers.

The actual travel impacts during reconstruction have not yet been documented, since the project is still underway. However, preliminary analyses suggest that traffic volumes on the Expressway decreased by 60 percent during the first reconstruction season. The traffic that diverted was widely dispersed over a large number of alternative routes. The volume counts also suggested that motorists shifted back and forth between the Expressway and the alternative routes in response to changing traffic conditions.

PennDOT officials (15) concluded:

> The long-range planning for the expressway rehabilitation, the mitigating traffic measures--including the monitoring during construction--and the largest public information program ever undertaken by the department for a construction project, combined to make the expressway project a success.
>
> No massive traffic jams materialized, life went on in the City of Philadelphia, the tourists came as usual, and the region's drivers proved that given choices and information they could be quite resourceful and successfully cope with a major reconstruction project.

US-10, John C. Lodge Freeway, in Detroit

The Lodge Freeway is a six-lane freeway connecting downtown Detroit and its northwestern suburbs. It carries approximately 130,000 vpd. In 1986, the Michigan Department of Transportation undertook a $39 million project to reconstruct a 7.8-mi section of the freeway between IH-75, near downtown, and Wyoming Avenue, to the northwest. The project includes (1) widening the outside shoulders, (2) constructing a safety shaped barrier wall at the edge of the outside shoulders, (3) extending and upgrading the drainage and storm sewer system, (4) removing and replacing the pavement, (5) improving several interchanges, (6) redecking several bridges, (7) improving landscaping and erosion control, and (8) repairing the pavement on a new section of the freeway north of the project limits. The two-year project began in April 1986 and is scheduled to take two construction seasons (April through November). The contracts for the work include $12,000/day incentive/disincentive clauses. Since the project is still underway, only limited documentation currently is available (18).

The work conducted in 1986 (primarily items 1-3 above) required only relatively minor capacity reductions. All three lanes were kept open in the peak direction during rush hours. The outside lane in each direction was allowed to be closed during off-peak periods. Lanes were narrowed from 12 to 11 ft, and the median shoulders were narrowed by 3 ft to provide a 6 ft right shoulder. Ramps were closed, but no more than two consecutive ramps at a time. During special events, all lanes and ramps were kept open. A 45 mph speed limit was established through the reconstruction zone. The capacity reductions in 1987 are more severe. One direction of the Freeway at a time is being closed for the pavement removal and replacement.

Project planners estimated that the alternative routes in the Lodge corridor could handle 78 percent of the traffic expected to divert from the freeway in 1987. The use of HOV modes and other city streets would have to accommodate the rest. Planners estimated that travel times in the corridor would increase by 20 percent.

To mitigate the impacts on motorists, improvements were made to alternative routes, including:

1. Resurfacing one route

2. Improving signing and lighting

3. Improving connectors between a major traffic generator in the corridor and an alternative route

4. Retiming traffic signals

Improvements were also made in HOV services in the corridor, including:

1. Increased efforts to attract carpoolers and vanpoolers

2. Expanded bus service

Motorist services that were provided included:

1. Free tow truck service on the freeway within the reconstruction project limits

2. Increased police patrols on alternative routes

A public information program was also implemented by a public relations consultant. The public information program included:

1. Traditional public relations tools (public meetings and presentations, media briefings, public service announcements)

2. Informational signing

3. Distribution of a variety of informational materials,

4. A telephone hotline

5. An ombudsman

Even though the capacity restrictions in 1986 were relatively minor compared with 1987, the impact mitigation strategies were implemented in 1986. Motorists were encouraged to prepare for 1987 by identifying and starting to use alternative routes and modes. Only preliminary results are available at this time, but the strategies appear to have had positive results. Officials estimated that traffic volumes on the Freeway during the 1986 reconstruction season were almost 20 percent lower than pre-reconstruction levels.

Since the Lodge Freeway reconstruction project is still in progress, only limited documentation is available. Additional data and analysis will be needed to evaluate the actual impacts of reconstruction, especially during the more critical 1987 season.

3. REVIEW OF EXISTING COMPUTER MODELS

A primary objective of Study 1108 is to develop a sound analytical approach, in the form of a computer model, to estimate more accurately the changes in traffic patterns and road user costs resulting from freeway construction options. The model must be able to (1) analyze a variety of traffic management strategies typically used during freeway construction activities, (2) account for any changes in traffic patterns, due to diversion, that occur during construction, (3) estimate traffic flow characteristics and road user costs both before and during construction, (4) produce results that replicate actual conditions well, and (5) do all of these things with reasonable input data requirements.

A review of existing computer models was undertaken to determine the capabilities and limitations of existing models with respect to the prediction of traffic patterns and additional road user costs resulting from freeway construction projects and to identify the modifications to the existing models that would be required to make more accurate predictions.

Summary

A review of the literature did not uncover an existing computer model that satisfies all of the requirements stated above. However, each of the nine models reviewed in this chapter has capabilities that may be useful in estimating the travel impacts of freeway construction options. The models reviewed are: QUEWZ, FREWAY, PASSER IV, CORQ-CORCON, HEEM-II, FREQ, FREFLO, INTRAS, and CARHOP. Each model was evaluated with respect to five criteria: work zone traffic management schemes that can be analyzed, theoretical basis for the analytical techniques, assumptions implicit in the model, input data requirements, and model output. A brief summary of the models is provided before presenting a more detailed evaluation of each model.

QUEWZ is a work zone evaluation model that was specifically designed to evaluate alternative freeway work zone configurations, to analyze traffic flows with and without the work zone, and to estimate the additional road user costs per hour due to the work zone. For a recent application, a diversion algorithm was added to QUEWZ. The algorithm is based upon several simplifying assumptions and has not yet been validated, but it does account, in a simplified manner, for the changes in traffic patterns that occur in response to freeway construction activities.

FREWAY can be used to estimate the capacity and level of service of basic freeway segments with or without a work zone and to estimate queues and delays resulting from a work zone. FREWAY does not estimate user costs and does not account for changes in traffic patterns during work activities.

PASSER IV is a freeway corridor traffic assignment model. It assigns traffic among the freeway, frontage roads, and alternative surface streets in a corridor so that the estimated travel times along each route are equal. It does not provide estimates of traffic flow characteristics, except a volume-to-capacity ratio, or of road user costs. However, the traffic assignment capabilities of PASSER IV could be used to model diversion.

CORQ-CORCON is also a freeway corridor traffic assignment model. It uses a link-node representation to model the freeway and parallel arterials. It has several special features that would be useful in evaluating freeway construction impacts, including the ability to consider time-varying supply (link characteristics) and demand, and to model the effects of queueing on route selection. It does not estimate road user costs. The model is proprietary and its applications have been limited.

HEEM-II is an economic model that estimates the benefits and costs associated with improvement alternatives on a particular highway segment. Its primary focus is on costs before and after an improvement is made. An important component of HEEM-II is a corridor traffic analysis procedure that allocates traffic among routes in the corridor on a minimum user cost basis. HEEM-II could be used to estimate before-versus-during or during-versus-after construction costs by appropriately specifying the existing condition and the improvement alternative. HEEM-II evaluates traffic conditions on a daily rather than an hourly basis, which limits the types of traffic management strategies that can be analyzed and which also may affect the accuracy of traffic estimates.

FREQ, FREFLO, and INTRAS are freeway traffic simulation models. Both FREQ and FREFLO model traffic flow macroscopically, whereas INTRAS models traffic flow microscopically. The use of these models involves considerable effort. Each uses a link-node representation of the freeway, which requires extensive input data and calibration for each freeway that is modeled. All three models could simulate work zones and, with appropriate calibration, should produce good estimates of traffic conditions. None of the models estimate diversion internally, although the user can specify certain diversion characteristics that the models will use. None of the models translate the traffic flow estimates into user cost estimates.

CARHOP is not a new model, but rather an interface between the user and the existing computer models FREFLO, TRAFLO, TRANSYT-7F, and TRAFFIC. FREFLO is a macroscopic freeway simulation model. TRAFLO is a macroscopic arterial simulation model. TRANSYT-7F is a traffic signal timing optimization program. TRAFFIC is an equilibrium traffic assignment model. CARHOP simplifies the mechanics of using the models by providing an interactive, menu-driven environment for inputting data, running the models, and processing the output. CARHOP was designed to analyze the traffic impacts of alternative reconstruction options but does not estimate road user costs.

Findings

Each of the models reviewed was designed for a specific application. The level of detail and sophistication in the spatial and temporal representation of the freeway as well as the amount and accuracy of required input data vary. Clearly, in selecting a model for a particular application, one must first determine whether a model provides the level of accuracy that is desired. One must balance the level of accuracy that can be attained against the level of effort required to attain it. One must also consider whether a model provides the types of information desired or, if not, how feasible and practical it would be to make the changes or additions necessary to produce that information.

The traffic simulation models (FREQ, FREFLO, INTRAS, and CARHOP) provide the most sophisticated analysis of traffic flows, but they also have the most demanding input and calibration requirements. FREQ and INTRAS have algorithms that model traffic diversion away from the freeway in response to operating conditions on the freeway and, thus, could estimate changes in traffic patterns. FREFLO has a ramp metering algorithm that adjusts entrance ramp volumes but does not account for the traffic that is diverted away from the ramp. CARHOP uses equilibrium traffic assignment to estimate changes in traffic patterns. A limitation of these models is that they do not compute the road user costs required for the applications in Study 1108.

HEEM-II could be used to evaluate the changes in travel patterns and road user costs resulting from long-term highway reconstruction projects. HEEM-II has the ability to assign traffic among alternative routes in a corridor, to estimate traffic characteristic, and to translate those estimates into road user costs. The primary limitation of HEEM-II is that traffic conditions are evaluated on a daily rather than an hourly basis, which restricts the traffic management strategies that may be evaluated and which affects the accuracy of estimates of traffic characteristics.

PASSER IV and CORQ-CORCON are freeway corridor traffic assignment models. PASSER IV is a quick-response equilibrium traffic assignment procedure ,that was developed to quickly analyze urban freeway corridor alternatives. PASSER IV minimizes input requirements by coding many important parameters directly into the program, which may limit its accuracy in certain applications. CORQ-CORCON is a more sophisticated assignment model that considers time-varying supply and demand and accounts for the effect of queueing on route selection. These features would be useful in evaluating the changes in traffic patterns due to freeway construction options. However, CORQ-CORCON is proprietary and only a few applications have been documented by its developers.

FREWAY has two capabilities that are applicable to Study 1108. It can be used to perform capacity analysis on basic freeway segments under normal operating conditions or with a work zone lane closure in place. It can also estimate queueing characteristics using input-output analysis. However, QUEWZ also has these capabilities.

QUEWZ provides estimates of both traffic characteristics and road user costs on an hourly basis. It falls between the freeway simulation models and HEEM-II in terms of the level of sophistication in modeling traffic flow. It is structured specifically to analyze alternative traffic management strategies for freeway construction. Recently, a diversion algorithm has been added to the model. This algorithm may be able to satisfy the required capability to estimate changes in traffic patterns, although testing and validation of the algorithm is needed.

The overall conclusion, based upon the review of existing computer models, is that QUEWZ provides the best framework upon which to build a more accurate analytical tool for estimating the effect of freeway construction activities on traffic patterns and road user costs. However, many features of the model, particularly the new diversion algorithm, should be carefully tested, validated, and upgraded to improve the accuracy and capabilities of the model. In addition, the other models reviewed have important capabilities that might be incorporated into QUEWZ to enhance its usefulness and accuracy.

PASSER IV, CORQ-CORCON, HEEM-II, and CARHOP have traffic assignment capabilities that may be useful in estimating changes in traffic patterns. FREWAY, FREQ, FREFLO, and INTRAS have important freeway simulation capabilities that may be valuable in estimating traffic flow characteristics before and during construction activities. The feasibility and desirability of incorporating these capabilities into QUEWZ need further evaluation.

QUEWZ

QUEWZ, Queue and User Cost Evaluation of Work Zones, was developed at TTI for the SDHPT under Study No. 2-18-81-292, "Handling Traffic in Work Zones" (19, 20). The model analyzes traffic flows through freeway work zone lane closures and estimates the queue lengths and additional road user costs that would result. QUEWZ2 is a modified version of the original model that was developed under Interagency Contract 84-85-0413 with SDHPT District 12 (21). Another version of the model, QUEWZ412 was developed for use in SDHPT Study No. 2-6-85-402, "Project Completion Times and Project Overruns" (22). A microcomputer version, QUEWZ-85, has also been developed (23, 24).

Traffic Management Schemes

QUEWZ was specifically designed to analyze alternative freeway work zone lane closure configurations. The model can be applied to basic freeway segments with as many as six lanes in each direction and can analyze any number of lanes closed in one or both directions.

Theoretical Basis

QUEWZ analyzes traffic flows through work zones using traditional macroscopic techniques. It estimates speeds and queueing characteristics both with and without the work zone and then translates those characteristics into estimates of the additional road user costs due to the work zone.

The following speed characteristics are estimated: normal approach speed, average and minimum speed through the work zone, and average and minimum speed through the queue. The normal approach speed and average speed through the work zone are computed from the relationship between speed and volume-to-capacity ratio presented in the 1965 Highway Capacity Manual (25). The model user has the option to modify the parameters of the relationship to more accurately represent the freeway being analyzed. The minimum speed through the work zone is estimated using a linear regression model that was developed at TTI. In a queue, the minimum speed is assumed to be zero and the average speed is estimated using a kinematic wave model developed by Messer, Dudek, and Friebele (26).

When approach volumes exceed the capacity of the work zone, the length of queue and vehicle hours of delay are computed using the traditional input-output approach presented in the 1985 Highway Capacity Manual (27).

Road user costs are estimated in three components: travel time, vehicle running, and speed change cycle costs. Vehicle running and speed change cycling costs are estimated using equations derived from the AASHTO Manual on User Benefit Analysis (101). The equations estimate costs as a function of speed. Accident costs, which are another user cost component, are not included because of the sparcity of data on changes in accident rates during work zone activities. Road user costs on the affected freeway segment are estimated both with and without the work zone. The additional costs per hour due to the work zone are reported.

Assumptions

Several important assumptions influence the model results. The original model assumed that no traffic diverted from the freeway in response to delays caused by the work zone (19). However, in the version of the model adapted for use in Study No. 2-6-85-412, an algorithm was added that would divert traffic away from the work zone so that delays or queue lengths never exceeded a user-specified maximum acceptable level (22). Several assumptions are made about the diversion route in order to estimate the additional costs to diverting traffic: (1) the length of the diversion route equals the length of the work zone plus the length of queue, (2) the travel time for diverting traffic equals the time for a vehicle at the end of the queue to travel through the queue and the work zone, (3) the diverting traffic maintains a uniform speed equal to the length of the diversion route divided by the travel time, and (4) trucks do not divert. The diversion algorithm does not consider characteristics of the alternative routes, including capacities and travel times, that may influence decisions to divert.

Another important assumption relates to the speed-volume relationship. It is assumed that the same relationship applies both with and without the work zone. Butler (28) and Abrams and Wang (29) made the same assumption in their work. However, Rouphail and Tiwari (30) concluded that the speed-volume relationships at four freeway lane closures in Illinois were considerably different from the relationship in TRB Circular 212 "Interim Materials on Highway Capacity" (31). Additional research will be required to determine the appropriate speed-volume relationship for work zones.

The model uses the work zone capacities reported by Dudek and Richards (32, 33) and included in the 1985 Highway Capacity Manual (27). Dudek and Richards (33) present the cumulative distributions of work zone capacities observed at 28 maintenance and construction zones in Texas for various lane closure configurations. The model selects a work zone capacity based upon a user specified percentile value which represents the percentage of sites at which observed capacities equal or exceed the value selected.

Another assumption that influences user cost estimates is the behavior of traffic in a queue. It is assumed that vehicles make three, 0-to-10 mph speed changes per mile of queue length. This assumption was based upon a series of speed profiles developed from instrumented vehicles traveling through queues.

The fundamental assumption of the input-output analysis technique is that both the arrival rate (approach volume) and departure rate (work zone capacity) are uniform throughout each hour.

Input Data Requirements

The principal input requirements are a description of the work zone and an estimate of the hourly approach volumes to the work zone. The model also employs several default values that the user can override.

The description of the work zone includes the configuration of the lane closure and the schedule of work activity. The configuration of the lane closure is described by the closure strategy (single direction or crossover), the total number of lanes in each direction, the number of lanes open through the work zone, and the length of the work zone. The schedule of work activity is defined by the beginning and ending hours of restricted capacity and the beginning and ending hours of actual work activity.

The user may also override several default values. For example, by default, costs are estimated in 1981 dollars; however, a cost update factor can be input to adjust costs to more current dollar values. The parameters that define the speed-volume relationship can also be changed. The default percentage of trucks can be modified. Finally, the user may specify a work zone capacity rather than accept the capacity the model would estimate.

Model Output

The original version of QUEWZ (19) summarized its output in one table which reported, for each hour and direction, the following estimates:

1. Approach volume
2. Freeway capacity
3. Approach speed
4. Work zone speed
5. Queue length
6. Additional road user costs

QUEWZ2 (21) added a second output option: a schedule of acceptable times for closing lanes in one or both directions and a matrix, for each possible lane closure configuration, of the queue lengths during each hour of the day.

Application to Study 1108 Requirements

QUEWZ satisfies most of the requirements of Study 1108. It estimates the changes in both traffic operating characteristics and road user costs resulting from freeway work activities. QUEWZ has had some validation and several successful applications (92), but additional validation should be performed. The major area that requires additional effort is in estimating diversion. A simple diversion algorithm has been added to QUEWZ, but that algorithm has not been validated. The diversion algorithm should be tested and modified as necessary.

FREWAY

FREWAY is a microcomputer program developed by Rouphail, Spencer, and Rivers (34, 35). It performs routine capacity and delay calculations for basic freeway segments either under normal operating conditions or with work zone lane closures.

Traffic Management Schemes

FREWAY was designed to analyze basic freeway segments under either normal or work zone conditions. It can analyze single direction freeway lane closures as well as reductions in lane widths or lateral clearances.

Theoretical Basis

Capacity calculations for normal operating conditions are based upon the standard procedures and adjustment factors presented in the 1965 Highway Capacity Manual (25). Capacity calculations for lane closures are based upon the procedure and data presented by Dudek and Richards (32). Traffic performance measures related to queueing are estimated using traditional input-output analysis techniques.

Assumptions

Essentially, FREWAY is a computerized version of traditional analysis techniques. FREWAY uses the capacity analysis procedures in the 1965 Manual (25), which have been updated in the 1985 Manual (27). The procedure and data presented by Dudek and Richards (32) were discussed earlier. The assumptions implicit an input-output analysis have also been identified.

Input Data Requirements

The input data requirements are minimal. The calculation of capacity under normal conditions requires the following inputs: length and percentage of grade, percentage of trucks and buses, number of lanes, lane widths, and lateral clearances. The calculation of capacity during a lane closure requires only three inputs: the total number of lanes in one direction, the number of lanes closed, and the desired percentile value from the distribution of capacity estimates. For the calculation of queueing characteristics, the user must specify the times the work activity starts and ends, the length of the volume count interval, and the demand volumes for each interval. The user also has the option of providing default values for both normal and work zone capacity.

Model Output

The output from FREWAY includes capacity estimates under both normal and work zone conditions. The program will also report the following traffic performance measures for queueing conditions:

1. Maximum queue length

2. Queue stack and dissipation time

3. Queue at end of hour

4. Total vehicle delay

5. Average delay per delayed vehicles

6. Average delay per approach vehicle

7. Percentage of vehicles delayed

Application to Study 1108 Requirements

FREWAY uses traditional procedures to estimate capacity under normal and work zone conditions as well as traffic performance measures for queueing conditions. It does not provide estimates of user costs. Its procedure for estimating normal capacity, which are based upon the 1965 Highway Capacity Manual, is outdated. It uses the same procedures as QUEWZ for estimating work zone capacity and for predicting queueing characteristics. Essentially, the capabilities of FREWAY are a subset of the capabilities of QUEWZ.

PASSER IV

The PASSER IV model provides quick-response procedures for analyzing alternatives within a freeway corridor. The model is a traffic assignment program, assigning flows to the freeway, frontage roads, and arterial streets so as to optimize travel times through the corridor. The model is deterministic and microscopic. The program was developed at TTI as part of Study No. 2-18-80-281, "Development of a Freeway Corridor Evaluation System" (36), for the SDHPT.

Traffic Management Schemes

PASSER IV could approximate many traffic management schemes by properly defining section lengths, number of lanes, and per lane capacities to represent work zone operating conditions.

Theoretical Basis

PASSER IV is a traffic assignment model. It is based on Wardrop's first principle of equilibrium flows which states that motorists choose travel paths so as to minimize their total trip time (37). Consequently, the model estimates travel times for the freeway, the frontage road, and parallel arterial routes, and assigns volumes (through an iterative procedure) to the various routes so that travel times are the same on all routes in the freeway corridor.

The program uses empirical relationships for computing travel times on the various routes. These relationships are dependent upon several factors, including volumes, capacities, speeds, and signal densities. The relationships used are either identical or modified versions of the relationships used in the FHWA Micro Assignment model (38).

Assumptions

Several key assumptions are made in PASSER IV to facilitate the computations of travel times for the various routes (freeway, frontage roads, arterial streets). The major assumptions are as follows:

1. Travel times on the freeway can be estimated as a function of volume-to-capacity ratio, and travel times on frontage roads and arterial streets can be estimated as a piecewise linear function of the volume-to-capacity ratio, posted speed limit, and signal density

2. All drivers attempt to minimize their actual travel times and choose the route that allows them to do this

3. Drivers have exact knowledge about operating conditions on all possible routes before they choose a particular route

4. The minimum average speed on a facility is assumed to be 10 mph. This is reached when the volume-to-capacity ratio exceeds 1.5

5. The freeway is not metered (although lane capacities can be adjusted to simulate the presence of metering)

Input Data Requirements

For each route in the corridor, including the freeway, frontage road, and one or more arterial streets, the following information is required: (1) number of lanes, (2) length of segment, (3) posted speed limit, and (4) per-lane capacity. For the frontage road and arterial streets the signal density must also be specified. In addition, the total corridor demand must be provided.

Model Output

Three types of output are provided by PASSER IV. First, a summary of the input data is repeated. Next, the equilibrium travel time for the corridor is provided. Finally, the volumes distributed to each route in the corridor are presented, along with the corresponding volume-to-capacity ratio for each route.

Application to Study 1108 Requirements

PASSER IV provides a quick-response procedure for assigning traffic to various routes in a freeway corridor. It would not be able to satisfy Study

1108 requirements as a stand-alone program because it was not designed to compute the delays and user costs resulting from freeway construction activities. However, it might be useful in conjunction with QUEWZ or another program as a mechanism for estimating changes in traffic pattern caused by freeway reconstruction efforts.

CORQ-CORCON

CORQ-CORCON is a proprietary freeway corridor traffic assignment model. CORQ (CORridor Queuing) was developed by Yagar and was modified by Easa and Allen, who renamed it CORCON (for freeway CORridor assignment and CONtrol) (39). Some testing and validation of the model has been performed by the developers (40,41). CORQ-CORCON has several features that could be useful in evaluating changes in traffic patterns caused by freeway reconstruction projects including the abilities to consider time-varying demands and link characteristics and to model the effects of queueing on driver route selection.

Traffic Management Schemes

CORQ-CORCON uses a link-node representation to model the routes within the corridor. This representation allows the model user to define many types of traffic management schemes, including those used in work zone applications. One interesting feature of the model is the ability to allow the physical properties of link-node network to be varied at periodic time intervals. Consequently, temporary or time-dependent conditions which affect traffic operations, including incidents and temporary lane closures, can be modeled and evaluated. The program is currently configured to allow analysis in only one direction of travel at a time.

Theoretical Basis

CORQ was specifically configured to estimate the effects of time-varying demand and queueing on driver route selection within a corridor (42, 43). In CORQ, time-varying demand is handled by dividing time into small uniform intervals called "time slices," commonly on the order of 15 minutes, over which demand is assumed to remain homogenous. The program propagates these demand "slices" sequentially in time, assigning flows to the various routes so as to minimize unit travel costs based on corridor conditions existing at the beginning of the time slice.

A unique feature of CORQ is its treatment of oversaturated conditions within the corridor. Demand in excess of capacity at a given link during a time slice is queued at the upstream node and is combined with the demand for the next time slice. Queued vehicles are, in effect, allowed to reselect a new minimum travel cost route, based on conditions existing in the corridor at this new time. This feature gives the model a dynamic assignment capability not provided in previous traffic assignment or freeway operations models.

Traffic flows in the corridor are treated macroscopically, as a fluid leaking through the system (44). Signalized intersections on the non-freeway routes in the corridor are treated only as capacity restrictions. (The effects of signal timing and progression are not considered in the model.) The program includes a capacity-sharing routine developed by Yagar to address the effects of flow-dependent capacities at freeway on-ramp merges and weaving sections upon traffic conditions. Finally, the relationship between travel costs and traffic flows on a facility is treated as a step function where costs are assumed constant over a given range of flows (42).

As stated previously, CORCON is a modification of the original CORQ model. The primary enhancement is the incorporation of a diversion algorithm that allows traffic assigned to its minimum travel route to divert to another route if queueing develops somewhere on the original, assigned route. The algorithm assumes driver knowledge of conditions downstream, and can be thought of as simulating the effect of recurrent congestion where drivers develop knowledge of expected conditions and change their travel patterns accordingly. The amount of diversion allowed by the algorithm is controlled by an exponential parameter, which must be calibrated to properly reflect the conditions being modeled (41).

Assumptions

The traffic assignment procedure, even though it treats the dynamic fluctuations of demands and operating conditions in the corridor, is still based upon the Wardrop's principle that road users attempt to minimize their perceived travel costs (42). Drivers are assumed to have perfect and complete knowledge of conditions throughout the corridor and to select the route that actually does minimize their travel costs.

Input Data Requirements

Currently, program documentation and user manuals for the CORQ-CORCON model are not publicly available, since the model is proprietary and has not yet been released for distribution. For this reason, it is difficult to determine exactly what input data are required to run the program.

However, since the program is basically a traffic assignment model, one can make an educated guess as to the type of input needed. Undoubtedly, the link-node representation of the corridor must be described in the input routine. One would expect required link data to include section lengths, number of lanes, and capacities. Also, origin and destination nodes (the beginning and ending points of the various travel routes) would have to be defined, and an origin-destination trip table would be needed for each time slice being evaluated (43).

Model Output

The developers of CORQ-CORCON admit that the output from the model is limited and needs to be improved (45). Apparently, the output consists of link-by-link summaries of flows, travel times, and queues for each time slice evaluated. Further processing and analysis of this information must be done manually.

Application to Study 1108 Requirements

CORQ-CORCON has several limitations with respect to use in Study 1108. The most significant drawback is that the model is proprietary and has not been released for public use. The input requirements include link-node data and origin-destination information, which would require considerable effort to assemble. With regards to the actual program, the model was not designed to estimate the road user costs associated with reconstruction options.

The advantage of CORQ-CORCON is its dynamic assignment algorithm which accounts for time-varying demand and link characterstics and models the effect of queueing on route selection. These traffic assignment capabilities would be useful in estimating changes in traffic patterns during freeway reconstruction projects. Such capabilities would be useful in Study 1108.

HEEM-II

The Highway Economic Evaluation Model (HEEM) was developed by McKinsey and Company, Inc., and implemented in 1976 by the SDHPT (46,47). In 1983, TTI delivered a revised version, HEEM-II, to the SDHPT (48). HEEM-II analyzes proposed highway improvements and calculates a benefit-cost ratio and a mobility measure for each improvement. The objective is to identify those improvements that maximize future public benefits.

Traffic Management Schemes

HEEM-II was not specifically designed to analyze work zone traffic management strategies, but certain work zone configurations could be approximated in HEEM-II by specifying a highway type and technical and safety factors that adjust for lane and shoulder width, horizontal and vertical alignment, and the percentage of trucks. HEEM-II evaluates traffic conditions on a daily rather than an hourly basis and, therefore, could not analyze work zone configurations that change during the day.

Theoretical Basis

HEEM-II is an economic model for calculating the benefits and costs associated with alternative improvements to a particular highway segment. One component of the model that is of interest in this review is the procedure for allocating traffic to the primary, alternative, and diversion routes throughout the service life of the improvement.

The traffic allocation procedure, which is based upon Wardrop's principle, allocates traffic in a way that minimizes total user costs (48). HEEM-II employs a marginal cost allocation algorithm, which can be thought of as an equilibrium assignment procedure. The program assigns traffic to each route such that no individual can reduce his marginal user costs by switching to another route.

Assumptions

HEEM-II uses several assumptions in estimating economic benefits and costs. Questions about certain assumptions in the original version of the model prompted the SDHPT to authorize TTI to review the key assumptions, including the percentage of trucks, the value of time for passenger cars and trucks, the inflation rate, the construction cost escalation rate, the discount rate, and the speeds on urban and rural diversion routes (50). The assumptions used in HEEM-II were updated based upon this review. In addition, there are several other types of assumptions made in the program, including the pattern of traffic growth (51, 52), traffic peaking characteristics, technical and safety factors used for each highway type, design life of highway improvements, the traffic allocation procedure, congestion speed, truck speed, accident rates, vehicle speed/ operating cost relationships, cycling costs, and maintenance user costs.

Input Data Requirements

The input data requirements are fairly simple and straightforward. Table 7 summarizes these requirements (48).

Model Output

HEEM-II provides an array of graphical and tabular output for the particular highway segment under consideration as well as for the entire corridor. Table 8 summarizes the types of output that can be obtained from the model.

Application to Study 1108 Requirements

HEEM-II has the framework and data base for estimating the changes in traffic patterns and road user costs resulting from freeway construction options. The input requirements are reasonable and output from the model is detailed. The primary limitation of HEEM-II, from the perspective of Study 1108 requirements, is the level of precision in estimating traffic characteristics. Currently, traffic characteristics are estimated on a daily basis. As a result, HEEM-II could not analyze traffic management strategies in which the configuration of the work zone changes during the day; for example, freeway lanes may be closed only during off-peak hours. In addition, the estimation of traffic characteristics on a daily rather than an hourly basis affects the accuracy of those estimates. Memmott and Buffington (48) have recommended that HEEM-II be revised to evaluate highway improvements on an hourly basis, but this recommendation has not yet been implemented. HEEM-II would more closely satisfy Study 1108 requirements if that revision were made.

TABLE 7. INPUT DATA REQUIREMENTS FOR HEEM-II

Required Data

1. Characteristics of existing, proposed/expanded, and alternate highway routes in each segment
   a. Length of segment
   b. Highway type code
   c. Safety and technical performance factors
   d. Speed limit (conventional highways only)

2. Corridor ADT for current year and two projected years

3. Current year, and years for the two projected ADTs

4. Construction year and expansion year (if any)

5. Construction costs and expansion costs (if any)

6. Problem number

7. Segment number

8. Card number

9. Run type

Optional Data

1. General assumptions for problem
   a. Length of planning horizon (years)
   b. Percentage of trucks and buses
   c. Value of time for cars and trucks
   d. Inflation rate
   e. Construction cost escalation rate
   f. Discount rate
   g. Diversion route speed (urban and rural)

2. Route segment assumptions
   a. Percentage of trucks and buses
   b. Occupancy rates for cars/vans and trucks/buses
   c. Percentage of vehicles using HOV bypass
   d. HOV inconvenience cost per mile for vans/carpools and buses
   e. Adjustments to safety and technical performance factors

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Source: Memmott and Buffington (48)

TABLE 8. OUTPUT PROVIDED BY HEEM-II

Type of Data	Segment	Problem	System
1. All input data	yes	yes	no
2. Allocation of corridor traffic yearly (graphic and tabular)			
a. For do-nothing alternative	yes	no	no
b. For if-construct alternative	yes	no	no
3. Discounted benefits yearly (graphic and tabular)			
a. Hours of delay saved	yes	yes[a]	no
b. Delay savings	yes	yes[a]	no
c. Reduction in operating costs	yes	yes[a]	no
d. Reduction in accident costs	yes	yes[a]	no
e. Reduction in maintenance costs	yes	yes[a]	no
f. Total benefits	yes	yes[a]	no
4. Mobility of traffic yearly in miles/hr. and daily vehicle miles			
a. Whole corridor			
(1) For do-nothing alternative	yes	yes	yes
(2) for if-construct alternative	yes	yes	yes
b. State facility			
(1) For do-nothing alternative	yes	yes	yes
(2) For if-construct alternative	yes	yes	yes
5. Totals			
a. Present value of benefits	yes	yes	yes
b. Present value of construction costs	yes	yes	yes
c. Net present value	yes	yes	yes
d. Benefit-cost ratio	yes	yes	yes
e. Internal rate or return	yes	no	no
f. Delay savings	yes[b]	yes[b]	yes
g. Reduction in operating costs	yes[b]	yes[b]	yes
h. Reduction in accident costs	yes[b]	yes[b]	yes
i. Reduction in maintenance costs	yes[b]	yes[b]	yes

[a] only tabular discounted yearly benefits are presented for problem summaries
[b] totals are presented at the bottom of the yearly discounted benefits listing

Source: Memmott and Buffington (48)

FREQ

FREQ was developed in the late 1960's at the University of California - Berkeley to analyze proposed improvements to 140 miles of freeway in California (39). FREQ has been enhanced and modified several times, with the latest version being the 9th generation of the model. Its primary enhancements have been in the simulation of priority entry and priority lane improvements. The state of Texas has used the FREQ models (particularly the 6th and 7th generations) for the analysis of proposed transitway additions to freeways in Houston and Dallas (53-56). In addition, the state has designated FREQ as the preferred model for estimating traffic performance characteristics within a freeway corridor (53).

Traffic Management Schemes

FREQ defines the routes within a freeway corridor (mainlanes, frontage roads, alternative routes) using a link-node representation. The links are defined by their physical properties. Since a representation of the freeway corridor to be investigated must be "built" in the model, it would be possible to model nearly any type of work zone traffic management scheme.

Theoretical Basis

FREQ was designed to evaluate the impacts of various freeway configurations upon traffic in the corridor. It uses simulation to model traffic behavior, and then monitors various performance measures of the simulated traffic. The model is macroscopic, i.e., it simulates and monitors section-wide estimates of speed, flow, and density. FREQ uses the shock wave analysis procedure developed by Lighthill and Whitham (57) to model the effect of bottlenecks on traffic flow. FREQ models weaving areas using an algorithm patterned after the procedures in the 1985 Highway Capacity Manual (27).

FREQ also has algorithms to estimate spatial, modal and temporal diversion in the freeway corridor (58). An algorithm for spatial diversion uses an iterative technique to redistribute traffic when the difference between freeway and alternative route travel times exceeds a user-specified threshold. The model also allows for modal shift (diversion to high-occupancy vehicle modes) based upon differences in travel times between the alternative modes. Finally, three algorithms to estimate temporal diversion are included in FREQ. One algorithm estimates diversion to a different time based upon whether traffic conditions change travel times beyond a driver-perceived travel-time-difference threshold. Another, simpler approach that may be used is to shift the entire demand curve by some time interval. A final algorithm adjusts departure times in response to changing traffic demands so that arrival times remain approximately the same as before traffic changes.

Assumptions

There are a number of assumptions implicit in the FREQ formulations. Among the most important are:

1. Time is handled discretely, segmented in short uniform intervals

2. Within a given time slice, traffic conditions are uniform

3. Traffic demand, once loaded into the system, propagates downstream instantaneously link to link, unless the demand exceeds the capacity of the link. If this occurs, the excess demand is held over and added as input demand to that link for the following time slice

These assumptions allow FREQ to operate fairly efficiently. However, they also limit the accuracy of the results, especially when the model attempts to simulate severely congested conditions. When precision is critical, Cohen and Clark (59) have suggested that a dynamic model may be more appropriate. However, the model has performed well in many applications.

Input Data Requirements

The input data requirements to FREQ are summarized in Table 9. The supply characteristics data required to define the link-node representation of the corridor are extensive. Even more demanding is the origin-destination (O-D) matrix that is required for each time slice. The O-D matrix can be generated synthetically using the SYNPD2 module. Work with this module (60) has shown that errors in the O-D matrix have little effect on the traffic performance measures monitored by the program. It has been noted, though, that the synthetic O-D matrix tends to overestimate the number of short trips on the facility.

Since FREQ is a simulation model, it does require a significant calibration effort. Traditionally, this has been accomplished by modifying the link-capacities and then comparing output queue patterns with those actually measured in the field.

Model Output

The types of output available from a simulation run, for each time slice, are as follows:

1. Input data summary

2. Freeway performance summary, including

   - travel times through the system
   - average speed
   - delay
   - queue lengths
   - fuel consumption estimates
   - emission estimates
   - v/c ratio

3. Arterial performance summary (similar to freeway summary)

TABLE 9. INPUT DATA REQUIREMENTS FOR FREQ

Input	Freeway	Alternative Route(s)
Supply Characteristics		
Section Length	x	x
Number of Lanes	x	x
Gradient	x	x
Design Speed	x	x
Truck Factor	x	x
Capacity	x	x
Ramp Location	x	
Ramp Characteristics	x	
Ramp Metering	x	
Signalization Characteristics		x
Demand Characteristics		
[a]O-D Trip Table	x	
Vehicle Occupancy	x	x
[a]Volumes on each Link		x

[a]Needed for each time slice simulated

The following higher-level output forms are also available:

1. Arterial and ramp volumes

2. The speed-flow curve used in simulation

3. O-D tables (if generated synthetically)

4. Distribution of vehicle occupancy rates used

5. Contour maps of queueing effects on the facility

Application to Study 1108 Requirements

FREQ satisfies most but not all of the requirements for Study 1108. There are several advantages to using FREQ. It has a solid theoretical basis, and its assumptions should be valid for the level of detail required. It has been adopted by the state of Texas as a preferred model of traffic operations on freeways, and as such, several people in the SDHPT have knowledge of the model. The model has had considerable validation and application in the field.

There are also several disadvantages that must be considered. FREQ is fairly sophisticated and requires extensive input data and calibration. It is an operations model, and as such considers only operating characteristics. Modifications would be needed to estimate road user costs. FREQ relies on user-defined parameters and empirical formulations to estimate diversion away from the freeway. FREQ has been used in Texas primarily to evaluate the effectiveness of freeway improvements. It has the potential to estimate the traffic impacts of freeway reconstruction projects but has not been formally tested in such an application. The data collection and calibration efforts required to run FREQ may be justified only for the largest reconstruction projects. However, it may be desirable to test FREQ for a reconstruction project on a freeway for which the model has already been calibrated.

FREFLO

FREFLO is a macroscopic freeway simulation model that has been incorporated into the TRAF system of computer models currently supported by FHWA (61). FREFLO was developed by Payne (62) and is a successor to the MACK family of computer programs. The basic formulation of FREFLO was used in the development of FRECON and FRECON2 at the University of California - Berkeley to simulate and evaluate various control strategies for a freeway management system (63, 64).

Traffic Management Schemes

FREFLO uses a link-node representation to model the freeway. Thus, FREFLO should be able to examine a number of traffic management schemes. However, the user would have to adjust the various input parameters to accurately simulate conditions present at a work zone.

Theoretical Basis

FREFLO is a macroscopic, deterministic, dynamic model of freeway traffic. It is primarily an operations model, concerned with sectionwide estimates of speed, flow rate, and density on the freeway. The model is based on the law of conservation of vehicles within the system and a dynamic speed-density relationship (65).

FREFLO simulates freeway traffic conditions corresponding to user-defined ramp origin-destination volumes. It can adjust entrance ramp volumes, as part of a metering algorithm, based upon queue waiting times at the ramp but has no mechanism for reassigning the ramp traffic that is diverted.

The dynamic speed-density relationship has three key components: (1) a convection term that represents the influence of upstream traffic speeds upon speeds downstream, (2) a relaxation term that represents the desires of traffic to converge to an equilibrium speed, and (3) an anticipation term that accounts for the influence of downstream conditions on upstream speeds.

FREFLO has had problems in accurately predicting speed, flow, and density under congested conditions (66, 67). Several techniques and modifications have been considered in attempts to improve the accuracy of the model under congested conditions. Babcock (63) indicated that FREFLO could model at least moderate congestion if the freeway sections were divided into small intervals, i.e., 0.01 miles in length. However, this approach would lead to extremely long processing times for freeway segments of substantial distances. Payne (68) suggested that a discontinuous speed-density relationship should be used. Meanwhile, Rathi (69) addressed the problem by abandoning the dynamic speed-density relationship under congested conditions and placing flow restrictions on the congested links, from which speeds and densities were derived. These changes led to improved model performance and have been incorporated into the version of FREFLO currently supported by FHWA (69).

Assumptions

The most critical assumptions relate to the formulation of the convection, relaxation, and anticipation terms in the speed-density relationship for uncongested condition and to the use of flow restrictions in estimating speed and density under congested conditions. Alternative formulations have been proposed. For example, FREFLO uses an anticipation term expressed in terms of the downstream speed; whereas, the FREECON model uses a formulation by Phillips (70) in which the anticipation term is a function of the variance in downstream speed.

Input Data Requirements

As with nearly all freeway traffic simulation models, FREFLO requires an extensive amount of input data. These requirements are summarized in Table 10. Geometrics, in the form of a link-node representation of the section of freeway under consideration, must be provided. Traffic characteristics must also be supplied along with simulation parameters, ramp control parameters, and incident characteristics (if they are to be simulated).

TABLE 10. INPUT DATA REQUIREMENTS FOR FREFLO

Link Geometry Data
- Number of lanes
- Length
- Capacity
- Location of ramps
Traffic Data
- Density or speed at run initialization (by link)
- Upstream traffic volumes entering simulated section
- On-ramp volumes
- Off-ramp fractions
Simulation Parameters
- Speed-density relationship
- Parameters corresponding to the convection, relaxation and anticipation components of the speed-density relationship
Ramp Control Parameters
- Type of control
- Characteristics (metering rates, etc.)
- Diversion thresholds of proportions
Incident Characteristics
- Location of incident
- Time and duration of incident
- Nominal capacity around incident

Model Output

FREFLO provides a series of output forms and tables. These include:

1. Input data summary

2. Speeds, densities, and flows for each link and time interval

3. Emissions, fuel consumption for each link and time interval

4. Systemwide estimates of

    - travel time (ramp and freeway)
    - freeway travel times
    - ramp delay
    - diverted volume

5. Surveillance parameter estimates

Application to Study 1108 Requirements

FREFLO has a solid theoretical basis for simulating freeway traffic and, therefore, may be a viable option for analyzing reconstruction-related traffic impacts. However, there are several drawbacks to using the model. Considerable input data and calibration effort are required to run the model. The model has had problems simulating congested flow conditions and recent enhancements to improve its performance have not been thoroughly validated. FREFLO estimates freeway traffic characteristics including speeds, flow rates, densities, and travel times; but it does not estimate road user costs or queue lengths. FREFLO does not consider alternative routes in the freeway corridor and was not designed to estimate changes in traffic patterns.

INTRAS

INTRAS is a microscopic traffic simulation model that has its roots in the NETSIM model (71, 72). The original version of INTRAS is documented in a four volume report (73-76). FHWA currently has a project underway to upgrade INTRAS, entirely reprogramming it and making it modular in design. It is also hoped that the updated version will be more user-friendly than the original INTRAS. The restructured model is to be called FRESIM and should be available in early 1988 (59).

Traffic Management Schemes

INTRAS defines the freeway and surface street system using a link-node representation and should be able to model most work zone traffic management schemes by supplying the appropriate input data.

Theoretical Basis

INTRAS is a microscopic, dynamic model of traffic behavior on a freeway and surface street system. Individual vehicle-driver units are created, assigned appropriate attributes, and loaded onto the system to represent input flow to the segment of the system being modeled. Once loaded, the program tracks each unit's trajectory through the system and monitors segmentwide performance estimates. The creation of the vehicle-driver units and the assignment of the attributes to each unit are stochastic processes which represent the variations in driver response and vehicle performance characteristics.

The model is based upon a car-following algorithm, derived from NETSIM's crash-avoidance algorithm, and a lane-changing algorithm, derived from an algorithm developed at Northwestern (73). These algorithms simulate driver behavior in maintaining appropriate following distances and in selecting lane position as a function of destination, vehicle interactions, roadway geometrics, guide signing, and other traffic control devices.

INTRAS also has the capability to simulate ramp metering strategies, diversion from the freeway to alternative routes, and stop sign and signalized intersection control. The freeway diversion algorithm is empirical and requires the user to input the percentage of traffic that diverts from the freeway to other routes.

Assumptions

The fundamental assumptions in the model are that vehicle dynamics at a microscopic level can be adequately represented through the car-following and lane-changing algorithms. In turn, the algorithms themselves rely on a few assumptions, including desirable vehicle deceleration and acceleration rates. Most of the values used in the program do have some empirical support from various sources, but users must assume that these values apply to the specific set of conditions being modeled.

Input Data Requirements

INTRAS has been called "user-unfriendly" (59). The input data and calibration effort required to run the model are considerable. INTRAS is perceived as unfriendly primarily because of the complex algorithms and types of data required to simulate traffic at a microscopic level.

Table 11 summarizes input data requirements. In addition to these, numerous optional inputs may be entered to adjust the default values for various parameters in order to reflect the conditions being modeled.

TABLE 11. INPUT DATA REQUIREMENTS FOR INTRAS

	Freeway	Ramps	Surface Street (and Frontage Road)
Geometrics			
Link Lengths	X	X	X
Free Flow Speed	X	X	X
Number of Lanes	X	X	X
Grade	X	X	X
Curvature	X	X	X
Pavement Type	X	X	X
Superelevation		X	
Operational			
Signal Operations		X (ramp metering)	X
Turning Movements			X
Volumes	X	X	X
Diversion Strategy	X		
Incident Specifications	X		

Model Output

INTRAS has a large number of standard and optional output formats. The available forms of output include:

1. An input summary
2. Statistical reports and comparisons of delay, travel time, speed, volume, and density for each freeway link (similar reports for surface street links also include descriptive statistics of intersection operations including queues and cycle failures)
3. A speed and headway summary
4. A report of fuel consumption and emissions
5. Plots of vehicle trajectories and speed contours

Application to Study 1108 Requirements

INTRAS has most of the capabilities that are required to estimate the changes in traffic patterns resulting from freeway reconstruction options. INTRAS simulates traffic on a freeway and surface street system at a microscopic level. It reports traffic characteristics for each link but does not estimate road user costs. When enough effort is expended in parameter calibration, the model seems to be able to simulate traffic conditions quite well (59). Unfortunately, considerable expertise is required to calibrate the model. The level of effort required to satisfy the input requirements and to calibrate INTRAS may be justified on only the largest and most critical freeway reconstruction projects.

CARHOP

CARHOP (Computer Assisted Reconstruction--Highway Operations and Planning) was recently developed at the University of California - Irvine (77) to assist in the evaluation and assessment of the traffic disruptions caused by major reconstruction projects. The creators of CARHOP view it as a convenient tool for use by both traffic engineers and transportation planners in the selection of appropriate reconstruction plans and schedules.

CARHOP is not a new modeling procedure. Rather, it provides an interactive, menu-driven environment that facilitates the use of existing simulation and optimization programs. The CARHOP "environment" can be used to access several programs in the TRAF System (78), including FREFLO, a macroscopic model of freeway traffic; TRAFLO, a macroscopic model of arterial traffic; and TRAFFIC, an equilibrium traffic assignment model. In addition, CARHOP uses the TRANSYT-7F model (79) to optimize the signalized intersections in the arterial street system.

Traffic Management Schemes

The programs that can be accessed through CARHOP use a link-node representation of the transportation network. The CARHOP environment provides the capability of building a base network and then modifying the network to generate several "scenarios" that represent particular traffic management strategies. It is possible, for instance, to identify detour routes for short and long-term operations, and subsequently to analyze the effect of the detour relative to the base condition. Nevertheless, it is the responsibility of the user to input appropriate speeds, capacities, and curvature on a link-by-link basis to model a particular traffic management scheme.

Theoretical Basis

CARHOP is simply a tool that facilitates the use of other models. It does not possess its own theoretical basis but employs the theoretical basis of those models. It uses macroscopic models of freeway and arterial traffic flow, an equilibrium traffic assignment model, and a network model for optimizing signal timing.

Assumptions

The most important component of CARHOP, from the perspective of Study 1108 requirements, is the use of FREFLO to model freeway traffic operations and the use of an equilibrium traffic assignment model to allocate traffic among alternative routes in the freeway corridor. The assumptions in FREFLO were discussed earlier. The assumptions underlying equilibrium traffic assignment were identified in the discussion of PASSER IV.

Input Data Requirements

Inputs to CARHOP consist primarily of the data needed to create the link-node representation of the transportation system. CARHOP uses this general representation, along with the user-supplied modifications, to evaluate scenarios for various traffic management strategies. Obviously, the requirements of each of the programs used by CARHOP must be met. Much of the same input data can be used by the different programs, eliminating redundancy; in fact, a primary advantage of CARHOP is to coordinate and manipulate the same data for use by the different programs.

It is not evident from the available literature on CARHOP (77) whether all of the program-specific input requirements must be supplied by the user when the data base is created or whether CARHOP provides default values which may be accessed and modified by the user to simplify input. In some cases, CARHOP uses the output of one program as input for another. For instance, the TRANSYT-7F program may generate optimized signal timing plans which are input into TRAFLO to simulate the arterial network with optimal signal timings.

Model Output

Output from the various programs is recorded, categorized, and summarized in the CARHOP environment. A summary of the input data is provided. Next, typical performance statistics, including travel time, average speed, vehicle trips (to identify changes in travel patterns), and vehicle miles are compared on a link-by-link, subnetwork-by-subnetwork, and global-by-global network basis. Estimates of diverted or detoured traffic, derived via the application of equilibrium traffic assignment, are also presented.

Application to Study 1108 Requirements

CARHOP is essentially a data base manager and program executor for applying some of the standard TRAF programs to modeling freeway reconstruction scenarios. The limitations of CARHOP are the same as those of the programs it supports. Specifically, the model is designed around an operational evaluation format and economic measures have not been included. A number of modifications and additions would be necessary to generate the economic measures desired.

CARHOP is an advancement in the use of simulation to analyze the traffic impacts of maintenance and reconstruction activities. CARHOP has had limited testing on a freeway reconstruction project in Los Angeles. However, the extensive input requirements and expertise required to calibrate the models to reflect actual work zone conditions make its use time consuming and complex.

4. REVIEW OF LITERATURE ON WORK-ZONE-RELATED TRAVEL IMPACTS

This chapter reviews the literature on work-zone-related travel impacts that may be useful in upgrading existing procedures for estimating the magnitude of those impacts. First, the estimation of important traffic flow characteristics is discussed. Second, the response of drivers to work-zone-related delays is considered. Third, the estimation of road user costs is reviewed.

Traffic Flow Characteristics

The magnitude of changes in traffic flow characteristics resulting from freeway construction options is influenced primarily by (1) the capacity of the affected freeway segment under both normal and work zone conditions and (2) the demand volume approaching the freeway segment. A work activity that requires lane closures or reductions in lane and shoulder widths represents a bottleneck whose capacity is less than that of the upstream and downstream segments. The work-zone-related bottleneck will cause reductions in average speeds and, when demand volumes exceed work zone capacity, the development of queues. Delays increase as the difference between demand volumes and work zone capacity increases. However, as delays grow, increasing numbers of approaching vehicles divert away from the freeway to avoid the work zone. Therefore, the keys to the accurate estimation of the traffic impacts of freeway construction activities are knowledge of the capacity and demand volumes for the affected freeway segment and of the response of drivers to work-zone-related delays.

Normal and Work Zone Capacity

The 1985 Highway Capacity Manual (27) is the principal reference for capacity-related information. The procedures for estimating freeway capacity under normal conditions are based upon a long history of research results and are widely accepted. The 1985 edition is the first edition of the Manual that has included material on the capacity of freeway work zones. The procedures for estimating work zone capacity are based upon a more limited data base and are relatively new. Therefore, this section concentrates on the issue of work zone capacity. The material on work zone capacity in the 1985 Manual (27) is drawn primarily from studies by Dudek and Richards (32, 33) and Kermode and Myyra (80).

Dudek and Richards (32, 33) reported the average and the distribution of observed work zone capacities for various lane closure configurations based upon a total of 41 capacity studies at 28 maintenance and construction zones in Texas. A configuration is defined as a combination of the number of lanes in one direction under normal conditions and the number of lanes open in one direction through the work zone. The variation in observed work zone capacities for a particular lane closure configuration can be attributed to several factors, including the geometry (proximity to ramps, vertical and horizontal alignment) and design speed of the work zone, the percentage of trucks in the traffic stream, and the type and intensity of work activity. No attempt was made to analyze statistically the effect of these factors because of the limited data base that was available.

Kermode and Myyra (80) reported observed work zone capacities for several lane closure configurations as a function of the type of operation underway. They caution that their estimates were based upon "a very limited amount of data" for some typical maintenance and construction operations on freeways in the Los Angeles area in the late 1960s. They do not report the geometry or percentage of trucks for which their estimates apply.

Dudash and Bullen (81) measured flow rates at the entrance and exit portals of the Squirrel Hill Tunnel on the Penn-Lincoln Parkway East in Pittsburgh during the reconstruction of the Parkway. The Tunnel consists of two, two-lane directional tubes. Flow rates were measured in the right lane of the eastbound tube under three operating conditions: (1) normal two-lane, one-way flow, (2) one-lane, one-way flow with the left lane closed, and (3) two-lane, two-way flow with westbound traffic using the left lane. Dudash and Bullen (81) report flow rates that agree reasonably well with the capacities reported by Dudek and Richards (32, 33) for similar lane closure configurations.

An issue related to capacity is the relationship between average speed and volume-to-capacity ratio. The 1985 Manual (27) quantifies this relationship for normal operating conditions. However, a question has been raised as to whether the same relationship applies under both normal and work zone conditions. In 1974, Butler (28) compared speeds and volumes measured at work zones with the basic speed-volume relationship presented in the 1965 Highway Capacity Manual (25) and concluded that "There was tremendous scatter of the speeds at particular volumes around the capacity manual curves, but no reason not to adopt the capacity manual curves." More recently, in 1985, Rouphail and Tiwari (30) studied speeds and flow rates at single-lane closures on four-lane divided highways in Illinois in an attempt to estimate the effect of the intensity of work activity on observed speeds. They compared the speed-flow relationship for the work-zone data with the relationship presented in the "Interim Materials on Highway Capacity" (31), and concluded that the mean speeds they observed at four single-lane closures averaged 3 mph slower than the mean speed estimated from the speed-flow relationship in the "Interim Materials" (31) at the same volume, lane width and lateral clearance, and percentage of trucks. Additional research will be necessary to determine whether the speed-volume relationship in a work zone is indeed the same as or different from the speed-volume relationship that applies to normal freeway operations.

Queueing Characteristics

When demand volumes exceed work zone capacities, queues form upstream of the work zone. The two standard macroscopic techniques for modeling the formation of queues and estimating the magnitude of delays are input-output analysis and shock-wave analysis.

Input-output analysis is the technique presented in the 1985 Manual (27) for estimating queue lengths and delays due to bottlenecks. Abrams and Wang (29) also use input-output analysis for estimating queueing due to work zones in their procedures for planning and scheduling work zone traffic control. Both QUEWZ and FREWAY use input-output analysis to estimate queueing characteristics.

Shock-wave analysis was developed by Lighthill and Whitham (57) for describing the changes in flow characteristics along a roadway and particularly upstream of a bottleneck. Messer, Dudek, and Friebele (83) used shock wave analysis to predict travel times on an urban freeway under incidents conditions. FREQ uses shock wave analysis to model queueing.

Additional research will be necessary to compare the accuracy of the two techniques in replicating work zone situations.

Driver Response to Work-Zone-Related Delays

If the appropriate work zone capacity and speed-volume relationship can be identified so that work-zone-related delays can be estimated, the next critical question is how drivers will respond to that level of delay. More specifically, the relationship between the level of delay due to a freeway maintenance or construction activity and the percentage of traffic that diverts away from the freeway work zone must be determined.

This section reviews two analytical techniques for estimating the impacts of freeway maintenance and construction activites upon driver route choice and overall travel patterns in the freeway corridor. First, the driver decision-making process and subsequent behavior (with respect to diversion) is examined, along with a review of the recent and ongoing research in this area. Then, two possible techniques for estimating diversion are reviewed.

The Driver Decision-Making Process

Before presenting the methods available for estimating diversion, it is necessary to provide some background on the current understanding of the driver decision process. This background is important both to understand the observable behavior (i.e. route choice and departure time decisions) and to identify the major assumptions inherent in current traffic assignment methodologies.

Perhaps the most fundamental principle about driver route choice and tripmaking behavior is that of user optimization. The principle, originally proposed by Wardrop (37), states that individuals have fixed origins and destinations on a trip and that they seek paths from origin to destination that minimize their travel times. Researchers and practitioners subsequently expanded the principle to include the minimization of travel costs, of which travel time is the primary, but not the only, component. Other viewpoints of the user optimization principle also exist; some of these will be identified later, in the discussion of equilibrium traffic assignment.

Application of the user optimization principle to traditional traffic assignment methodologies has required some significant simplifications about driver perception and knowledge of conditions in the transportation system. For example, it is assumed that as drivers proceed to their destination, their perceived travel time and costs are equal to those actually experienced or calculated using traffic engineering techniques. This simplification has been necessary primarily because of the lack of understanding (and available data) as to how driver perceptions relate to the real world. However, Clark (83) has examined the validity of this simplification and suggested that there are significant differences between perceived and actual travel times.

Application of the user optimization principle also assumes that drivers have complete knowledge of actual operating conditions on all facilities in the transportation system prior to the selection of route and departure time. Given this "perfect" knowledge, drivers then optimize their tripmaking decisions.

In the traditional traffic assignment applications, the simplifying assumptions of user optimization are fairly well accepted. It is believed that drivers "learn" about the performance characteristics of the transportation system over a period of time and distribute themselves throughout the system to achieve a user-optimized condition. In effect, drivers develop the knowledge necessary to optimize their tripmaking decisions. When only the final optimized distribution is of concern, the simplifying assumptions described earlier can be accepted.

A problem arises, however, when work zone activities or incidents disrupt the normal operating conditions on a facility. In such cases, the driver does not have complete information about conditions throughout the system and the simplifying assumptions are not necessarily valid. In this context, it is necessary to go back and reconsider the decision-making process with regard to driver tripmaking behavior.

Recently, Mahmassani and his colleagues have begun investigating the dynamics of driver judgement and choice with respect to the tripmaking behavior (84, 85). His efforts, though, have focused on how commuters adjust their departure time in response to peak period congestion. One interesting result has been a better understanding of how a driver's previous personal experience and knowledge of past operating conditions influence tripmaking decisions, and conversely, how the individual tripmaking decisions of a group with similar past experience and information about conditions collectively affect operating conditions on a system. This work is in the early stages and much more research will be necessary to achieve a full understanding of this process.

Equilibrium Traffic Assignment

Equilibrium traffic assignment is a well established procedure based on the user optimization principle. This procedure assigns vehicle trips to routes in a transportation network so that all vehicles with the same origins and destination have the same utility (costs, delay, travel time) and that no vehicle can improve upon its utility or disutility by taking another route. Generally speaking, the assumptions about drivers' perception and complete knowledge of operating conditions underlie the assignment process.

Initial attempts at equilibrium traffic assignment were based on user optimization of travel time. The measure was eventually modified to include travel costs (48). Recent developments and improvements of equilibrium assignment have included consideration of time-dependent demand (86, 87), departure time and route choice together in a single, unified framework (88), and the effects of limited user time and money resources on tripmaking behavior (89).

An inherent difficulty exists in the application of this assignment principle to a transportation network. Driver tripmaking choices depend on operating conditions (such as travel times) in the system. However, operating conditions depend on the collective tripmaking choices made by drivers. This interdependency can be solved by (1) nonlinear programming techniques or (2) iterative convergence techniques. For the most part, the iterative methods tend to dominate in traffic engineering applications, basically because past electronic computing capabilities did not have the power to handle the nonlinear programming requirements of a system assignment in a cost-efficient and timely manner.

For iterative solutions, estimates of free-flow operating conditions throughout the system are computed and then used to assign each individual trip to the "best" route through the system. The operating conditions are recomputed as though these initial assignments were in the system; this is followed by a reassignment of traffic based on these new operating conditions. This process is repeated a number of times until the assignment adequately converges to a solution.

In typical nonlinear programming formulations, an objective function, representing the goal of user optimization, is constructed. This is followed by a series of constraint equations to limit individual trips to only one path and to eliminate unacceptable paths. Typical nonlinear programming solution techniques are then applied. A recent comparison (90) of iterative versus nonlinear programming assignment indicated that nonlinear programming solutions provided better assignment results with equal or less computational effort (time) than iterative solutions. However, the nonlinear technique is more difficult to comprehend, and most practitioners do not have enough experience with the technique to use it effectively and efficiently.

Traffic Assignment in Freeway Corridor Analysis

Several of the computer models reviewed in Chapter 3 use equilibrium traffic assignment in analyzing a freeway corridor. PASSER IV (36) takes the simplest approach, which loosely follows the quick-response methodologies presented in NCHRP Report 187 (91). The model is based upon the minimization of travel time. Travel times are estimated using a piecewise linear relationship between travel time and the volume-to-capacity ratio for each roadway type (freeway, frontage road, alternate route). These relationships guide the assignment of vehicle trips to the roadways in the corridor such that travel times on each route are equal.

A more sophisticated approach is found in the CORCON model (41). The model predicts traffic volumes, travel times, and queueing characteristics within the freeway corridor. A simplified link-node representation is used to model the roadway system within the corridor. The program assigns traffic thoughout the corridor to computed minimum travel-cost paths in a user optimization process. CORCON requires an extensive origin-destination matrix as input to the analysis. Because the model is proprietary, validation and application examples are somewhat limited.

Finally, the TRAFFIC model which can be accessed through the CARHOP environment (77) is the traffic assignment algorithm supported by FHWA as part of the TRAF modeling system. TRAFFIC is a user-equilibrium-based traffic assignment model.

Delay Tolerance

Delay tolerance is another concept that can be used to predict how drivers respond to changes in operating conditions resulting from freeway reconstruction activities. It is based on the premise that drivers will tolerate a certain amount of delay (measured as the additional travel time on their primary travel route), beyond which they will seek out and divert to alternative routes. The concept of tolerable delay has been applied to several instances of planning and scheduling work zone traffic control (92-94).

A few studies have attempted to quantify delay tolerance. These studies have relied on subject responses to questionnaires; no operational data have been collected. An early study (95) asked drivers in Los Angeles, St. Paul, and College Station, at what level of delay they would divert to an alternative route. The results indicated that a majority of drivers would divert if delays exceeded 20 minutes. Interestingly, the value was consistent across all three geographic areas. Another interesting result was that there existed a group of drivers who would not divert, regardless of the level of delay specified.

Another study of similar design was conducted using freeway drivers in Houston, Texas (96). In this scenario, drivers were told they were on a freeway and that parallel frontage roads, a design prevalent in Texas but not elsewhere, were present. Given this information, most drivers responded that they would divert to the frontage road when delays exceeded only 5 to 10 minutes, rather than the 20 minute value found previously. The apparent discrepancy in the later survey results were attributed to the fact that the subjects were experienced freeway drivers and were familiar with using frontage roads as convenient diversionary routes. The earlier study did not specify the availability of such frontage roads.

Recent enhancements to the QUEWZ model (97) included an algorithm which estimates diversion based on a delay tolerance of 20 minutes. However, this algorithm has not been validated against actual field conditions.

Limitations of Equilibrium Assignment and Delay Tolerance

As discussed previously, equilibrium traffic assignment relies upon simplifying assumptions about driver perception and knowledge of the operating conditions on all potential travel routes from origin to destination. When long-term freeway reconstruction efforts result in consistent and severe degradation of operating conditions on the freeway, equilibrium traffic assignment may be useful as a tool for predicting the travel pattern changes throughout the transportation system because drivers are able, over a period of time, to "develop" the knowledge of conditions throughout the system. Janson et al. (98) tested the use of an equilibrium traffic assignment model to estimate the impacts of the Parkway East reconstruction project in Pittsburgh and reported marginally acceptable results. However, for estimating diversion arising from maintenance or construction activities that are not consistent in time or location (as is the case with many freeway work activities), the assumptions underlying equilibrium traffic assignment do not appear to be valid.

Delay tolerance does not rely on the simplifying assumptions inherent in equilibrium assignment. Drivers are assumed to tolerate a certain amount of delay before seeking alternative routes; the amount of delay tolerated would intuitively reflect driver perception of travel times (and/or costs) on the various routes as well as other factors which affect driver decision-making. (For instance, some drivers may desire to remain on primary routes and to avoid routes with signalized intersections.) Unfortunately, very little data on this topic has been collected. The data that has been collected (i.e. subject questionnaires) do not reflect how drivers perceive delay in real world settings and whether their responses reflect their actual driving practices. This type of data will be needed before the delay tolerance methodology can be used effectively to estimate and understand diversion.

Equilibrium traffic assignment and delay tolerance are the best methodologies currently available to estimate traffic diversion resulting from the changes in operating conditions arising from freeway reconstruction activities. This is not to say that other models for freeway corridor analysis or even traffic assignment do not recognize diversion as a real and significant occurrence. In fact, some do attempt to take diversion into account. However, the approach taken is generally to have the user specify the amount of diversion that is going to occur, from which the model then estimates its impact upon operating conditions in the corridor. The algorithms used to estimate diversion in these types of models vary dramatically, from a simple percentage of approach demand (99, 100) to exponential parameters requiring extensive calibration (41).

Road User Costs

Changes in freeway operating conditions translate into changes in road user costs. Road user costs have three basic components: vehicle running costs, travel time costs, and accident costs. The additional road user costs due to a freeway construction activity are the difference between the costs on the freeway segment under normal operating conditions and under work zone conditions.

Vehicle running costs and travel time costs are a function of the speed profile of traffic along the roadway. The standard procedures for estimating these costs are presented in AASHTOs A Manual on User Benefit Analysis of Highway and Bus-Transit Improvements (101). The procedures are based upon empirical data from various sources. QUEWZ uses these standard procedures for estimating vehicle running and travel time costs under both normal and work zone conditions.

QUEWZ does not include accident costs in its estimates of the total additional road user costs due to the work zone activity because of the lack of data on the changes in accident rates through work zones. Since the mid-1970s, studies of vehicle accident characteristics in work zones have been conducted in Texas (102), as well as in Virginia (103), Ohio (104), and North Carolina (105); however, these studies reported only the frequency of accidents by type in highway work zones. Graham, Paulsen, and Glennon (106) examined accident rates on highway segments before and during construction projects at 79 work sites in seven states. They reported an average increase in accident rates during construction of 6.8 percent. However, the variability of the changes in accident rates from project to project was tremendous: "31 percent of the projects experienced decreased accident rates during construction," whereas "24 percent of the projects experienced increases of 50 percent or more" (106). Additional research will be needed before reasonable estimates can be made of the changes in accident rates and costs associated with various construction activities and traffic management strategies.

Recommendations for Additional Research

Several areas have been identified in which additional research will be needed in order to improve estimates of the magnitude of work-zone-related traffic impacts. These include work zone capacities, speed-volume relationships in work zones, the appropriate analytical techniques for modeling queues resulting from work zone bottlenecks, the response of drivers to work-zone-related delays, and changes in accident costs during freeway construction activities. Additional data in each of these areas will be collected as part of Study 1108.

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