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**Effectiveness of Accelerating Highway
Rehabilitation in Urban Areas**

SWUTC/95/60058-1



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**EFFECTIVENESS OF ACCELERATING
HIGHWAY REHABILITATION
IN URBAN AREAS**

by

Eduardo Trujillo Olguin, Brent T. Allison, and B. Frank McCullough

Research Report SWUTC 60058-1

Research Project 60058

Energy Consumption Related to Excessive User-Delay During Highway Rehabilitation

conducted by the

CENTER FOR TRANSPORTATION RESEARCH

Bureau of Engineering Research

THE UNIVERSITY OF TEXAS AT AUSTIN

March 1995

ABSTRACT

The purpose of this research report is to establish guidelines for identifying highway rehabilitation projects warranting acceleration within Texas. Reduction in the total number of days allocated for project completion is recommended if savings in user costs are greater than the additional costs of accelerating the project. Throughout this report, the short-term impacts to road users and the environment were analyzed, and methods for quantifying user costs were reviewed. The potential consequences of accelerating rehabilitation projects were also presented. A methodology to estimate additional construction costs was developed to assess the effectiveness of accelerated construction schedules. Finally, recommendations are made to identify candidates within the Texas Highway system for expediting highway rehabilitation by means of threshold traffic volumes warranting project acceleration.

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EXECUTIVE SUMMARY

This research effort was conducted in order to examine the energy consumption related to excessive user delay during highway rehabilitation. Under certain circumstances the acceleration of highway rehabilitation can be a benefit, in terms of energy, time, and production costs to the citizens of Texas. The purpose of this research report is to present guidelines that help to identify candidates for accelerated highway rehabilitation strategies.

This will be accomplished by examining the short-term impacts generated by highway rehabilitation on the several parties impacted by the rehabilitation process. Because these impacts are a function of the traffic-handling techniques used, a review of common types of work zones is also presented. Next, a review of the existing methodologies used to quantify the adverse impacts on road users from highway rehabilitation will be examined. The resulting data is then used in economic analyses of alternatives. The next section is concerned with acceleration strategies that mitigate the impacts generated by rehabilitation activities. An examination of the several potential consequences of accelerating rehabilitation projects is presented. This analysis is focused on determining how the cost of the project is affected by acceleration. There is also a methodology established for evaluating the effectiveness of accelerating rehabilitation projects as a mitigation measure for total user costs and fuel consumption. This methodology, presented in the former chapter, is applied to a factorial experiment. Guidelines for identifying projects warranting acceleration are developed in this from this. Finally, conclusions and recommendations are presented in the final chapter.

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CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

As the U.S. Interstate Highway Program nears completion, and as vehicular traffic continues to grow in urban areas, state and national highway officials must increasingly turn their attention away from the building of new facilities to the rehabilitation of older ones (Ref 1.1). The need for improvements is likely to continue well beyond the year 2000 for more than 40 percent of the Interstate highways and for about 70 percent of the arterials (Ref 1.2).

Unfortunately, highway rehabilitation activities undertaken on Texas' major freeways, especially in urban areas, create temporary negative impacts on road users, adjacent property owners, and the environment. Highway users are affected by increased travel times and operating costs resulting from excessive delays, as well as the need to reduce vehicular speeds within the construction site. At the same time, property owners often experience a reduction in business revenues owing to restricted or inconvenient access to their businesses. And finally, the increased congestion and fuel consumption resulting from construction delays can compromise air quality through a concomitant increase in tailpipe emissions.

Construction activities can also adversely impact the supervising highway agency — especially when traffic operations must be maintained during the project. If the agency, represented in Texas by the Texas Department of Transportation, does a poor job of handling the conflicts between construction activities and traffic operations, then the agency's credibility with the public can be impaired. And contractors may lose efficiency and productivity because of a lack of space for construction operations (Ref 1.3).

Because of their ostensible convenience and their array of abutting commercial development, Texas' urban freeways typically carry large volumes of traffic. During rehabilitation projects, competition for space takes place between traffic operations and construction activities. When a limited right of way exists, the facilities under rehabilitation experience severe congestion, even if only a small portion of the road is temporarily closed.

The Texas Department of Transportation has recognized that the initial cost of construction, along with the ongoing maintenance costs, is not the only budgetary considerations involved in selecting the best alternative for rehabilitation projects. Highway user costs, including vehicle operating costs, travel time costs, and accident costs, must be considered when total life-cycle cost analyses are used to evaluate rehabilitation alternatives (Ref 1.4). The costs of improving the highway network are usually justified by the long-term benefits that accrue to road users and to the community. Reduced vehicle operating costs, reduced travel times, enhanced economic development, and increased property values are among the long-term benefits.

However, special attention must be given not only to long-term benefits for road users and the community, but also to those temporary negative impacts associated with

construction activities. The severity of these short-term impacts on users, property owners, and the environment is related to (1) the traffic volumes disrupted while the facility is under rehabilitation, and (2) the duration of such disruption. As shown in Figure 1.1, highway user costs increase during rehabilitation and reconstruction operations. These user costs are the sum of three main components: vehicle operating costs, user travel-time costs, and accident costs. Even though highway improvements reduce long-term user costs, potential temporary increases in congestion, fuel consumption, and vehicle emissions can be extremely significant if available measures to mitigate such negative impacts are not applied at the right time or to the proper extent.

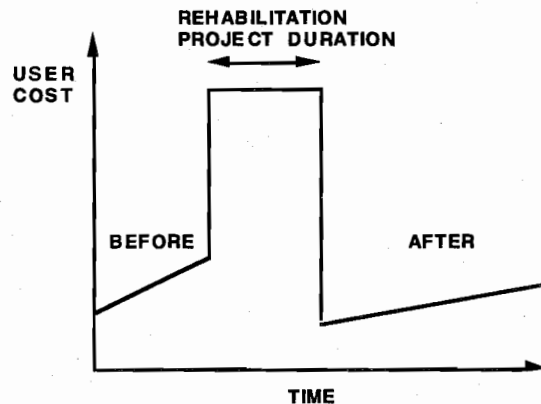


Figure 1.1. Highway user costs affected by rehabilitation activities (Ref 1.5).

Other negative impacts (in addition to increased user costs) also vary in accordance with the duration of the project and the traffic handling strategy used during highway rehabilitation. Potential negative effects of highway rehabilitation activities, which have been identified in past research (Refs 1.1, 1.3), are summarized as follows:

- a) Increased vehicle operating costs, including increased fuel consumption as a result of excessive idling, stop-and-go driving conditions, and longer alternative routes.
- b) Increased user-delay costs resulting from induced congestion.
- c) Increased safety costs (both for traffic handling requirements and increased likelihood of accidents).
- d) Increased environmental costs (i.e., the air pollution that results from excessive vehicle emissions during congested periods).
- e) Constrained access to adjacent commercial property that reduces potential revenue earnings during the construction period.
- f) Interference with third parties, such as utility owners or delivery companies, whose services might be restricted by construction activities.

There are techniques to quantify some of the negative effects of rehabilitation, including user delays, fuel consumption, and vehicle emissions. To mitigate other negative impacts, such as a loss of business by adjacent commercial property, researchers must rely on subjective evaluations of local experience (Ref 1.3). There are two common practices used for mitigating the negative effects of highway rehabilitation activities. The first of these practices involves avoiding conflicts between construction activities and traffic operations by conducting construction during low-demand periods or by diverting traffic to other routes. The second most common practice used for expediting construction involves reducing the duration of the project and, thus, diminishing the temporary negative effects caused by the rehabilitation (Ref 1.3).

Project duration affects the total project cost, since user costs and the administrative costs increase linearly with time, while the construction costs increase as the duration of construction is reduced (Ref 1.4). Figure 1.2 shows the effect of project duration on the total project cost.

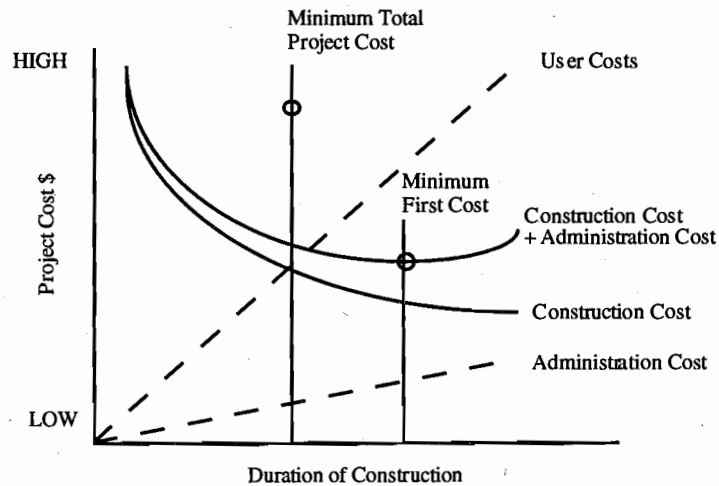


Figure 1.2. Effect of project duration on the total project cost (Ref 1.4).

1.2 OBJECTIVE OF STUDY

Research study 60058, "Energy Consumption Related to Excessive User Delay During Highway Rehabilitation," was conducted in order to analyze the relationship between the excess fuel consumption resulting from highway rehabilitation in Texas and the increased construction costs resulting from expediting the entire construction schedule. If the costs associated with the energy wasted by motorists idling on the freeway could be quantified, the cost of modifying the construction schedule might be justified and, thus, be a great benefit to the citizens of the state. The study has the following objectives:

1. For various traffic levels, estimate both the quantity and costs of fuel consumed by motorists experiencing excessive travel delays caused by highway rehabilitation.

2. For identical construction scenarios and traffic levels, estimate the additional construction costs that would be incurred if congestion was expedited and/or forced to off-peak hours.
3. Compare the costs identified in objectives 1 and 2 and then, using the results, develop guidelines for engineers to follow when developing construction schedules.
4. Determine the feasibility of incorporating these guidelines in a computer model that could be used by engineers to balance the trade-off between energy consumed during user delays and the cost of modifying the construction schedule.

Increased fuel consumption, however, is only one of several negative impacts caused by highway rehabilitation activities. In highly trafficked corridors, highway rehabilitation can result in excessive user delays, increased vehicle operating costs, potential accidents for both motorists and working crews, increased tailpipe emissions from vehicles, and potential loss of revenues to adjacent businesses.

The temporary negative impacts of rehabilitation projects rise in proportion to the traffic that uses the facility. The more traffic volume expected to use the facility, the higher the cost per day of such negative impacts. These negative effects increase excessively at a certain level of traffic, necessitating the acceleration of the rehabilitation project. The following graph shows the relationship between traffic volumes (ADT) and daily costs of negative impacts resulting from rehabilitation activities. These costs are a function of the traffic volumes, hourly traffic distribution, traffic composition, speed of vehicles approaching and passing through the work zone, the work zone configuration, and the number of hours of actual work.

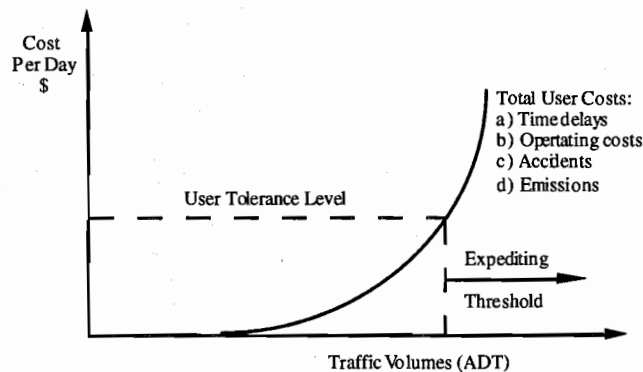


Figure 1.3. Relationship between traffic volumes (ADT) and daily costs of negative impacts due to rehabilitation activities.

Highway users, however, are not willing to accept increased travel costs and delays for long periods of time or over a certain dollar amount. Because the degree of tolerance that highway users may accept varies from one project to another, estimates of user tolerance are based on intuition conditioned by local experience (Ref 1.3). These levels of

tolerance also apply to the rate of vehicle emissions that can be allowed before expediting of the construction process becomes imperative.

The number of days for significant user and environmental costs to accumulate is directly related to the amount of traffic traveling through construction zones (Figure 1.4). Therefore, if acceptable user and environmental costs could be established, the number of days within the tolerance level could be determined. As a result, rehabilitation projects lasting longer than the number of days within the tolerance level for user and environmental costs require the implementation of expediting construction strategies.

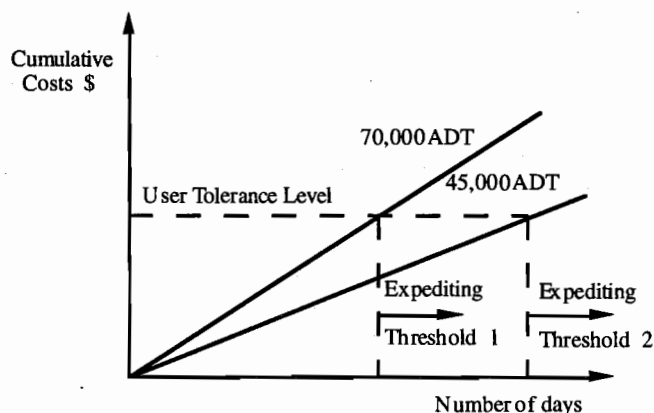


Figure 1.4. Relationship between traffic volumes and the number of days required to reach tolerance in user and environmental costs.

The purpose of this research report is to document the development of guidelines to identify suitable projects warranting implementation of accelerated construction schedules within Texas. Accelerating highway rehabilitation could be justified by comparing existing traffic volumes with those given in the guides as the minimum volumes required before expediting construction is recommended. In this fashion, the cost of expediting construction can be justified by the reduced negative impacts to road users and the environment, if the expected traffic volumes are greater than those provided in the guides for a range of work zone configurations.

1.3 REPORT ORGANIZATION

This research report consists of eight chapters. Chapter 1 is the introductory chapter. Chapter 2 describes the short-term impacts of highway rehabilitation projects on the several parties involved, including those who use the facility or are serviced by it. Because these impacts are a function of the traffic-handling techniques used, a review of common types of work zones is also presented. Chapter 3 deals with existing methodologies used to quantify the adverse impacts on road users from highway rehabilitation; the resulting data are then used in economic analyses of alternatives. Chapter 4 is concerned with strategies that mitigate those impacts generated by rehabilitation activities. Chapter 5 analyzes several

potential consequences of accelerating rehabilitation projects. This analysis focuses on determining how the cost of the project is affected by acceleration. Chapter 6 establishes a methodology for evaluating the effectiveness of accelerating rehabilitation projects as a mitigation measure for total user costs and fuel consumption. Chapter 7 applies the methodology presented in the former chapter to a factorial experiment. Guidelines for identifying projects warranting acceleration are developed in this chapter. Finally, conclusions and recommendations are presented in Chapter 8.

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CHAPTER 2. SHORT-TERM IMPACTS FROM HIGHWAY REHABILITATION IN URBAN AREAS

2.1 BACKGROUND

Higher traffic volumes and heavier vehicles have increased highway network deterioration. Unfortunately, the sections of the highway system suffering the most are those associated with high mobility and heavy traffic, and whose infrastructures are rapidly aging. Therefore, many of these sections require major rehabilitation and reconstruction to preserve the integrity of the system. Moreover, most of the major freeways in large urban areas already operate under saturated conditions for long periods every day. Consequently, furnishing adequate space for reconstruction activities, while minimizing delays and property inaccessibility, is a challenging task for transportation agencies (Ref 2.1).

Highway rehabilitation and reconstruction commonly require a minimum of several weeks and may involve multiple construction seasons. A basic characteristic of long-term work zones is that traffic control strategies must (1) accommodate both daytime and nighttime conditions, and (2) provide a safe and expeditious traffic flow throughout the conflict zone. The type of traffic control adopted for a specific rehabilitation project has been dependent on the work involved and regulated by uniform standards and guidelines (e.g., the Manual on Uniform Traffic Control Devices). The main purpose of such traffic control standards is to enhance safety at work zones, both for road users and work crews. The magnitude of the short-term negative impacts of highway rehabilitation projects on road users and adjacent businesses (including user delays, increased operating costs, and emissions from vehicles), depends on the type of traffic control as well as on the duration of the project.

The common practice of adapting traffic to the work zone by establishing a standard traffic control plan is becoming obsolete for major travel corridors in urban areas. A different approach must be established in these corridors, one in which the work zone is adapted to the traffic conditions (Ref 2.4). Alternative traffic control strategies must be analyzed to identify the one that generates the least impact on users and adjacent businesses. Also the issue of safety comes into play in areas with high volumes of traffic. The most common traffic control strategies for highway rehabilitation are summarized below.

2.2 TRAFFIC HANDLING TECHNIQUES

In urban environments, there are alternative ways for securing a portion of the roadway when conducting reconstruction activities. Closures may involve a shoulder, one or more lanes, a whole direction of the highway, or even the entire highway. Heavy traffic demands on urban freeways, however, prevent the use of dramatic closures, given that traffic operations must be maintained throughout the rehabilitation work. The most common

closure strategies related to highway rehabilitation activities include lane closures, lane alterations, median crossovers, and detours (Refs 2.3, 2.4, 2.7).

2.2.1 Lane closure

A lane closure forces the traffic stream to merge into another lane (leaving the closed lane). Because this strategy reduces the total number of lanes, a careful analysis is recommended to determine whether serious congestion and delays will result from the lane closure. Closing an auxiliary lane, such as a turn bay or a deceleration lane approaching an off ramp, is not considered a lane closure, since the number of available lanes is not reduced.

On multilane facilities, more than one lane may need to be closed to conduct the required rehabilitation work. If two or more lanes are to be closed, a common practice is to close them one at a time, leaving a minimum length between each closure for speed reduction and merging operations. If the work zone is located on a central lane of a multilane facility, it is recommended that the adjacent outer lane be closed to avoid an island situation. Figure 2.1 shows a lane closure.

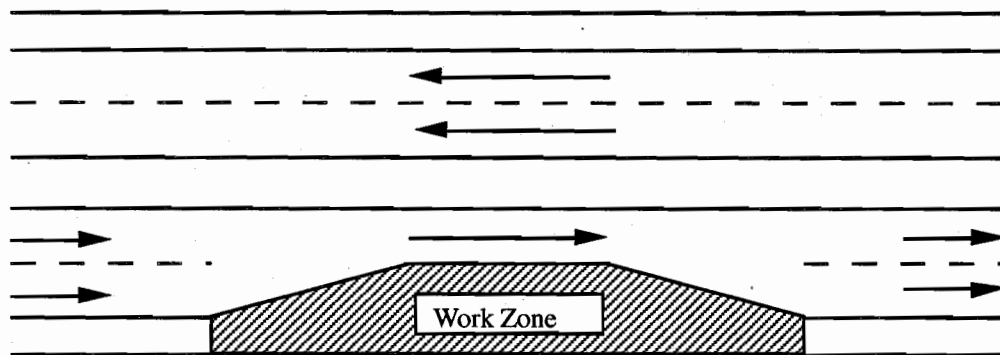


Figure 2.1. Lane closure.

2.2.2 Lane Alteration

Lane alteration is another method for providing space for rehabilitation activities on urban freeways. The basic premise of lane alterations is to keep the maximum number of open lanes through the conflict area, reducing potential disruptions to traffic. Lane alteration involves the lateral displacement of one or more traffic lanes from their normal alignment in order to accommodate a rehabilitation work zone. In this type of closure, usually all lanes are carried through and no merging operations are involved. Lane narrowing, use of shoulder or median, and adding temporary lanes are means of establishing lane alterations.

Lane Narrowing. This type of lane alteration is configured by reducing the width of those lanes carried through the work area. The maximum number of open lanes is maintained on the remaining space once the work zone has been delineated. The minimum

lane widths that must be provided depend on the type of facility and on the length of the work zone (Ref 2.4). Table 2.1 summarizes the minimum lane widths that must be provided with narrow lanes.

Type of facility	Minimum lane width (ft)	
	Passenger cars only	Mixed Traffic
2-way 2 lanes	9	10
Undivided > 2 lanes	10	11
Divided < 3.5 miles	9	11
Divided 3.5 - 5.5 miles	10.5	11
Divided 5.5 - 9 miles	11.5	11
Divided > 9 miles	12	12
Contra-flow lanes	10	11

Table 2.1 Minimum lane width according to the type of facility (Ref 2.4).

Also, a minimum clearance between the edge of the temporary lane and the work area itself must be provided, usually 2 to 3 ft. Figure 2.2 illustrates a lane-narrowing closure strategy.

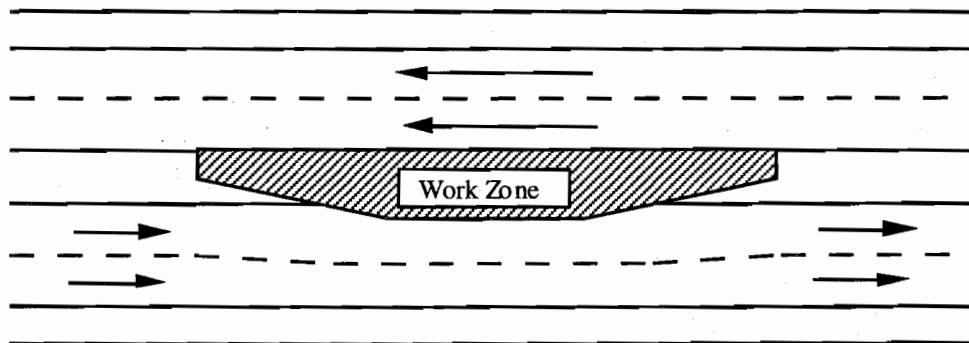


Figure 2.2 Lane narrowing.

Use of shoulder or median. This strategy involves the use of shoulders or the median as a temporary traffic lane. When using this kind of alteration, it is necessary to ensure that the shoulder or the median surface will adequately support the expected traffic loads, and that the traffic can travel safely through the temporary lane. It is important to keep the heavy loads from truck traffic off the inside shoulder, to avoid excessive damage on the permanent pavement structure. Whenever lane layout is altered to carry traffic in other parts of the roadway, appropriate geometric characteristics, such as turning radii, should be

provided for the speeds at which temporary lanes are to be traveled. Some examples of this technique are shown in Figure 2.3.

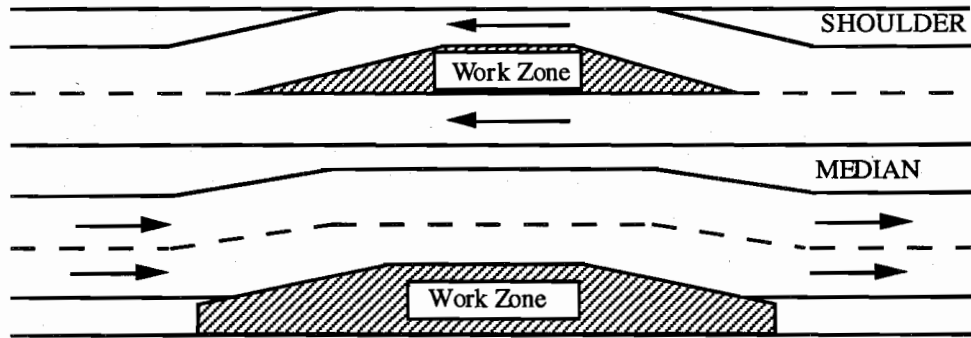


Figure 2.3 Use of shoulder or median.

Adding temporary lanes. This type of work zone consists of rerouting traffic to a temporary roadway constructed within the existing right of way, usually by widening the original cross section. This strategy requires extensive preparation of the temporary roadway in order to support the traffic loads. Frequent maintenance is also needed to ensure a safe operation. Generally, in urban areas, space is no longer available to implement such a traffic control alternative. Figure 2.4 illustrates this work zone strategy.

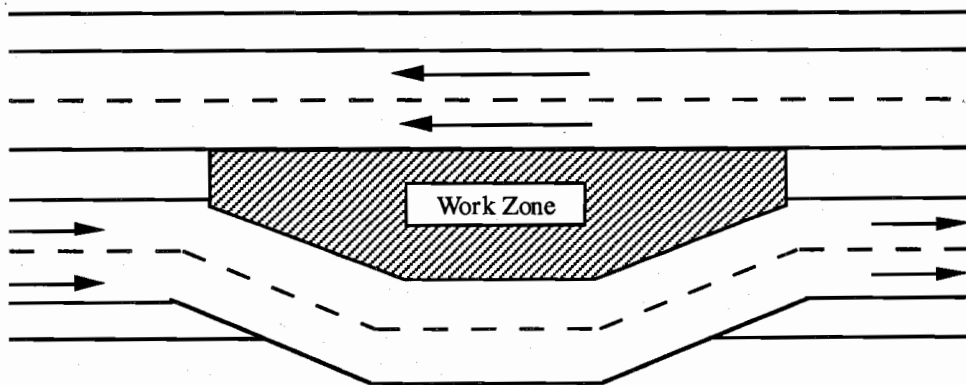


Figure 2.4. Adding temporary lanes.

2.2.3 Median Crossover

In this work zone scheme, traffic traveling in the direction where disruption occurs is routed across a median to the opposite traffic lanes. Traffic carried diagonally across the median into the other direction can be partial or full. In the case of partial crossover, only a fraction of the traffic is diverted, while the remaining vehicles continue to use the disturbed roadway. Full median crossover means that all traffic is diverted to the opposite side in a

two-way operation. In any case, opposite traffic must be separated with barriers, drums, cones, or vertical panels throughout the length of the two-way operation.

The transition roadway used to divert traffic from one direction to the opposite must be equal to or better than the geometric standards of the permanent road. This kind of alternative might also be combined with other strategies, including lane narrowing or the use of shoulders, in order to maintain the same number of lanes. See Figure 2.5 for some examples of median crossovers.

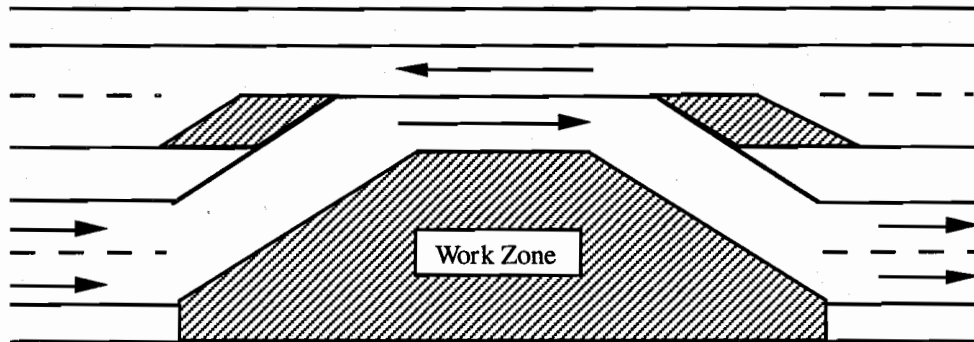


Figure 2.5. Median crossover.

2.2.4 Detour

A detour is used to divert traffic to another facility in order to bypass the work site that, in this case, entails total closure of the roadway. This closure strategy is desirable when there are underutilized routes running parallel to the main route. However, the strategy is not desirable in urban areas where the surrounding network, usually inferior to the main network, is already saturated, and the extremely high volumes carried by the freeway cannot be handled by smaller streets. Detour disadvantages include:

- Longer travel times as a result of longer routes and reduced speeds.
- More delays and higher operating costs.
- Lower levels of service.
- Higher accident rates than those at the work zone itself.
- Congestion and deterioration of alternative routes.
- User confusion if adequate information is not provided.

In order to be acceptable by users, traffic detours require:

- That the substitute route be capable of handling the additional traffic.
- That drivers be well informed.
- That the alternate route be thoroughly and clearly marked.

An example of a detour is shown in Figure 2.6.

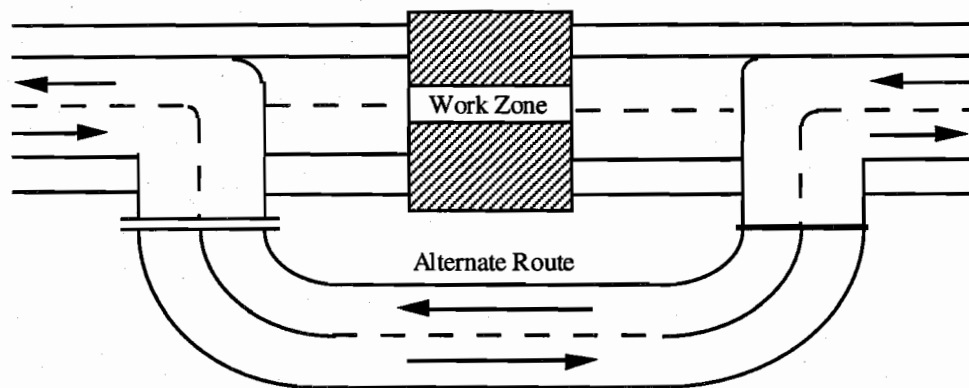


Figure 2.6. Detour.

Undesirable effects occurring during highway rehabilitation include congestion, safety problems, limited property access, and high vehicle fuel consumption. These impacts on existing traffic and economic activity need to be assessed during the project planning stage (Ref 2.5). It is also necessary to find the best combination of two contradictory objectives: conducting rehabilitation activities at a minimum cost, while reducing the negative impacts on users and the economy. Closing the entire facility, or just one direction, so that construction is unimpeded and motorists are not exposed to hazards, generates the least rehabilitation cost. However, inadequate levels of service usually exist on alternate routes on major corridors, so that traffic cannot be accommodated and unacceptable delays and increased user costs result. A compromise must then be made between the two conflicting interests: construction and traffic operations (Ref 2.5).

Several parties are affected by highway rehabilitation projects, including road users, adjacent businesses, transportation agencies, contractors, and third-parties. The impacts generated by the rehabilitation activities on each party are identified below:

2.3 IMPACTS ON ROAD USERS

Highway users include all of those who may be using any portion of the highway right-of-way and its immediate environs (e.g., vehicle operators and their passengers). The increase in the cost of travel resulting from highway rehabilitation disruptions is the primary concern of highway users. By far the greatest concern to road users is the increase in travel time resulting from the slower speeds required while passing through the work zone (or the additional travel time associated with traveling on alternate routes if diversion of traffic occurs).

Slower speeds and longer travel distances also give rise to changes in vehicle operating costs. Although the additional expenditure in fuel consumption, oil consumption, vehicle maintenance, tire wear, and depreciation may not be noticed by road users, they represent an economic loss for the community as a whole. Moreover, local, regional, and

national transportation goals may be jeopardized by the accumulated effects of highway rehabilitation; for example, energy conservation goals may not be attained if fuel is wasted in queues generated by rehabilitation activities.

In addition, the number and severity of accidents may increase as a result of the presence of a work zone. For example, the extra travel on diversion routes may lead to an accident rate greater than that associated with the work zone itself.

These three cost components — travel time, vehicle operating costs, and safety — are used to assess the impacts of highway rehabilitation projects on road users. The methodology for estimating the increase in the cost of travel is presented in the next chapter.

2.4 IMPACTS ON BUSINESSES

Businesses that depend on passing traffic and, consequently, convenient property access are attracted to major transportation corridors. These types of businesses are concerned about potential losses in sales caused by reduced or inconvenient customer access resulting from rehabilitation activities. Property owners are also concerned about the extent to which reduced access will decrease the value of their property. In 1989 the Wisconsin Department of Transportation published a study analyzing the impacts of highway rehabilitation on businesses (Ref 2.6). Business impacts were assessed by surveying businesses adjacent to a number of reconstruction projects. This study concluded that the overall level of business activity occurring during reconstruction operations declined an average of 10 percent. Impacts on employment were less than the impacts on sales, since businesses were reluctant to lay-off full-time employees during a short-term decline in business activity. The impact on adjacent businesses was related directly to the length of the disruptions. The faster the project was completed, the less severe the impacts on business (Ref 2.6).

Loss of business and decline in property values resulting from highway rehabilitation, however, are difficult to quantify in a credible manner, since changes in the level of sales or employment may be tied to factors other than the rehabilitation project. Therefore, impacts on businesses must rely on subjective evaluations of local experience; accordingly, they are not typically included in economic analyses of rehabilitation alternatives (Ref 2.6).

2.5 IMPACTS TO THE TRANSPORTATION AGENCY

Transportation agencies are also affected in terms of economic and political interests. While the responsibility of the agency is to provide as many transportation services as available resources permit, the allocation of these resources for mitigating negative effects of rehabilitation projects reduces the level of investment in permanent facilities. The transportation agency, therefore, has two extreme courses of action. First, by providing extensive mitigation measures, the total number of completed projects may be reduced (or proposals for projects may have to wait longer before approval). On the other hand, by not

providing mitigation measures, the agency may suffer a loss of esteem in the eyes of the public (Ref 2.6).

2.6 IMPACTS ON CONTRACTORS

Contractors experience an increased element of risk when rehabilitating existing highways (more so than when constructing entirely new facilities). The most common risks are the unpredictability of costs associated with traffic handling and safety concerns, conflicting utility services, access to adjacent property and the project site, third party involvement, plan deficiencies, and atypical weather conditions. These risks are more likely to be found within an urban environment, where there are greater volumes of traffic. In addition, the need for transporting labor, supplies, and equipment through adjacent traffic can create conflicts that may be resolved only by reducing either construction operations or traffic operations. Contractors may fail to comply with required contract schedules (and face financial losses) if they are unable to cope with these risks (Ref 2.6).

2.7 IMPACTS ON THIRD PARTIES

The impact of rehabilitation can also affect third parties. These third parties include utility companies and parties using the highway facilities to serve other public interests (e.g., fire departments, law enforcement agencies, public schools, public transit agencies, and others). The interests of these parties may be affected by highway rehabilitation projects. Utility companies, for example, may have facilities located within the highway right-of-way and may have to reduce services during the reconstruction period in order to expedite the work. The transportation agency must identify the affected parties and negotiate the necessary agreements in order to coordinate the work of contractors with that of the third parties (Ref 2.6).

2.8 SUMMARY

This chapter focused on the qualitative assessment of temporary negative impacts of highway rehabilitation on urban areas. These impacts are a function of the traffic handling techniques applied to accommodate both the construction operations and traffic operations. The most commonly used traffic handling strategies were reviewed and compared. Several parties are involved in providing and using the highway network. The short-term impacts of highway rehabilitation projects on road users, adjacent businesses and property owners, transportation agencies, contractors, and third-parties were identified in this section.

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CHAPTER 3. ESTIMATION OF ADVERSE IMPACTS ON ROAD USERS FROM HIGHWAY REHABILITATION

3.1 BACKGROUND

An economic analysis of potential rehabilitation alternatives must consider a number of indirect costs that are related to the road user. The selected rehabilitation strategy must provide benefits to road users over the service life (by means of lower travel costs resulting from smoother and safer facilities) that outweigh the cost of the rehabilitation. The strategy must also minimize the temporary increases in user costs resulting from the rehabilitation itself.

The adverse impacts on road users resulting from highway rehabilitation can be reduced by two general approaches: first, by implementing a range of mitigation strategies during the rehabilitation project, and, secondly, by adopting a rehabilitation alternative that may reduce the number of rehabilitation cycles (i.e., a more durable rehabilitation method).

In order to conduct an economic evaluation of alternatives, researchers should estimate the adverse impacts on road user costs resulting from disruptions to traffic during highway rehabilitation. User costs are a function of traffic volumes, road geometry, time and duration of the rehabilitation work, the geometry of the work zone, and traffic management techniques implemented (Ref 3.1).

3.2 OVERVIEW OF STUDIES IN ROAD USER COSTS

Studies on the cost of operating motor vehicles were initiated in the United States soon after World War I by Agg (1923), who studied the performance of a small fleet fitted with fuel flowmeters (Refs 3.2, 3.4). This study reported fuel consumption as a function of speed and initiated a series of vehicle operating cost studies. By 1935, a broad knowledge base had been developed by experimental studies. Significant contributions were made by Agg and Carter (1928), who reported on the effect of geometry on operating costs; Winfrey (1933), who analyzed truck operations in Iowa; Paustrian (1934), who studied tractive resistance and road surface types; and Moyer (1934), who identified tire skidding characteristics, surface types, and safety.

Years later, the difficulty in estimating non-fuel costs from test vehicles was recognized, along with the need to complement experimental studies with information obtained from vehicles under real-world conditions. Accordingly, surveys of vehicle owners were increasingly used to gather reliable aggregated data. One of the earliest surveys of operating costs was reported by Moyer and Winfrey (1939), who examined the fuel, oil, maintenance, and tire costs of rural mail carriers. Saal (1942) also extended his experimental fuel consumption data using survey information. Moyer and Tesdall (1945) complemented these studies with the results from tire wear experiments (Ref 3.4).

By the 1940s, it was a common practice in both Texas and the United States to consider road user benefits when evaluating highway investments. In the early 1950s, the first manual containing road user costs was published by the American Association of State Highway Transportation Officials (AASHTO, 1952). In this manual, data were available only for passenger cars in rural areas, and truck costs were predicted using correction factors. The manual established a methodology for conducting economic evaluations of highway improvements at a planning level; however, its usefulness became limited by the 1960s because many of its technical relationships were by that time obsolete (Refs 3.2, 3.4).

With the improvements in computer technology, the focus of user cost studies shifted to the development of prediction models based on speed, highway, and vehicle characteristics. Models were developed by Conguad (1958), Sawhill and Firey (1960), and Claffey (1960). Further road user surveys were conducted by Kent (1960) and Stevens (1961) to incorporate tire, maintenance, and depreciation costs as part of the total operating costs. Winfrey (1963) synthesized the available experimental and survey operating cost data to produce a comprehensive guide for economic analysis of highways. A revised version of Winfrey's work was published in 1969 to include a section on accident costs (Ref 3.4).

In 1966, de Weille, in a study sponsored by the World Bank, conducted a review of vehicle operating cost studies. He concluded that U.S. data were not well suited for use in other economic environments. The World Bank then initiated a program of joint international research to develop models adapted to conditions in developing countries. This program (1972-1986) included the studies in Kenya (Hide et al., 1975), the Caribbean (Hide, 1982), Brazil (GEIPOT, 1982), and India (CRRI, 1982). Some of these studies contributed to the development of a mechanistic approach to the prediction of speed and fuel costs, as well as to pavement deterioration models for use in management systems (Ref 3.4).

The latest experimental investigation of vehicle operating costs in the United States was conducted by Zaniewsky et al. in 1981. This updated manual from an early version of the Federal Highway Authority Vehicle Operating Cost and Pavement Type manual, based on Winfreys (1969) and Claffey's (1970) work, reported tables containing operating costs for a range of vehicle types at constant speeds and at various speed cycles. Zaniewsky conducted a series of fuel experiments on paved roads using a test fleet of four cars, a pickup, and three types of trucks. The study also investigated vehicle emissions and accident related costs (Refs 3.4, 3.5).

3.3 USER COSTS COMPONENTS

User costs comprise five major elements: (1) vehicle operating costs, (2) user travel-time costs, (3) accident costs, (4) tailpipe emissions, and (5) social externalities (Ref 3.2).

Past studies on user costs have provided information about the relationship between highway characteristics and vehicle operating costs (useful in the economic evaluation of highway investments). Vehicle operating costs that can be credibly quantified represent a significant proportion of the user costs incurred while traveling on low-volume roads and inter-urban highways. In urban areas, however, high traffic volumes and capacity restrictions result in congestion and excessive delays; consequently, user travel time costs become more dominant (Ref 3.2). The last three components — accidents, emissions, and social externalities — are difficult to properly allocate in a credible manner, owing to the lack of reliable data. Even though these components have been recognized as relevant, more time is needed to gather enough information to develop accurate prediction models.

3.3.1 Factors affecting vehicle operating costs

Motor-vehicle operating costs consist of all automobile and truck expenses generated by vehicle operation. They include costs for fuel consumption, tire wear, oil consumption, and the portions of maintenance and depreciation that are related to vehicle use. Fuel consumption is the gasoline or diesel oil required to propel vehicles. Tire wear is the loss of tire tread material caused by the frictional contact of tires on road surfaces. Oil consumption is the deterioration and/or dissipation of motor oils that occurs when automobile engines are in operation. Maintenance cost is the periodic expense for servicing, adjustment, replacement, or repair of broken or worn vehicle components. Depreciation cost is the

difference between a vehicle's original cost and the amount recovered in the terminal sale of the vehicle for scrap (Ref 3.3).

The cost of operating a vehicle is affected by the following groups of variables (Refs 3.3, 3.6):

1) Road attributes, which comprise the relevant geometric and surfacing characteristics of the road (e.g., vertical and horizontal alignment and surface roughness).

2) Vehicle attributes, which comprise the relevant physical and technological characteristics of the vehicle (e.g., weight, payload, engine size, suspension design, transmission, etc.).

3) Regional factors, which comprise the relevant economic, social, technological, and institutional characteristics of the region. These characteristics include speed-limits, fuel prices, relative prices of new vehicles, parts and labor, driver training, and driving attitudes toward lane discipline and safety.

4) Traffic conditions, which refer to traffic volumes or traffic control devices that interfere with a vehicle's ability to maintain a uniform speed.

Effects of road attributes

Vehicle operating costs, including fuel and oil consumption, tire wear, and vehicle maintenance and depreciation, are strongly related to highway design and conditions. Road gradient is particularly important as a determinant of motor-vehicle fuel consumption and tire wear. The steeper the grades, the greater the energy required to climb them. Similarly, the greater the steepness and frequency of grades on a roadway, the greater the tire wear caused by the extra traction needed to overcome the grade resistance. Oil consumption and engine maintenance costs of motor vehicles are affected by the extra load imposed on engines as a result of operation on grades, particularly when this load requires the engine to operate in a lower gear (Ref 3.3).

Curvature, a major factor in motor-vehicle tire wear, also affects fuel consumption, oil consumption, and maintenance. Tire wear from curvature is evident for the tires on each wheel of a vehicle, though more pronounced for steering-wheel tires. These latter tires suffer

extra wear on curves because of the pavement friction resistance induced by turning the steering wheels against the direction of vehicle motion to develop the necessary turning force. The extra fuel consumed on curves provides the additional energy needed to propel the vehicle against this induced pavement friction (Ref 3.3).

Road surface conditions have an important bearing on fuel and oil consumption, tire wear, maintenance, and use-related depreciation. Extra energy is needed on rough gravel or loose-stone surfaces, either to force wheels up and over the stones or to push the stones aside. Tires are subject to extra wear either on loose-stone or on slip-resistant surfaces, where they are subject to the deteriorating effects of heavy buffeting (in the case of stone roads) or excessive friction wear (in the case of abrasive pavements). Oil consumption is affected by the dust-producing characteristics of road surfaces: the more dusty the surface, the greater the frequency of engine oil changes. Maintenance is related to road surface principally through the effects rough roads have on vehicle suspension systems and dusty roads have on the wear of cylinder walls, piston rings, and bearing surfaces (Ref 3.3).

Effect of Pavement Type and Condition on Fuel Consumption

Measurements taken by Zaniewsky (Ref 3.5) included fuel consumption rates and operating costs of vehicles traveling on portland cement concrete, asphalt concrete, surface treatment, and gravel sections to determine if surface types had an influence on fuel consumption. Three asphalt concrete sections were used to test the influence of surface conditions on fuel consumption. Student's t values were computed for each of the individual combinations of speed and pavement roughness to determine if there were any significant differences in fuel consumption. In general, there were no statistically significant differences at the 95 percent level in the fuel consumption on the paved sections. Fuel consumption on the unpaved section was slightly higher than the fuel consumption on the paved sections. The findings of this research relative to the effect of pavement roughness are in direct conflict with the findings of Claffey (Ref 3.3), where pavement roughness was found to influence fuel consumption by as much as 30 percent. However, the rough paved sections in the latter study were badly broken, potholed, and patched and, thus, were not representative of realistic operations in the United States (Ref 3.5).

Effects of vehicle attributes

Vehicle operating costs are affected by the particular characteristics of a wide range of vehicle types. Even though the cost of tires, maintenance, and depreciation are strongly related to the type of vehicle, which in turn is determined by the user's preference or needs, fuel consumption has been the focus of several studies (Refs 3.7 – 3.11) concerning the influence of vehicle attributes on consumption rates.

Fuel consumption is affected by variables that determine the energy efficiency, rolling resistance, and aerodynamic drag of a vehicle. Fuel consumption increases linearly with engine size and vehicle weight (Ref 3.7). In addition, larger engines usually are associated with heavier vehicles (Ref 3.9). Other vehicle characteristics, such as transmission and power steering, also affect fuel consumption. Vehicles with automatic transmissions consume more than vehicles with manual transmission, while vehicles with power steering also consume more than vehicles without power steering (Ref 3.8). Other features, such as air conditioning, the size and shape of the vehicle, its maintenance level, and its age, have also been identified as factors influencing fuel consumption rates (Refs 3.7, 3.10, 3.11).

Effects of traffic conditions

High traffic volumes affect vehicle operating costs by interfering with a vehicle's ability to maintain uniform speeds (Ref 3.3). As congestion develops, vehicles may be slowed to stops or even to a series of stop-and-go operations, with a corresponding increase in fuel and oil consumption, tire wear, and maintenance.

For multilane facilities or urban freeways, fuel consumption rates are affected by traffic volumes that range from approximately 800 to 1,800 vehicles per hour per lane. On arterials and collector streets, irregular traffic interruptions caused by the presence of traffic signals at intersections, curb parking, and pedestrian movements have a pronounced effect on vehicle fuel consumption. On lower-volume local streets fuel consumption is affected by traffic control devices (stop and yield signs) needed for ensuring the safety of drivers and pedestrians at intersections (Ref 3.3).

3.3.2 Factors affecting user travel time costs

The time spent in traveling has a different value for each occupant of a variety of vehicles on the highway network. This value of time holds a significant share of the total user costs when congestion and delays are present. There are a number of theories attempting

to assign a value for the travel time of road users (Ref 3.12). Generally, this value depends on the purpose of the journey; which can be divided into two large categories:

- 1) travel in the course of work, or working time;
- 2) travel for all other purposes, including commuting to and from work, and non-working time.

Working time is valued as the cost to an employer of a traveling employee. It has a value equal to a national average gross wage rate, weighted by the amount of road user travel among different income groups, plus an allowance for employers' overhead (Ref 3.12).

The value of non-working time is derived from studies of people's behavior when they are faced with a trade-off between the time and cost of travel (for example, the choice between a slow but cheap mode of travel and a faster but more expensive one). Studies conducted in the United Kingdom (Ref 3.12) suggest that, on average, people value the savings in non-working travel time, which amounts to approximately one-quarter of their gross hourly wage rates.

When allocating a value to the travel time of vehicles, it is important to remember that different classes of vehicles are likely to contain a varying number of occupants traveling for different purposes. For example, a freight vehicle normally travels in the course of work, and it is likely to contain only the driver; a car, on the other hand, may have more than one occupant when on a leisure trip, but probably only the driver when commuting to work (Ref 3.12). Variations in vehicle occupancy and trip purpose (and, thus, variations in the value of travel time) may occur for different hours of the day and for different days of the week.

3.4 MODELS USED TO ESTIMATE USER COSTS

Research aimed at developing user cost prediction models over the past 15 to 20 years may have used two broad approaches: an aggregate-correlative (or macroscopic) approach, or a micro-mechanistic approach (Refs 3.6, 3.17).

a) Aggregate-correlative approach

This approach relies on regression analyses of large databases obtained from surveys and field experiments using test vehicles. The algebraic functions generated are

expressed in relatively simple form and in terms of important vehicle and road descriptors. These models tend to rely on trends indicated by the data, rather than on a more rigorous theoretical relationship (Ref 3.6). Modeling under this approach is suitable for large-scale systems in which a study of the behavior of groups of units is sufficient. This is the case in studies of urban-wide effects of traffic management or planning policies (Ref 3.19). These types of models, however, are formulated upon data sets that often are ambiguous. Moreover, they usually do not extrapolate for conditions other than the ones covered by the data. Also, the model coefficients are difficult to interpret in physical terms and, therefore, are difficult to adapt to local conditions (usually achieved by using correction factors to bring predictions closer to locally observed values) (Ref 3.6). The regression equations proposed by de Solminihac (Ref 3.18) to estimate fuel consumption and other vehicle operating costs, based on results from Zaniewski (Ref 3.5), are examples of models developed under this approach.

b) Micro-mechanistic approach

This approach relies on theories of vehicle mechanics and driver behavior to simulate a detailed speed profile of the vehicle as it transverses the road section. Fuel consumption and other operating costs are predicted in increments at small distance intervals along the road. Micro-mechanistic models are able to incorporate the results of previous work, since parameters have readily interpretable meanings. In addition, the values of unknown parameters can be determined from relatively small-scale experiments. Because of their strong theoretical basis, these types of models have an inherent tendency to transfer and to extrapolate well (Ref 3.6). However, the extensive requirements for detailed information on road geometry cannot yield quick answers for policy analyses. Moreover, these models generally have undergone insufficient validation by independent data (Ref 3.6). The instantaneous model of fuel consumption developed by the Australian Road Research Board (Refs 10, 11) is an example of predicting fuel consumption based on detailed information of vehicle characteristics, speeds, and road profiles.

Not all models are suitable for all purposes, and the suitability of a model will depend on the type of analysis required, the availability of input information, time and budget constraints, and accuracy needs. The following classification of fuel consumption models,

arranged in a hierarchy of aggregation, shows the type and detail of information required, as well as the most suitable application scenarios for each type of model.

3.4.1 Types of fuel consumption models

Existing fuel consumption models can be classified into four categories in order of aggregation: (1) instantaneous models, (2) four-mode elemental models, (3) running speed models, and (4) average travel speed models (Refs 3.19, 3.20).

(1) Instantaneous model of fuel consumption. Fuel consumption is related to the fuel needed to maintain engine operation. The energy consumed is further separated into drag, inertial, and grade components. Because the model needs to be evaluated every time interval (usually one second) a computer program is used to calculate the instantaneous fuel consumption rates. This type of model is suitable for use in the detailed assessment of the impacts of proposed traffic management schemes for individual intersections, road sections, or small networks. Instantaneous traffic data must also be available, including instantaneous values of speed, acceleration, and grade (Ref 3.20).

(2) Four-mode elemental model of fuel consumption. Fuel consumption over any road section is estimated as the sum of the fuel consumed during each mode of driving used over that section, including cruise, deceleration, idle, and acceleration. This type of model is suitable for predicting the incremental effect of delays and number of stop/starts resulting from traffic control devices, geometric conditions, or traffic volumes. Macroscopic data, such as cruise speeds, number of stops, and stopped time, are required. The section distance and average grade prior to and after the intersection or bottleneck for each road section are also required. More accurate estimates will be obtained if initial and final speeds in each acceleration and deceleration are known (Ref 3.20).

(3) Running speed model of fuel consumption. The running speed model estimates the fuel consumed during the idle and non-idle (or running) modes separately. The running speed model is suitable for estimation of fuel consumption for a trip, typically longer than one mile, but not for short road sections or for the design of traffic management schemes. The minimum data required are travel time, distance, and stopped time over the total trip (Ref 3.20).

(4) Average travel speed model of fuel consumption. Fuel consumption is estimated per unit distance. The average travel speed model is suitable for estimating total fuel consumption in large urban traffic systems and for assessing the impacts of transportation management schemes that are likely to impact on average travel speeds and the level of travel demand. This type of model is not suitable for average speeds greater than 30 mph; however, this value is close to or even greater than the average speeds encountered within the CBD of a large urban area. The only data required are the vehicle travel distance and either the average travel speed or the travel time (Ref 3.20).

As a general conclusion, it can be stated that the level of aggregation of the model will influence the level of detail of input information required. As the model tends to a micro-mechanistic approach, more detailed information is needed; and although a properly validated model is more accurate, the process can be costly and time consuming if a large system is to be analyzed.

User costs incurred during highway rehabilitation can be estimated by means of existing traffic models that give information about vehicle speeds, idling time, and average number of speed-change cycles. The additional user costs generated by the work zone activities can be predicted by subtracting the user costs incurred during the rehabilitation from those incurred under normal conditions. In order to accurately predict user costs, the engineering model must reflect variations in user costs resulting from road attributes, vehicle attributes, regional factors, and traffic conditions.

For the type of policy analysis under consideration in this research report (the evaluation of mitigation strategies used during highway rehabilitation), and for the type of traffic system under analysis (multilane highways or urban freeways with high traffic volumes), an aggregated approach is recommended. This approach reflects variations resulting from vehicle attributes and the specific regional factors encountered in the United States. Simplicity of the analysis and a fair level of accuracy are also achieved by using statistical information of aggregated data. A mechanistic approach, on the other hand, would require detailed information of every vehicle entering the system and for a number of time intervals. This latter approach, while more accurate for individual predictions, might produce less accurate results when the individual predictions are added, that is, compared with the aggregated approach if the mechanistic model was not properly calibrated.

Furthermore, the type of user cost and fuel consumption model required for estimating the impacts of a rehabilitation project will be a four-mode elemental model type that can accurately predict costs if information about each driving mode (cruising, idling, accelerating or decelerating) is available.

3.4.2 Models to predict user costs at work zones

Thorough reviews of existing traffic and user cost models are available in the literature (Refs 3.17, 3.18, 3.21). The purpose of this section is to summarize their findings and experiences, and to identify candidates for further development in the analysis of freeway reconstruction projects. Impacts on user costs during work zones can be assessed by both manual and computerized procedures.

a) Manual procedures. A comprehensive manual procedure for evaluating work zone impacts is described in the user guide "Planning and Scheduling Work Zone Traffic Control," which provides methods for estimating delays, vehicle operating costs, fuel consumption, and accident costs (Refs 3.18, 3.23).

Another manual method is the 1985 Highway Capacity Manual, which provides estimates of work zone capacity and procedures for estimating queue lengths and delays (Refs 3.18, 3.14).

b) Computer Models. Some of the available computer models are summarized below:

FREWAY (Ref 3.25) calculates the effects of freeway lane closures. It calculates normal and work zone capacities and measures traffic performance in terms of queue behavior and delay for approaching and traveling vehicles. While this model is a good traffic analysis tool, it does not compute user costs.

QUEWZ (Refs 3.15, 3.24) is designed to assess the additional user costs generated by freeway work zones. This model can evaluate single direction closures and crossover strategies. The cost calculations include estimation of vehicle capacity through the work zone, calculation of average speeds, delay through the work zone, queue delay, cost of speed-change cycles, change in vehicle running costs, and total user costs.

QUADRO2 (Refs 3.12, 3.18) provides an economic assessment of highway maintenance strategies. The program estimates the user costs of a network consisting of a main route containing the work zone and diversion route. QUADRO2 estimates the additional user costs by evaluating the network with and without the work zone. Increases in accident costs resulting from the presence of the work zone are also modeled. Changes in travel times, operating costs, and accidents are computed for diverting traffic.

CARHOP (Computer-Assisted Reconstruction Highway Operations and Planning) (Ref 3.22) provides a method for testing various transportation system management (TSM) alternatives related to the reconstruction of freeways and arterial networks. CARHOP has the ability to generate reconstruction scenarios consisting of any combination of freeway lane constrictions and detour strategies, and to evaluate the performance of the transportation network by analyzing characteristics of the surrounding arterial network and signal timings. Statistics output includes vehicle speed, vehicle miles, vehicle trips, and vehicle minutes. They are compiled on a link-by-link basis and aggregated for the freeway and arterial subnetwork, as well as for the entire network as a whole. Although it does not calculate user costs resulting from reconstruction of the freeway system, the traffic assignment capabilities of this model are useful in estimating changes in travel patterns.

CORQ-CORCON (Ref 3.21) is a family of traffic models that analyzes the traffic flow characteristics of freeway corridors. The key ingredient of the CORQ Model is the assignment capabilities that allow one to choose between the freeway and alternative routes in the corridor. To run this model, origin-destination demand data are required. Additional user costs are not assessed with this model.

INTRAS (Refs 3.17, 3.21) is the only microscopic computer simulation model available for freeway corridors. It is designed to predict traffic performance for a directional freeway and surrounding surface streets. The network design includes specifications for each link, namely, link type, number of lanes, and connectivity to other links in the network. The expected flow rate on each link is specified by vehicle classification and lane usage. The traffic control can include ramp control and signal control. The model has been applied in the following investigations: effects of location of freeway traffic sensors on incident detection, evaluation of control strategies in response to freeway incidents, energy

conservation studies, evaluation of freeway reconstruction projects, evaluation of the effects of truck accidents, and bridge studies. Even though user costs are not modeled, the detailed information on vehicle speeds and accelerations, instantaneous values of grades, and traffic conditions make this model suitable for implementing a mechanistic approach to user costs estimation.

FREQ (Ref 3.21) is a family of simulation models containing such special features as control and design improvement optimization (including ramp metering and priority lanes), spatial and modal traveler responses, fuel and emission measures of effectiveness, incident and reconstruction investigation options, and others. Another improvement in later versions of this family of models is the synthetic origin-destination (O-D) formulation that allows users the option of directly entering O-D information or entering ramp counts and having the model generate synthetic O-D information.

FRECON2 (Ref 3.21) is a dynamic macroscopic freeway simulation model used to evaluate freeway performance under normal and incident conditions. The special features include traffic responsive priority control, improved means of handling flows and queues at bottleneck locations, and modeling parallel routes with spatial diversion owing to entry control. Traffic performance measures include travel times, queue characteristics, delay, fuel consumption, and emissions. The input data required includes subsection geometrics influencing capacity and origin-destination information.

Models Examined

The QUEWZ Model, along with later modifications (QUEWZE, QUEWZEE), is considered the best method for assessing the additional user costs at work zones. Most of the equations contained in this model were used in this report to estimate the impacts on user time costs, vehicle operating costs, and emissions. These equations can be found in Appendix A. A further modification in reporting additional fuel consumption is proposed in a later section.

The QUEWZ Model performs a macroscopic analysis of a freeway section, with the estimation of vehicle operating costs based on an aggregated-correlative approach. This model isolates the freeway section so that a complete analysis of variables affecting user costs at the work zone can be made. It is an effective, quick, and easy-to-use planning tool;

however, it is also recognized that freeway systems in urban areas are not isolated from the adjacent arterial networks. Changes in travel behavior, including changes in routes, modes, or demands, must be better understood. Models like CARHOP and CORQ-CORCON have important traffic assignment capabilities useful in estimating changes in traffic patterns. Models such as FREQ, FRECON2, and INTRAS have traffic simulation capabilities that may be useful in estimating traffic flow characteristics.

With a further development of a micro-simulation model (e.g., INTRAS), engineers have the opportunity to estimate user costs by means of micro-mechanistic models. A mechanistic approach would facilitate the adaptability of the model to local conditions. The accuracy of this latter approach, however, can be costly and time consuming as far as inputting and processing information is concerned.

3.5 WORK ZONE CAPACITY ESTIMATION

User delays and increased operating costs associated with major highway rehabilitation are a consequence of the reduction in vehicle capacity through the work area. Capacity, defined as the maximum flow rate that can be processed by the highway facility, is reduced as a result of the lane closure strategy used to accommodate the rehabilitation activities. When traffic demand exceeds the capacity of the work zone, vehicles begin to form queues until they progress through the work zone (Ref 3.13).

Several studies have been conducted to determine the reduction in capacity through work zones (Refs 3.13, 3.14, 3.15). It has been observed that work zone capacity varies according to the lane closure configuration and according to whether work is actually taking place. Work zone capacity can be as high as 90 percent of normal capacity when lanes are closed for relatively long periods with little or no construction activity. Lesser volumes can be handled when work crews and machines are in the work area. Research has also shown that the work zone capacity is sensitive to the type of work activity, the number and size of equipment at the site, and the exact location of equipment and crews with respect to moving traffic lanes (Ref 3.14).

Traffic flow through the work zone is also affected by merging, diverging, or weaving operations, as well as by grades, alignment, and truck traffic. Furthermore, capacities at long-term construction sites are higher than those for more temporary disruptions, primarily

because of the use of more permanent barriers and other traffic controls and because drivers, over time, become familiar with the site (Ref 3.14).

Capacities in the range of 1,800 vehicles per hour per lane were observed in Houston (Ref 3.14) at three- and four-lane segments having narrow lanes 10 to 11 ft wide. Portable concrete barriers were used to separate moving traffic from work operations (i.e., no lane closures). A procedure to estimate the work zone capacities for several lane closure strategies developed by the Texas Transportation Institute (TTI) (Refs 3.13, 3.15) is presented in Appendix A.

3.6 Speed Reduction Estimation

Vehicles crossing a work zone area during uninterrupted flow can experience a combination of free-flowing and congested traffic. When traffic demand volumes are not large enough to cause congestion and queuing, flow can be described with the volume and speed relationships. However, when volume increases, additional information, such as queue length, is required to characterize the traffic. Traffic passing through a work zone has been classified into three categories (Ref 3.16).

a. Vehicles traveling undelayed through the work zone. When demand is less than the work zone capacity and vehicles passing through the work zone do not experience any delay (and no variation in fuel consumption is noted).

b. Vehicles traveling through the work zone at a reduced speed. As traffic demand approaches the work zone capacity, the rate of vehicles flowing through the work zone decreases, reducing the overall speeds of vehicles. This situation forces vehicles to decelerate from the approach speed to a minimum speed near the work zone. Vehicles then have to accelerate to the work zone average speed from the minimum speed, travel through the work zone at a reduced average speed, and, finally, accelerate back to the pre-work zone speed (See Figure 3.1). In this case there are two main factors that affect fuel consumption. First, there is an increase in fuel consumption resulting from speed-change cycles. Secondly, there are savings in fuel consumption as a result of vehicles traveling the work zone at a reduced speed. Therefore, excess fuel consumption will be the algebraic sum of these two factors.

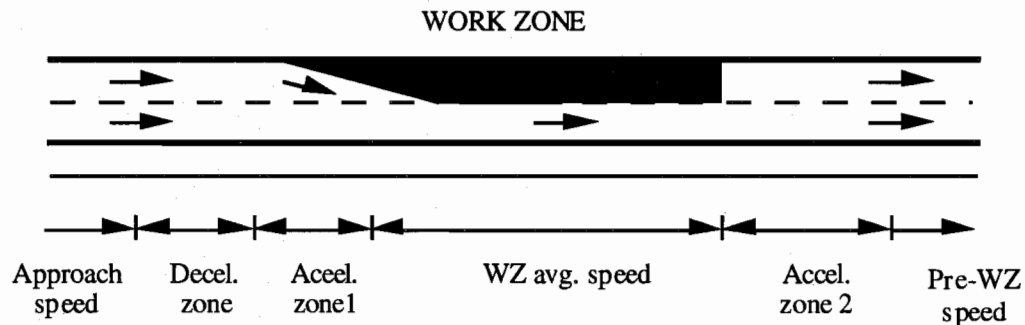


Figure 3.1 Traffic behavior near a work zone (no queue formation) (Ref 3.16).

c. Vehicles stopping near the work zone. When the traffic volume is greater than the work zone capacity, a queue begins to form upstream of the work zone. Travel through the zone in this case involves a deceleration from the approach speed to a full stop at the end of the queue. Short acceleration-deceleration movements occur as the vehicle progresses through the queue. Next, acceleration to the work zone speed at the beginning of the work zone begins. Finally, both passage through the work zone at the average work zone speed and acceleration to pre-work zone speed at the end of the work zone occur (see Fig 3.2). In this situation, fuel consumption increases drastically because of two factors: idling time while in the queue, and the numerous speed-change cycles experienced by vehicles progressing to the beginning of the work zone.

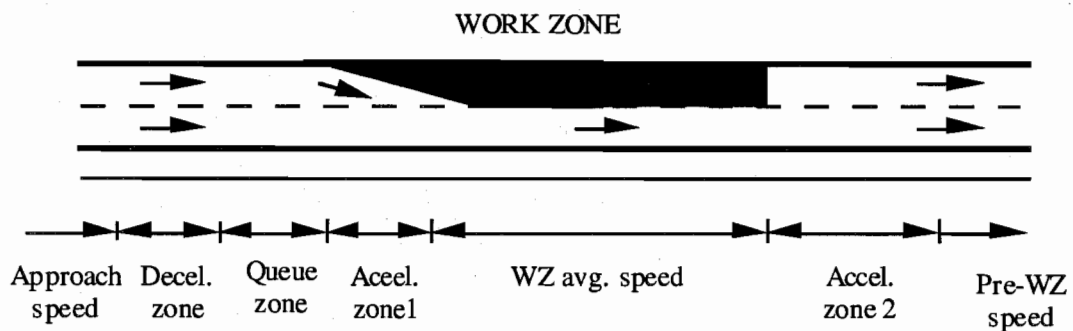


Figure 3.2 Traffic behavior near a work zone due to queue formation (Ref 3.16).

Existing traffic models use the theoretical speed-volume curve shown in Figure 3.3 to calculate average vehicle speeds (Ref 3.17). Based on this relationship between average travel speed and traffic volume, vehicles are free to travel at the maximum speed when

volume is very low. As traffic volumes increase or capacity is reduced at the work zone, the speed decreases until capacity is reached, at a speed of approximately 30 mph (48 kph). Further increases in traffic volume will result in a flow rate reduction from resulting congestion until eventually both speed and volume become zero (Ref 3.18). The procedure developed at TTI to estimate the average approach speed and speed reduction at work zones is detailed in Appendix A.

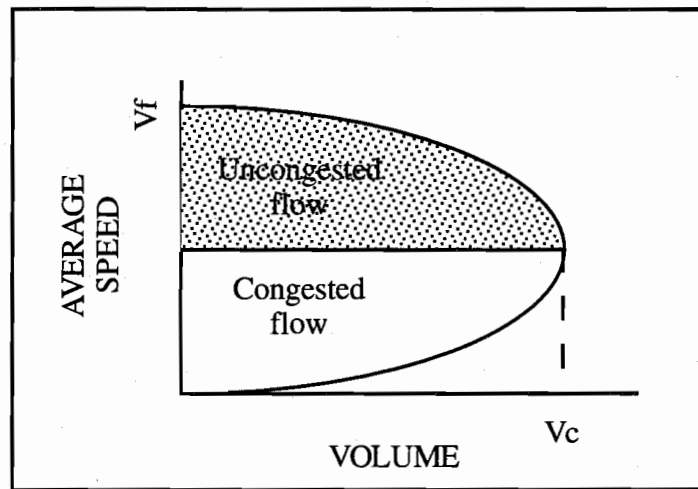


Figure 3.3 Relationship between speed and traffic volume (Ref 3.17).

3.7 USER DELAY ESTIMATION

Highway user delays at work zones depend on capacity restrictions imposed by the lane closure configuration and traffic volumes passing through. As traffic demand increases, the volume-to-capacity ratio also increases, and the speed of the vehicles is reduced. Vehicle speeds decrease according to the speed-volume curve shown in Figure 3.3 until capacity is reached at a speed of approximately 30 mph (48 kph). When demand exceeds capacity, only a volume equal to the work zone capacity can be processed through the work zone. Queues begin to form, with the excess traffic arriving at a constant rate.

Highway users experience delays at work zones for three main reasons:

1. Traveling through the work zone at a reduced speed.
2. Time lost while slowing down and returning to the approach speed.

3. Delay if a queue has formed.

A detailed summary of the equations used to estimate delay costs is available in Appendix A.

3.8 ESTIMATION OF VEHICLE OPERATING COSTS

Changes in vehicle operating costs, including fuel and oil consumption, tire wear, maintenance and depreciation, result from a combination of vehicle maneuvers at or while approaching the work zone (e.g., cycles of deceleration and acceleration, idling time, or traveling at a reduced speed). Changes in vehicle operating costs as a consequence of work zones can be generated during any of the following scenarios.

1. Changes in vehicle operating costs while cruising at a reduced speed through the work zone. The fuel consumption portion of the operating cost may indeed be reduced while traveling at the work zone speed, around 30 mph (48 kph), compared with normal speeds of around 60 mph (96 kph) at which vehicle fuel economies are lower. Therefore, potential savings come from traveling at reduced speeds.
2. Changes in vehicle operating costs while passing through the queue if congestion develops. The average speed of vehicles traveling in a queue, including stop-and-go cycles, cruising, and stopped time, is generally around 6 mph (10 kph). At this speed, operating costs are greater than those associated with free flow speeds. In addition, the increases in operating costs are dependent on the length of the queue and, thus, on traffic volumes.
3. Increase in operating costs resulting from speed-changes for slowing and returning to approach speed. It is assumed that every vehicle will make a complete slow down-return to approach speed cycle. If a queue is present, the cycle will involve slowing down to a complete stop.
4. Increase in operating costs resulting from speed-change cycles for stop-and-go operations if congestion develops. For estimating stop-and-go operations, it is

assumed that each vehicle will make approximately three cycles from 0 to 10 mph (16 kph) per mile of queue.

Appendix A contains detailed procedures for estimating vehicle operating costs for each scenario mentioned above based on the modified QUEWZE Model proposed by de Solminihač (Ref 3.18).

3.9 ACCIDENT / INCIDENT COST ESTIMATION

Accidents/incidents involve direct and indirect costs to road users. Direct costs reflect the economic loss resulting from death, injury, costs incurred by the emergency services, police, insurance administration, and damage to property. Indirect costs are time delays and increased operating costs to passing traffic resulting from queues (Ref 3.12).

Direct costs of accidents vary with their severity in terms of the number and types of vehicles, as well as the number of people involved. Severity is also measured by the magnitude of the consequences on people (fatal, incapacitating injuries, non-incapacitating injuries) and on property damage. Indirect costs of accidents/incidents vary according to the time of day and the day of week of occurrence, which strongly relates to the traffic volumes that may be disturbed. Detection, response, and clearance time employed by the incident management team also affect the costs of traffic disruptions (Ref 3.25).

The rate of occurrence of accidents is generally measured in terms of number of accidents per million vehicle-miles traveled (VMT) at a specific section of the highway network. Accident rates are determined by the specific geometric, traffic, and environmental conditions of the facility under study. Variations in accident rates occur between different road-function classifications. For example, accident rates are different for the Interstate system, when compared with those of primary or secondary state highway systems (Ref 3.25).

Efforts have been made to estimate the cost of accidents and other incidents. In terms of indirect costs of congestion caused by the occurrence of accidents/incidents, Lindley (Ref 3.27) incorporated a routine within the FREWAY model to estimate delays and fuel consumption associated with accidents/incidents on an annual basis. The estimation is based on calculating the number of occurrences per year for each incident type for each hour of the day using an incident probability tree similar to that shown in Figure 3.4.

The methodology uses tables and freeway capacity and traffic volume information to estimate average incident duration times and the remaining capacity of the facility for each possible incident type in order to calculate the time until normal flow resumes following an incident. Delay and fuel consumption caused by the presence of an incident are calculated for each incident type and then extended from a single incident occurrence to a full year by multiplying by the number of annual occurrences.

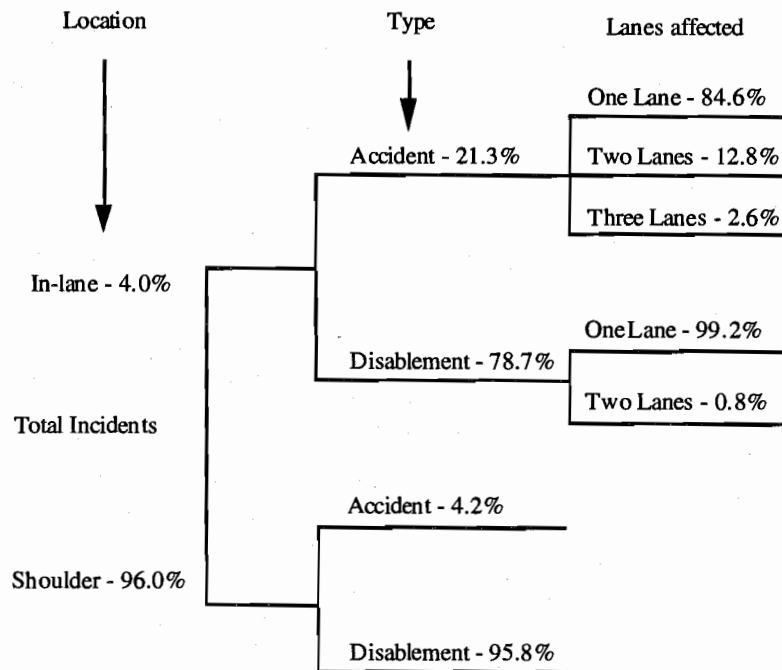


Figure 3.4 General incident tree (facility with adequate shoulders) (Ref 3.27).

A similar analysis may be conducted to estimate the congestion impacts from accidents during the construction period if the accident rates are known for the facility under rehabilitation.

Rollings and McFarland (Ref 3.28) proposed a methodology for estimating direct costs of accidents. In this method, they assigned costs on a per-accident basis. Accidents are classified into three broad categories, including fatal, injury, and property damage only (PDO) accidents. Injuries are further divided by their severity into incapacitating, non-incapacitating, and possible injuries.

The cost of fatal accidents is the sum of the economic loss by death and the correspondent cost of incapacitating, non-incapacitating, and possible injuries, together with

the property damage occurring during the fatal accident. The cost of non-fatal or injury accidents is the sum of the cost of incapacitating, non-incapacitating, and possible injuries, together with the property damage occurring during the non-fatal accident. Finally, the cost of property-damage-only accidents is added.

The following formulas can be used to estimate the cost of accidents as a function of the number of casualties per accident. The costs were updated to 1990 dollars using the Consumer Price Inflation (CPI) Index (Ref 3.29):

1. Cost per fatal accident:

$$\begin{aligned} \text{TOTAL COST} &= \$ 1,172,236 * (\text{number of fatalities per accident}) \\ &+ \$ 70,284 * (\text{incapacitating injuries per fatal accident}) \\ &+ \$ 13,305 * (\text{non-incapacitating injuries per fatal accident}) \\ &+ \$ 5,892 * (\text{possible injuries per fatal accident}) \\ &+ \$ 5,963 * (\text{number of vehicles per fatal accident}) \end{aligned}$$

2. Cost per non-fatal accident:

$$\begin{aligned} \text{TOTAL COST} &= \$ 22,830 * (\text{incapacitating injuries per non-fatal accident}) \\ &+ \$ 6,325 * (\text{non-incapacitating injuries per non-fatal accident}) \\ &+ \$ 2,733 * (\text{possible injuries per non-fatal accident}) \\ &+ \$ 2,588 * (\text{number of vehicles per non-fatal accident}) \end{aligned}$$

3. Cost per property damage only accident:

$$\text{TOTAL COST} = \$ 1,345 * (\text{number of vehicles per PDO accident})$$

The input data required to estimate direct accident costs are the following:

- a. Rate of occurrence of fatal, non-fatal, and PDO accidents (number of accidents per million vehicle miles traveled)
- b. Fatalities per fatal accident
- c. Incapacitating injuries per fatal and non-fatal accident
- d. Non-incapacitating injuries per fatal and non-fatal accident
- e. Possible injuries per fatal and non-fatal accident

f. Number of vehicles with property damage per fatal, non-fatal, and PDO accidents

This methodology can be difficult to use if the number of casualties per accident (incapacitating, non-incapacitating, and possible injuries) is not explicitly reported for fatal and non-fatal accidents, and if the number of vehicles per accident is not explicit for fatality, non-fatality, and PDO accidents.

Studies have also been conducted to determine whether the presence of work zones increases accident rates or accident severity. A four-year study on accidents at long-term freeway construction projects in Texas was conducted by TTI (Ref 3.26) to determine the change in accident rates during a construction period. This study started with a thorough review of past studies; the evidence did not indicate that work zones contribute to an increase in accident rates. Increases in accident rates had been reported up to 147 percent for one study, while another reported a 34 percent decrease in accident rates. The study of accidents at long-term construction zones in Texas concluded that, on average, accidents increased 28.7 percent during construction. Severe accidents (injury or fatality) increased an average of 38.8 percent, compared with an average 24.9 percent increase for property-damage-only accidents. These results suggest that accidents during construction tended to be more severe than normal.

The study also concluded that nighttime accidents increased an average of 37.4 percent compared with a 24.4 percent increase in daytime accidents. Rear-end accidents increased more than single-vehicle or other multi-vehicle accidents (45.7 percent compared with 13.9 and 14.7 percent increases). Nevertheless, project-to-project variations exist, and there are uncertainties for applying a general rule concerning increases in accident rates and accident severity at work zones.

3.10 ESTIMATION OF VEHICLE EMISSIONS

Automobiles produce air pollutants as a result of incomplete combustion of the fuel and air mixture in the piston chamber. These pollutants, a mixture of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), and particulate matter, are expelled through the exhaust system into the atmosphere (Ref 3.30). Moreover, automobiles account for 40 percent of the pollutants that create smog, a photochemical reaction of hydrocarbons and

nitrogen oxides that destroys the ozone layer, and for more than two-thirds of the carbon monoxide emitted into the atmosphere (Refs 3.29, 3.30).

Tailpipe emissions from vehicles represent a substantial problem at work zones because total emissions tend to increase at slower speeds. In addition to vehicle speeds and flow, emissions depend on vehicle conditions and driving patterns of the area. Acceleration, deceleration, and idling operations commonly encountered in work zones increase emission levels from vehicles, lower levels being found from vehicles traveling at free flow speeds. Vehicle age and maintenance levels also affect the amount of pollutants expelled into the atmosphere. Finally, geographic and environmental conditions, including altitude and temperature, also affect the level of emissions from vehicles (Ref 3.18).

Air pollution is measured by the concentration of pollutants in the air. Emissions from vehicles contribute to air pollutants; however, the concentration is determined by the dispersion of the emitted gases along and in the vicinity of the highway. Dispersion of pollutants is dependent on several factors, including wind direction and speed, vertical mixing height, precipitation, and the level of emissions (Refs 3.16, 3.31).

The QUEWZEE model (Ref 3.16) has a routine to estimate the excess quantity of vehicle emissions for traffic passing through the work zone. Excess emissions of carbon monoxide, hydrocarbons, and nitrogen oxides are estimated by subtracting the amount of pollutants that would be emitted if there were no capacity restrictions from that obtained during the closure strategy.

The first step involves characterizing the traffic flow by determining the time spent for each mode of operation, including acceleration, deceleration, and constant cruise speed. The next step involves calculation of the emission rates for each mode of operation estimated from a base scenario for each mode, speed, and pollutant. Base scenarios are obtained from the MOBILE 4.1 model (Ref 3.16) for the following conditions: a 1977 calendar year, low altitude, 75° F, and hot-stabilized, light-duty vehicle fleet.

Correction factors are used to estimate emission rates at different speeds and for trucks. Regression equations are also used to estimate the base scenario emission rates, since they are dependent on vehicle speed and acceleration. Finally, the quantity of emissions is calculated by multiplying the correspondent emission rates by the time spent in each mode of operation and by the traffic volumes.

Emission rates expressed in grams per hour are usually greater at higher speeds because the drag force on a vehicle cruising at speed S is proportional to the square of the speed and, therefore, a greater load on the engine is exerted at higher speeds (Ref 3.16). However, less time is required for a vehicle to travel a specific section of the highway if congestion is not a factor. Consequently, at reduced speeds, more pollutants are emitted for the same section of the road because more time is spent in each driving operation. Detailed equations for estimating vehicle emissions are presented in Appendix A.

The social cost of pollution has long been recognized and procedures have been proposed to allocate costs to vehicle emissions. Small (Ref 3.31) proposed a methodology in the late 1970's to estimate the costs of air pollution from transport modes. The cost of emissions was directly related to the damage caused to human health and the deterioration of materials.

Damage to human health was measured in direct medical expenditures plus lost earnings associated with premature death under the premise that changes in air pollution cause changes in the probabilities of illness and death. In order to allocate an estimate of total air pollution costs to specific contributing pollutants, it was necessary to know the relative severity of each, as well as the quantities that were emitted. For human health, it was assumed that the severity of a pollutant was inversely proportional to its ambient air quality standard.

To estimate the cost of air pollution on human health, regressions of total mortality rates were done for 117 U.S. statistical metropolitan areas using pollution levels as an explanatory variable in addition to other socio-economic characteristics, including population density and percentage of the population age 65 or older. This regression analysis determined the proportion of the total economic cost of disease and death in the U.S. owing to air pollution; the total economic cost was later applied to each type of pollutant proportionally according to its severity and to the quantity of emissions.

The cost of deterioration of materials owing to air pollution was obtained by estimating the total in-place value of materials subject to damage from air pollution, as well as the fraction exposed to air pollution. Estimates of the increased rate of deterioration resulting from air pollution were then used to allocate the costs of replacement, the cost of using more expensive materials less suitable to damage from pollution, and the damage incurred in spite of better materials. It was estimated that nearly half the cost was accounted

for by paint and by zinc in the form of galvanized steel and alloys. The damage to materials is caused mainly by nitrogen oxides (NOx), oxidants (OX), and sulfur oxides (SOx). The cost per urban emission was estimated by adding the damage cost to human health to the damage cost to materials and their values, which is shown in Table 3.1. The values are presented in 1990 dollars using the Consumer Price Inflation (CPI) Index (Ref 3.29).

Pollutant	Cost per urban emission 1990 dollars/ton	Transportation	
		U.S. contribution to emissions 1989 million tons/year	% of total emissions
Carbon Monoxide	16.48	40	65.7
Hydrocarbons	255.0	6.4	34.6
Nitrogen Oxides	840.0	7.9	39.7
Sulfur Oxides	1,039.0	1.0	4.7
Particulate Matter	493.0	1.5	20.8

Table 3.1 Allocation of U.S. damage to pollutants (Refs 3.29, 3.31).

The cost figures acquired from this methodology were obtained using national averages; accordingly, they must be corrected before applying them to a specific location. Correction factors are based on two main factors: first, there is local variation in the amount of atmospheric dispersion, which is proportional to the area's average frequency of days with high meteorological potential for air pollution known as "episode days." The frequency of these days is dependent on wind speed, vertical mixing height, and precipitation. The other kind of local variation is the density of economic activity, since the damage to health and materials per unit of pollutant emitted, for a given degree of atmospheric dispersion, should be proportional to the quantity of susceptible people and materials per unit area (Ref 3.31).

3.11 SUMMARY

This chapter reviewed the existing methodologies to estimate the impacts of highway rehabilitation on user costs. These user costs include vehicle operating costs, travel time costs, accident costs, tailpipe emissions, and social externalities. While the first two components can be credibly quantified, the others must rely on subjective evaluations.

Vehicle operating costs are affected by different factors, including road attributes, the characteristics of the vehicle itself, regional factors, and traffic conditions. Different models have been developed to account for all these variables. Some of them are designed for a broad analysis, others for a more detailed study. The level of detail of the analysis will be determined by the available information, resources, and time. The QUEWZ Model is the most suitable analysis tool for estimating the additional user costs (delay and vehicle operating costs) incurred during highway rehabilitation projects. While there are some methodologies developed to estimate accident costs and the cost of tailpipe emissions, they still have to go through calibration to obtain reliable outputs.

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CHAPTER 4. STRATEGIES TO MITIGATE ADVERSE IMPACTS FROM HIGHWAY REHABILITATION

A broad range of possible mitigation measures can be applied to reduce the magnitude of adverse impacts on existing traffic patterns and economic activity. Moreover, reducing the duration of the project by accelerating construction activities addresses only part of the problem. Frequently, the adverse effects of highway rehabilitation can be mitigated effectively without paying a premium for reducing the duration of a particular project (Ref 4.1).

Even though the need for implementation of one or a combination of mitigation measures must be assessed on an individual project basis, these strategies can be classified into six categories of activities associated with highway planning and construction. These categories include (1) design, (2) construction methods and equipment, (3) innovative materials, (4) project management, (5) traffic management, and (6) public relations (Ref 4.1). The primary purpose of these efforts, whether it be an innovation in construction technology or a creative people-moving strategy, is to reduce the magnitude of the adverse impacts of highway rehabilitation projects.

4.1 MITIGATION THROUGH DESIGN

Effective planning can reduce construction time. Plans that are inaccurate or too complicated increase the need for field changes (Ref 4.2). The duration of highway rehabilitation or reconstruction projects can be reduced by using simpler designs that require fewer pavement layers. The use of full-depth pavements eliminates numerous mobilization operations, testing procedures, and specification requirements associated with the construction of each layer of a multi-layer design (Ref 4.2). Other examples of simplifying the design to accelerate rehabilitation include (Ref 4.2):

- a) Using special admixtures and cement to produce high early-strength concrete in order to open the pavement to traffic within a day;
- b) Using an asphalt-stabilized base (instead of slow-curing base materials) to prevent delays associated with curing times, when eliminating a pavement layer is not feasible.

4.2 MITIGATION THROUGH CONSTRUCTION METHODS AND EQUIPMENT

Highway rehabilitation projects have been expedited through the use of innovative construction methods and equipment — especially for the removal of existing structures and for the installation of pavements (Ref 4.3). The innovative construction techniques may include the use of pre-cast concrete structures (instead of the usual cast-in-place structures); vacuum treatment of portland cement concrete; recycling pavement materials currently in place; and using unbonded concrete overlays, roller-compacted concrete, curing blankets, and a geogrid as a base supporter (Ref 4.4). More information about these techniques can be found in the literature (Ref 4.3).

Certain types of construction equipment can reduce considerably the duration of highway rehabilitation. Such equipment includes automatic dowel bar inserters, single-pass slip-formers, improved pavement pulverizers that speed demolition of existing pavements, quicker and more efficient pavement stripers, diamond wire saws for cutting reinforced concrete, and zero-clearance paving machines that allow single-lane reconstruction while maintaining traffic operations on adjacent lanes (Ref 4.4). The literature also explains how the equipment speeds up rehabilitation projects (Ref 4.3).

Another important innovation is the concept known as “constructability” (Ref 4.4), which provides for the optimum use of construction knowledge and experience both at the planning and design stages and during construction operations.

4.3 MITIGATION THROUGH INNOVATIVE MATERIALS

New or fast-setting materials for expediting highway rehabilitation are mostly found in portland cement concrete pavements. The most notable examples are the use of polymer concrete and other exotic adhesives for quick repairs in pavements and structures, and the use of high early-strength concrete pavement and bridge structures when traffic closure duration is important. Examples of fast-setting patching materials that have been tested in Texas include (1) cement-gypsum, (2) magnesium phosphate cement, (3) methylmethacrylate polymer, and (4) latex-modified cement (Ref 4.1).

The use of new materials, construction methods, and scheduling strategies has, however, raised several concerns about construction quality control. These concerns include (Ref 4.6):

1. Strength or curing characteristics of new materials.
2. Differences in road surface characteristics and structural integrity of segmental versus continuous construction, and between pre-cast versus cast-in-place construction.
3. Effects of traffic vibrations on the curing of materials.
4. Effects of traffic-handling strategies on the abilities of workers to operate machinery and perform different tasks.
5. Quality difference between day and nighttime work.
6. Change in workmanship when staffing requirements place excessive demands on the available labor supply.
7. Changes in quality owing to an accelerated schedule.
8. Effects on quality of less frequent inspections.

Even though these issues of quality control and accountability have become more complex, there is a general consensus that measuring quality is a very difficult task, since in-service quality deficiencies may not be obvious until some time later (Ref 4.6).

Research to improve quality control procedures during construction has led to statistical concepts and techniques applied to quality assurance in general, and to construction materials in particular. Guidelines for implementing quality assurance programs are also available through transportation agencies. Finally, alternative sampling and testing programs in pavement construction are being examined (Ref 4.6).

4.4 MITIGATION THROUGH PROJECT MANAGEMENT

Contract administration plays an important role in the on-time performance of a rehabilitation project. Recent experiences have shown that project management techniques, such as multiple contract letting on the same job, using computer tools in scheduling, the use of reasonable incentives and disincentives, and lane rental, can all create significant productivity improvements so that the total cost of the project is lowered (Refs 4.5, 4.6). In fact, these innovative contracting practices are the most effective way to motivate contractors to reduce the duration of rehabilitation projects. Project management techniques are described in more detail in the following chapter.

The difference between the four types of mitigation strategies already mentioned and the following two is that the former strategies are concerned with reducing the duration of the project, while the latter two are concerned with facilitating traffic through the work zone and reducing demands during disruptions to traffic.

Even though this research report is focused on the mitigation strategies associated with reduction in project duration, mitigation strategies involving traffic management and public relations are mentioned in the following sections because of their potential for enhancing safety, reducing traffic demands, changing travel behavior, and building the support and raising the tolerance of the public while the rehabilitation project is being conducted.

4.5 MITIGATION THROUGH TRAFFIC MANAGEMENT

The principal objective of traffic management during major highway rehabilitation is to use the transportation resources of the corridor in the most efficient way possible. Unlike short-duration routine maintenance operations that can be scheduled to avoid peak traffic periods, long-term lane closures and other capacity restrictions resulting from major freeway rehabilitation generate adverse impacts on traffic operations that may extend not only upstream of the work zone, but also to other nearby roadways as well. The effect of such capacity restriction during peak periods can be devastating if appropriate actions are not taken. Traffic management for major freeway rehabilitation focuses on how best to accommodate traffic through the work zone and on how to influence the redistribution of traffic among different routes or modes in the corridor (Ref 4.14).

The range of mitigation measures involving the use of traffic management techniques can be divided into four groups: (1) on-site measures, (2) off-site measures, (3) alternative-mode transportation systems management (TSM), and (4) all others.

4.5.1 On-site traffic management

The main objective of on-site traffic management is to provide safe and expeditious movement of traffic through the work zone while the rehabilitation progresses as rapidly, safely, and efficiently as possible. Traffic management strategies used at the work location must address the following fundamental principals (Ref 4.7):

- a. Motorists must be guided in a clear and positive way.
- b. Traffic safety must be a high priority element of every project.
- c. Disruptions to traffic must be minimized.
- d. Routine inspections of traffic control elements and traffic operations must be conducted.

Each element of the following classification of on-site traffic management strategies is intended to cope with one of the principles mentioned above; in addition, these elements should be used in combination to get the most effective results. These elements are traffic control, work zone speed control methods, accident/incident management, and traffic management teams.

Traffic Control

Traffic control is the process of regulating, warning and guiding, and advising road users to transverse a section of the highway in the proper manner. Signing and channeling devices are the techniques for establishing traffic control.

Signing. Signing consists of warning and regulatory signs, arrow boards, and changeable message boards (Ref 4.8). Signing is effective in warning the roadway users about changes in geometry, reduced speeds limits, and the presence of queues resulting from those modified conditions. Although warning and regulatory signs may not be as effective during nighttime as during the day, the use of additional reflectivity and flashing arrow boards can provide advance warning and directional information regarding lane changes to the roadway users. Changeable message boards are also effective in providing information about lane closures, alternate routes, real-time delays, queue lengths, and speed advisories.

Channeling devices: Channeling devices are used to warn and to alert drivers of hazards created by work activities in or near the road, and to guide and direct drivers safely past the hazards. Channeling devices include cones, vertical panels, drums, barricades, and traffic barriers (Refs 4.8, 4.10, 4.23). The effectiveness of channeling devices during night constructions can be increased by additional reflectivity and illumination.

Work Zone Speed Control

Excessive work zone speeds adversely affect the safety of workers and motorists; therefore, more emphasis has been placed on speed control methods at work zones. Safety can be enhanced through reduced speeds via flagging operations, law enforcement, lane width reduction, and real-time traffic management crews.

Flagging operations. Flagging operations offer minimum disruptions to traffic, are easy to move, and are effective in reducing speeds (Refs 4.8, 4.12). Flagging operations should occur during the day because of reduced visibility at night, and they can become expensive owing to labor costs with prolonged use. Even though flagging offers positive control over traffic performance, its effectiveness decreases with continual use.

Law enforcement. Stationary patrol cars with flashing lights and radar are effective in bringing about speed reductions through the work zone (Refs 4.8, 4.12). During low demand periods, random use of law enforcement encourages safer speeds. The use of this type of speed control device, however, depends on the availability of police officers and can be expensive over the duration of the project.

Effective lane width reduction. Lane-width reductions derived from channeling devices are also effective in bringing about speed reductions throughout the narrowed lane (Refs 4.8, 4.12). The use of positive traffic barriers and relocation of lane stripes increases the complexity and cost of set up and removal of this type of traffic control. In addition, the reduced driving space available through the narrowed lanes decreases capacity and increases the potential for accidents.

Real-time traffic management. Real-time traffic management refers to actions taken in real-time at the work zone to best facilitate continued safe and efficient traffic flow (Refs 4.14, 4.16). Real-time traffic management of both traffic demand and work zone capacity is possible. One method of adjusting work zone capacity is to manipulate the shoulder as a temporary travel lane when congestion develops, encouraging its use via highway advisory radio or changeable message signs. If traffic demands drop to the point that speeds begin to increase, the radio or signs would then be turned off, and the shoulder would not be used

for travel. Traffic demands can be managed in real-time by closing and opening entrance ramps as necessary.

Accident/Incident Management

The purpose of accident/incident management is to reduce delays, wasted fuel, and driver frustration arising from accidents and other incidents (Refs 4.8, 4.13, 4.14). The potential for accidents increases during rehabilitation projects owing to the combination of high traffic volumes in urbanized areas and the restrictive conditions placed on the roadway. Most accidents result from a driver's inability to react in a timely manner when merging, decelerating or stopping to other obstacles in the travel lanes. Other types of incidents, such as disabled vehicles or spilled loads, can reduce the capacity of the facility. This is of special concern during rehabilitation, since the normal capacity is already reduced and significant space is occupied by the construction operations. A reduction in service resulting from accidents/incidents depends on the detection, response, and clearance time; additionally, traffic volumes and work zone capacity determine queue clearance conditions.

Accident/incident management is a multi-jurisdictional effort involving enforcement agencies, highway agencies, contractors, and emergency services. Accident/incident management must incorporate one or more of the following elements along the work zone:

- Towing or service vehicles
- Emergency motorist call boxes
- CB radio monitors
- Cellular phone hotlines
- Alternative emergency access
- Motorist information systems

In addition to quick detection and response, effective accident/incident management must inform the roadway user of substitute routes in case of lane blockage. Changeable message signing is effective in providing information to the road user concerning closed lanes, diverting traffic to alternate routes, warning of slow traffic ahead, and giving real-time information. Radio and other news media are also useful resources for communicating current traffic conditions to roadway users.

Traffic Management Teams

The concept of traffic management teams involves regularly scheduled meetings of planners, engineers, consultants, police officers, and officials from numerous public and private entities, each of whom has a different perspective and primary concern regarding a project and its consequences (Ref 4.6). The types of agencies and organizations that have been involved in traffic management efforts at past projects include (Ref 4.14):

- State, local, and federal highway agencies
- Regional government councils, planning commissions, and chambers of commerce
- Automobile and trucking associations
- Transit agencies operating in the region
- Private ridesharing organizations
- Enforcement agencies
- Contractors

The team approach — used during initial traffic management planning and implementation and throughout the project — is essential in obtaining coordination and cooperation between the agencies and organizations mentioned above. Traffic management during major freeway rehabilitation does not stop once construction begins and the management plan has been established. Among other advantages, team efforts maintain the ability to modify traffic management actions in the corridor in response to changing traffic conditions (Ref 4.14).

4.5.2 Off-site traffic management

The objective of off-site traffic management strategies is to find and to use the additional capacity that is often available from surrounding facilities. One of the most effective mitigation strategies is to provide substitute routes capable of carrying the additional traffic being diverted from the freeway under rehabilitation.

Good substitute routes are difficult to select, since they are seldom acceptable to the traveling public, especially in urban areas where the surrounding network is already

saturated. Moreover, high traffic volumes from the main route cannot be easily accommodated by smaller roads. Road users may also be concerned about longer driving time, increased delays and operating costs, lower levels of service, higher accident rates than at the work zone itself, and congestion through the alternate route (Ref 4.7). In addition, not all arterials near a freeway may be desirable or feasible candidates for diversion routes (e.g., the arterial may pass by large schools, hospitals, or traffic-sensitive neighborhoods).

Again, a team effort must be adopted in determining the best alternative routes. These routes, in turn, may require improvements before they are capable of handling the additional traffic. These improvements can range from simple measures (i.e., revision of signal-timing plans, parking restrictions, one-way streets, turn restrictions, truck traffic restrictions, limits on delivery hours, reduction in tolls on alternate routes, and the presence of law enforcement officers at critical intersections) to more complex and expensive improvements requiring roadway repaving, widening, or channelization, and adequate vertical clearances and turning radii to accommodate trucks (Refs 4.3, 4.14, 4.21).

Coordination among agencies is also important in order to offset or delay construction work on alternate routes during the rehabilitation of the main route. Examples of implementation of traffic diversions are available in the literature (Refs 4.17, 4.19, 4.20). Public information campaigns play a key role in the successful handling of traffic.

4.5.3 Alternative-mode Transportation Systems Management (TSM)

The purpose of TSM strategies both within and outside the work zone is to help enhance the capacity of a roadway by altering modal splits (Refs 4.6, 4.14, 4.21). Mode shifts include changes from low-occupancy vehicles to high-occupancy vehicles (HOV) and transit. HOV ramps that allow priority passage of carpools, vanpools, and buses through a work zone can be implemented in conjunction with strategies outside the work zone, such as ridesharing incentives and special bus services that utilize these ramps.

Other TSM strategies for handling traffic in the corridor under rehabilitation may include additional bus transit, park-and-ride lots with express bus service, commuter rail service, ferry service, etc. TSM strategies that have been successfully used in rehabilitation projects are documented in the literature (Ref 4.14).

The effectiveness of any particular TSM mitigation measure, however, will vary widely. Rideshare programs, for example, have been very successful in some instances, but not in

others. Similarly, transit improvements that worked well in some situations might not be as effective elsewhere.

4.5.4 Other measures

Travel demand changes (other than mode and route shifts) may also reduce adverse impacts linked to major rehabilitation. Examples of travel demand changes are reductions in trip making, trip chaining, changes in departure times, or changes in destination choice (Ref 4.6).

Telecommuting can reduce demand on the infrastructure. Telecommuting involves working in a location other than the traditional office – that is, the home, satellite centers, or neighborhood centers (Ref 4.8). The practicability of telecommuting is dependent on the user's job (because it has to be adaptable to telecommunication) and on the employer's acceptance of such an agreement. Moreover, the employer must have the networking equipment. A few private firms and local governments have initiated telecommuting opportunities for some of their employees; such efforts represent a viable alternative to traffic management strategies for the near future.

Another method that can reduce the effect of congestion on the facility is flex-time, which is intended to reduce the sharpness of the peak demand periods for the morning and afternoon traffic. Flex-time, however, has limited usefulness in urban areas where both the peak and off-peak demands are high (Ref 4. 8).

Nevertheless, all traffic management mitigation strategies must be considered collectively as a package solution. While any one measure might do relatively little to reduce unwanted impacts of highway rehabilitation projects, combining them might produce highly desirable effects (Ref 4.6).

4.6 MITIGATION THROUGH PUBLIC RELATIONS

The purpose of a public relations program is to establish a communication link between roadway users, those in charge of the rehabilitation project, and the state. Good communication is essential to increasing the public tolerance of temporary inconveniences resulting from construction operations. The public must be informed about the particulars of the project (e.g., total length, expected delays, and the completion date). Greater public

support is likely to occur if users are informed about the purpose of the rehabilitation, the future benefits to be derived from it, and the details of the mitigation measures that are in place. Because good communication is always a two-way exchange, users must be provided with the opportunity to express their concerns.

Information can be disseminated to regular commuters by door-to-door handouts; direct mass mailings; indirect mailings using materials designed for enclosure with utility bills; handouts at parking garages, at intersections and ramps, on buses, and on trains; by interviews with news media; informational materials distributed through employers, chambers of commerce, various professional and business organizations; announcements at public events; paid advertising; and speaker bureaus (Ref 4.21). A public relations program can also help in managing traffic operations through and around the work zone. Roadway users must have advanced warning about potential disruptions to normal traffic activities as well as information about those alternatives that minimize the disruption. Highway advisory radio can provide information about the types of construction operations in progress, the expected duration of these operations, changes in lane configurations, and the duration of these changes. A public relations program should also consist of community meetings, press releases, maps of the project's construction phases, re-routing alternatives, and emergency routing. It is also important to provide telephone assistance to the public (Ref 4.8).

4.7 SUMMARY

The categories of mitigation strategies identified in this chapter give a broad sense of the different alternatives available when implementing mitigation measures for highway rehabilitation. Some of these mitigation strategies are intended to reduce the project duration by means of simpler designs, better equipment, or the use of rapidly setting materials. Innovative contracting practices are the most effective way to encourage contractors to improve their efficiency and to reduce the time required for project completion. Other strategies are intended to reduce traffic demands at the project location, to provide safe and expeditious movement of traffic through the work zone, to use the available capacity on surrounding facilities, to maximize the capacity of a corridor by altering modal shifts, and to build public support and tolerance of the inconveniences resulting from highway rehabilitation. All these mitigation strategies should be applied in combination for better results. The direct benefits will be passed on to the motorists.

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CHAPTER 5. FACTORS AFFECTING THE COST OF ACCELERATED CONSTRUCTION

This chapter presents an overview of traditional methods for determining project duration and describes some of the innovations in contracting practices that have been used for acceleration of projects. Also the general criteria used for warranting acceleration of projects are summarized herein. Potential impacts for the transportation agency, contractors, and the public arising from accelerating construction are discussed in another section. Finally, typical cost components for highway projects and the most common methods of rehabilitation by state transportation agencies are used to characterize the construction industry.

5.1 TRADITIONAL PRACTICES IN DETERMINING PROJECT DURATION

The state transportation agency spends considerable resources determining a reasonable time of completion for a construction or rehabilitation project, since each day of work beyond the predicted completion date generates costs for the agency, road users, and the general public. Contracts providing more time than is actually needed for a project may discourage innovative management or construction techniques, encourage contractors to bid more work than can be handled in a timely manner, and increase agency administrative and engineering costs. Contracts specifying less time than necessary for completion of a project, on the other hand, can result in higher bid prices and can eliminate some qualified contractors. But contracts specifying less time than necessary for completion of a project also encourage good management, high productivity, and lower administrative and engineering costs (Refs 5.1, 5.2).

5.1.1 Criteria for determining project duration

The transportation agency has the responsibility of determining the number of days allocated to conduct and to finish a rehabilitation project. Traditionally, the length of contract time has been based on one of the following criteria (Ref 5.1):

- a. **Construction season limits:** Favorable weather for certain surfacing and paving projects is present only a portion of the year. Therefore, the time limits are set at or shortly after the end of the construction season.

- b. **Quantity or production rates:** The agency computes a daily production rate for each critical activity that could significantly affect the project duration. Production tables, for work items used to specify the contract time with this criterion, are based on experience and past data from completed projects.
- c. **Work-flow techniques:** Techniques, including the critical path method (CPM), project engineering control (PROJECT), and program evaluation and review technique (PERT), are used for planning construction projects. These techniques are recommended for large, complicated projects requiring extensive coordination of materials, equipment, personnel, and administrative support.
- d. **Estimated costs:** The number of working days required to complete a construction project is related to the cost of the project. The procedure used by the New Mexico DOT, which is presented in a later section, is a sample of this criterion of using the project cost to estimate project duration.

5.1.2 Estimating Contract Working Days

This procedure developed by the New Mexico Department of Transportation (Ref 5.1) relates the project cost to the estimated number of workdays required to conduct the construction project under a regular schedule. This procedure can be used as input to estimate the initial duration required by the model, if the estimated project duration under conventional construction is not available. The steps listed below detail the process of estimating contract workdays for a construction project:

1. The current project cost estimate needs to be adjusted by the construction cost index to reflect 1992 construction costs. The table was developed for 1970 costs but was modified to reflect 1992 costs using the construction costs indices from Ref 5.13:

Table Estimate = Current Estimate (1992 Cost Index / current index)

2. Using the table estimate, select the base value for workdays from the contract workday table (modified from Ref 5.1 to reflect 1992 construction costs):

Table estimate (1992)	Base Value (days)	Acceptance Range
Less than \$350,000	-	< 100
\$350,000	100	75 - 125
\$900,000	125	100 - 150
\$1,800,000	150	120 - 180
\$2,600,000	200	170 - 230
\$3,500,000	250	215 - 285
\$7,000,000	300	260 - 340
\$11,000,000	350	305 - 395
\$18,000,000	400	350 - 450
\$25,000,000	450	400 - 500

Table 5.1. Contract Work Table (Ref 5.1).

3. Select the appropriate adjustment factors for project complexity as follows:

Contract Type:

New Construction	1.00
Reconstruction	0.90
Overlay & Widening	0.80
Overlay	0.70
Safety	0.60

Number of major structures:

0	0.90
1 - 2	0.95
3 - 5	1.00
> 5	1.10

Traffic handling:

Minor	0.90
Moderate	1.00
Major	1.10

Location:

Rural	0.90
Urban	1.10

Terrain:

Flat	0.95
Rolling	1.00
Mountainous	1.15

Special considerations:

Unusual items	0.9 - 1.1
Other	0.9 - 1.1

4. Compute the number of workdays using the workday equation.

$$\text{Workdays} = \text{Base Value} (1 + \text{SFactors} - \text{Number of factors})$$

5. Compare the number of workdays determined in Step 4 with the range of acceptable values in the contract workday table.

Figure 5.1 shows the relationship between the estimated project cost and the estimated project duration according to the New Mexico method:

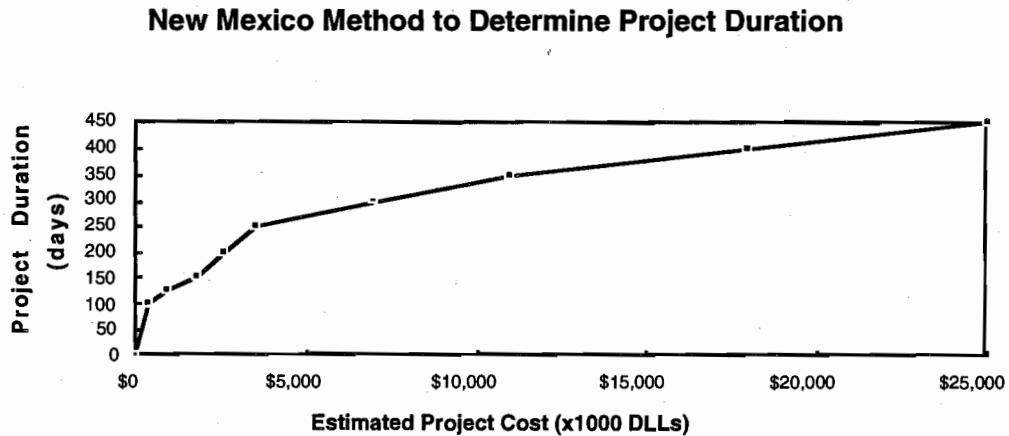


Figure 5.1. Relationship between project cost and duration (Ref 5.1).

5.2 INNOVATIVE CONTRACTING PRACTICES

The traditional method of awarding construction contracts in the United States involves a competitive bidding process whereby the construction is awarded to the bidder submitting the lowest price. Originally, the main objective of the competitive bidding system was to guard against corruption and mismanagement by public officials. Bidding was also supposed to provide the taxpayer with projects at the lowest possible price.

The current low-bid system, however, is inefficient because low price and high quality are more often than not contradictory terms. Low bidders frequently do not produce the most desirable combination of contract cost, product quality and project duration (Ref 5.3). Recently, it has been recognized that the criteria for a winning bid should include evaluation of the contractor's ability and commitment to provide project quality and minimum project duration, in addition to low-bid cost.

Several innovative contracting practices have been proposed (Refs 5.2, 5.4) to enhance the process of delivering highway services, especially in highly congested urban areas. These contracting practices are presented in the following paragraphs.

5.2.1 Cost-Plus-Time Bidding

The cost-plus-time bid concept (Refs 5.2, 5.4, 5.5) is a modification of the low-bid system with the added element of time. Contractors must submit a proposed contract time with their bid price. The low bidder is the one that provides the lowest total cost combination of both price and project time. The transportation agency determines the daily cost to the public resulting from the construction project. This cost should include the cost of administrating the construction project and the daily cost of inconveniences to the public because of delays and additional operating costs during construction.

Calculation of the total project cost is based on the following equation:

$$CT = C + R \cdot T$$

Where:

CT = Total combined project bid price

C = Contractor's bid price

R = Time value associated with inconveniences during construction

T = Contractor's time bid

This formula is used only to determine the lowest bidder not to determine payment to the contractor.

The advantages of using this concept (Ref 5.5) are summarized as follows:

- a) For critical projects that have significant impacts on road users, these impacts can be minimized by giving contractors the flexibility to establish their own completion time and by rewarding the more efficient contractors.
- b) The fundamental approach of the competitive low-bidding system is maintained.
- c) Based on limited usage to date, we know that costs have not proven to be significantly higher, and contract times established by the contractors have been reasonable and normally shorter than expected.
- d) Projects in which this method has been incorporated generally have attracted contractors that have efficient construction and engineering management

practices and that have sufficient supervisory control to keep large projects on schedule.

5.2.2 Lane Rental

This is a further modification of the cost-plus-time concept. In the lane rental method, a rental charge is assessed only when the contractor closes a portion of the roadway. The rental charge is based on the number and configuration of lanes closed. For example, the fee for having one lane and one shoulder closed would be less than that for having two lanes closed. In addition, higher rental amounts can be assessed for peak periods of the day. The rental charge is deducted monthly from the amount owed the contractor for work completed. Table 5.2 shows some examples of rental charges assessed on daily and hourly bases. The purpose of the lane rental method is to encourage contractors to plan their work so as to ensure that road user inconvenience is kept to a minimum in terms of both time and lane closures.

Closure or obstruction	Daily Rental Charge \$	Hourly Rental Charge \$	
		6:30 - 9:00 a.m. and 3:00 - 6:00 p.m.	All other hours
One lane	20,000	2,000	500
One shoulder	5,000	500	125
One lane and shoulder	25,500	2,500	625
Two lanes	45,000	4,500	1,250
Two lanes and shoulder	50,000	5,000	1,375

Table 5.2. Examples of lane rental charges (Ref 5.5).

5.2.3 Incentive / Disincentive Provisions

Highway construction and rehabilitation projects located within heavily trafficked sections are potential candidates for the use of incentive and/or disincentive provisions (Ref 5.2). An incentive is a payment to the contractor for early completion of a specified task. A

disincentive, on the other hand, is usually identified as liquidated damages that are charged to the contractor for failure to complete the work within the time specified.

The amount of the incentive and the disincentive must be of significant benefit to the contractor to encourage interest, to stimulate innovative ideas, and to maintain profitability while meeting tight schedules. The maximum amount of the incentive payment should be based on the expected savings to the public from an early completion, including those savings in delay and operating costs to road users, and reductions in accidents and pollution. The incentive payment should not exceed 5 percent of the total project cost (Ref 5.6) The maximum incentive/ disincentive was \$30,000 /day for a major urban freeway project.

5.2.4 Accelerated Projects Without I/D Provisions

There are alternative ways to accelerate rehabilitation projects without specifying incentives for early completion. Multiple contract lettings and other provisions may be implemented to reduce the number of allocated days for highway rehabilitation as follows:

a) Multiple contract lettings

A large highway construction project may have the option of letting the total work in a single contract or multiple contracts. A single contract means simpler contract administration for the owner and an easier traffic handling scheme within the project limits. Multiple contracts, unlike a single large contract, make it possible for several contractors to work simultaneously so that more material and management resources can be invested into the work, and, consequently, the work is completed more rapidly. The disadvantage of multiple contracts is the increased cost of management and administration (Ref 5.2).

b) Other provisions

For accelerated projects without I/D provisions, plans and specifications should clearly state that the contractor is expected to exert extra effort to meet the project's timetable, and they should also include ways to encourage efficiency, such as the following (Ref 5.7):

- 1) a note that more than one manpower shift in a 24 hours period will be necessary to meet the schedule:

provision that disqualifies the contractor from bidding on other projects if he falls substantially behind schedule;

- 3) a provision to withhold part of the monthly payment owed the contractor if he falls behind schedule.

5.3 CRITERIA FOR DETERMINING PROJECT ACCELERATION

Using recent experience, researchers have identified the criteria that affects the decision of whether to accelerate highway rehabilitation projects (Refs 5.2, 5.7, 5.8). Some guidelines are summarized here to identify those sensitive projects warranting accelerated construction:

1. Level of congestion in the facility under rehabilitation. To date, most freeway facilities experience congestion even if there is no construction or rehabilitation underway. Congestion, as a consequence of the disruptions to traffic by the work zone, is the most commonly used criterion for accelerating rehabilitation. When empirical formulas are used to conduct a work zone capacity analysis, researchers find that accelerating is usually appropriate whenever hourly volumes reach approximately 1,500 veh/hr/lane (Ref 5.8). A more informal approach is based on experience; projects located on a freeway with a traffic density above 15,000 vehicles per day per lane of average weekday traffic merit accelerated construction (Ref 5.7).
2. A second criterion is associated with projects that may involve substantial increases in user costs. Substantial, in these cases, is defined as \$100,000 or 20 percent of the estimated cost of the project.(Ref 5.2).
3. Other criteria are used as well to justify accelerated construction (Refs 5.2, 5.7):
 - Projects in which the expected delay is 10 minutes or more for each vehicle passing through.
 - Projects involving prolonged closure of one or more freeway lanes.
 - Projects in which access to retail business will be restricted or inconvenienced because of construction operations.
 - Projects needed by a specific date to provide service to some other traffic generator.

- Cost savings and/or safety benefits outweigh the cost of incentives and additional construction costs.

5.4 CLASSIFICATION OF ACCELERATED PROJECTS TO DETERMINE DURATION

Projects are classified according to the level of work that will be required for early completion in order to determine project duration under an accelerated schedule. The following classes are identified (Ref 5.7):

- a) **Conventional.** This is the normal construction schedule for projects that do not require an accelerated pace. Usually, only one shift is used with a workload from 40 to 60 hours per week. Traditional contracting methods are used.
- b) **Accelerated.** These types of projects meet one or more of the criteria, discussed before, that indicate acceleration is warranted. The contract time should be determined on a calendar day basis, excluding Sundays and holidays. The level of work suggested includes two shifts working a total of 96 hours per week.
- c) **Incentive / Disincentive.** This is a special case of the accelerated category applied to critical projects in which severe disruptions to heavy traffic volumes and high costs to users are involved. The level of work in this category is expected to be 120 hours per week with a minimum of two shifts.

5.5 IMPACTS OF PROJECT ACCELERATION

Conducting rehabilitation activities so that the inconvenience to the traveling public remains as minimal as possible is a challenge for both the transportation agency and the construction industry. The sooner such projects are done, the sooner the public will benefit from them. However, accelerating construction can have certain consequences for the transportation agency, the contractor, and the public as well.

5.5.1 Impacts to the transportation agency

The greatest impact to the transportation agency from accelerated rehabilitation activities is the increase in the cost of the project. The cost of accelerating construction has been around 10 to 20 percent more than the costs of a conventional construction schedule, according to past experience (Ref 5.7). Most of this cost increase is passed on by the

contractor to the transportation agency. In addition, the agency may have to bear the cost of early completion incentives, which usually is about 5 percent of the contract amount (Ref 5.7).

Also the cost of administration increases as more personnel and overtime is required to provide adequate inspection of work activities conducted at night or during weekends. Correspondence and paperwork also increases two to three times normal levels because contractors document every occurrence that might allow a claim for time if they failed to earn the incentives or allow a variance for payment of liquidated damages if they fell behind schedule (Ref 5.7).

The potential reduction in the quality of work by the contractor under an accelerated schedule is another concern of the transportation agency. Most of the problems with quality arise as a consequence of reduced visibility during nighttime operations (Ref 5.8).

5.5.2 Impacts to the contractor

Even though most of the additional costs of accelerated construction is passed on to the transportation agency, the contractor might be concerned about such additions because accurate estimates are difficult to assess when proportions of a project are performed during the day and when added costs of night constructions are buried in other pay items (Ref 5.8).

Most of the added costs are attributed to premium wages paid for overtime and shift work. Surveys of construction companies and experience (Refs 5.7, 5.8) show that labor costs can increase about 18 percent owing to shift premiums (work at night). The overall wage rate, including overtime and night-shift premiums, can increase about 50 percent.

The cost of materials could rise significantly if more expensive materials, such as fast-setting or early-strength products, are required to expedite a lane opening. Moreover, those contractors who do not have their own batch plants must pay a higher cost if the plant needs to remain open at night or during weekends.

Artificial lighting in the work place must be provided during nighttime construction. The lighting must be sufficient to permit clear visibility without creating a glare. Some operations are best performed with the use of supplementary hand-held lights, portable floodlights, or spot lighting. The cost of lighting is not considered burdensome, since it constitutes approximately a 1 percent cost increase on the total contract (Ref 5.8). Still, it is an expenditure not encountered on daytime projects.

Insurance rates also increase for accelerated construction because scheduled overtime and nighttime operations are associated with higher work-related accident rates. The increase in insurance rates can be 30 percent higher than conventional construction rates (Ref 5.7).

Several studies (Refs 5.9, 5.10) have been conducted to determine the effects of scheduled overtime in construction productivity. Results show that productivity can be significantly reduced after 9 to 12 weeks of sustained overtime operations. Productivity for a 60 hours week can be as low as 0.65 for long periods of scheduled overtime. This introduces the concept known as the "point of no return", often used to describe productivity loss owing to overtime. The point of no return is when the overtime schedule no longer produces more than a standard 40 hours week. In this fashion, keeping worker morale and productivity high is difficult over long periods of scheduled overtime, and usually it requires that additional measures be taken, such as giving more time-off.

Another problem related to long periods of scheduled overtime is the increase in turnover rates, which can be six times higher than the rates encountered with conventional construction (Ref 5.7). Productivity is also affected if the work site is overcrowded; crews can interfere with each other when a contractor, attempting to avoid falling behind schedule, puts more crews on site than needed. Usually, additional crews are hired through subcontractors, requiring better coordination. Communication between the transportation agency and the actual crew conducting the activity becomes more complicated. Inspection of the work is a problem if lack of staff from the transportation agency prevents the contractor from continuing the work during non-conventional hours. Decision making and approval authority for field changes must be available as construction is happening, regardless of the hour or date.

Noise from construction operations may be of particular concern if noise ordinances are more stringent at night, specially near residential areas that restrict certain activities from being conducted at night (Ref 5.8). Equipment breakdowns can also harm productivity if repair crews or backup equipment are not readily available.

Despite the potential negative effects of double shifts and nighttime operations, which are related to accelerated construction, productivity can benefit from an easier delivery of materials to the work site during periods of reduced traffic volumes. Also, it is more feasible to close more than one lane during low traffic volume periods.

Safety for both drivers and workers is a serious concern for the transportation agency and the contractor. Some studies have concluded that work-related accidents increase when

the intense effort to accelerate the work imposes a demanding work schedule on crews (Refs 5.9, 5.10). Fatigue and loss of morale can contribute to the increase in injuries and to the rate of incidence of work-related accidents. Reduced visibility, higher speeds, and a higher number of intoxicated or inattentive drivers during night construction increase the possibility of accidents, when compared with a conventional construction schedule with exclusive daytime operations.

The quality of work accomplished during an accelerated construction schedule is also a concern of both contractors and the transportation agency. Reduced quality may result from nighttime operations owing to the difficulty in providing sufficient lighting for the site. The placement of both asphalt concrete (AC) paving and Portland cement concrete (PCC) is affected during nighttime. Unevenness of the paving surface, inconsistency in the mix, poor compaction, and cold joints are among the problems identified by contractors and transportation agencies (Ref 5.8). In addition, cooler nighttime temperatures may limit PCC placement time in some areas. However, during the summer months, nighttime work offers more comfortable working temperatures, better workability and curing of concrete. In fact, it has been demonstrated during Project 1244 that a PCC placed at night has better quality than the sections placed during the day. Although the quality may meet established standards, defects in the finished surface for both asphalt and PCC pavements are apparent. Defects appear to be a trade-off that agencies are willing to accept for reduced congestion (Ref 5.8).

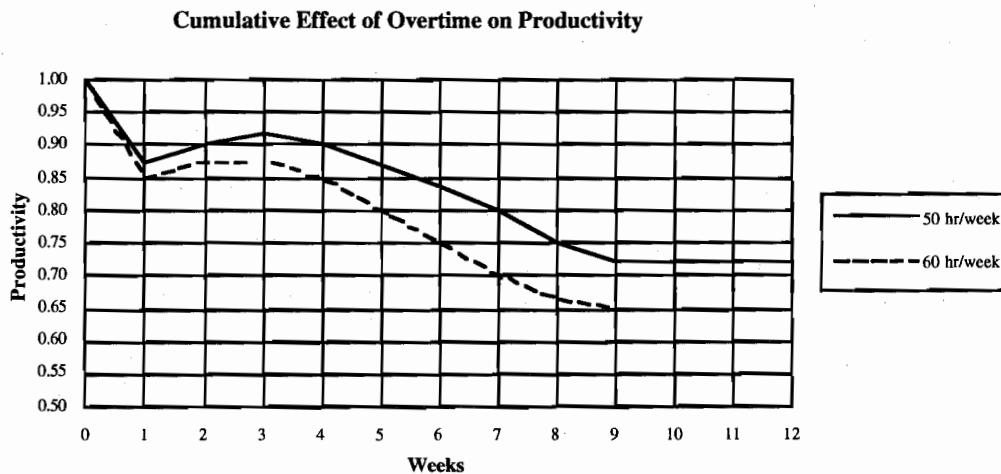
5.5.3 Impacts to the public

Even though the public is impacted by an accelerated construction schedule through increased exposure to hazards during nighttime operations, a lower quality of work, and increased construction costs, they receive most of the benefits. By minimizing the period of traffic disruption owing to rehabilitation activities, engineers can reduce total user costs. Reduction in construction time minimizes delays and additional operating costs associated with speed change cycles. Accident costs are reduced by minimizing the time traffic is exposed to hazards present in the work zones (Ref 5.6). Also, road users are more likely tolerate the inconveniences of work zones if they see active crews and daily progress rather than abandoned work areas.

5.6 ESTIMATION OF PRODUCTIVITY LOSS DUE TO SCHEDULED OVERTIME

Several studies (Refs 5.9, 5.10) have concluded that productivity is reduced for long periods of scheduled overtime. An equation was obtained relating productivity to the number of work hours per week based on the following assumptions:

- a. Productivity for a 40 hours week is 1.00 or 100 percent.
- b. Productivity for a 50 hours week is as low as 0.75 for long periods of scheduled overtime (see Figure 5.2).
- c. Productivity for a 60 hours week is as low as 0.70 for long periods of scheduled overtime (see Figure 5.2).



Figure

5.2. Cumulative effect of overtime on productivity (Ref 5.9).

The curve shown in Figure 5.3 is the best fit for a curve linking the three points of productivity for work loads of 40, 50, and 60 hours per week, assuming that the project duration is at least nine weeks.

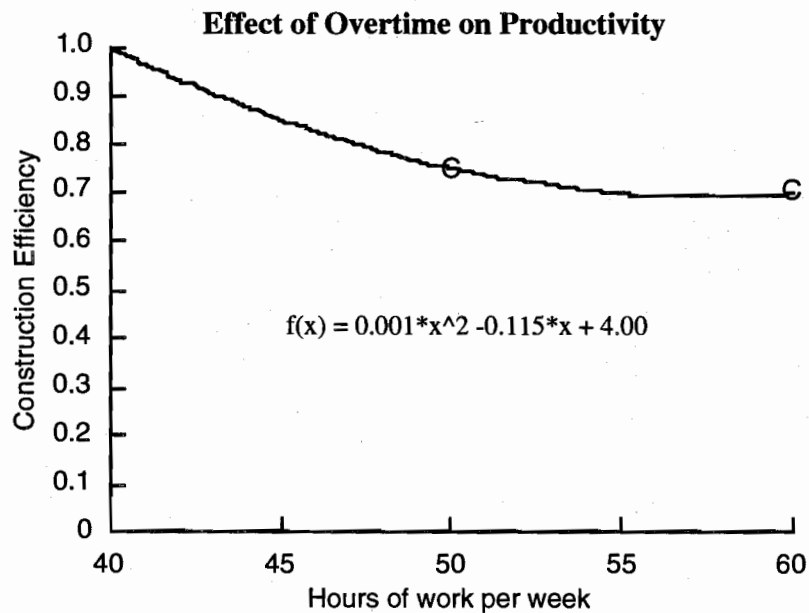


Figure 5.3. Effect of scheduled overtime on construction productivity.

Therefore:

$$a_1 = 4.00 - 0.115 W + 0.001 W^2$$

Where:

a_1 = Productivity of construction crew under scheduled overtime of at least 9 weeks.

W = Work hours per week shift

5.7 REHABILITATION METHODS AND THEIR COST COMPONENTS

Estimating the cost of a project is a very hard task since the type of work and local conditions have a major influence on the cost. An accurate estimate of construction costs can be made only for each specific project. However, the construction industry follows certain "rules" that are common to the majority of its projects, and therefore, these projects can be characterized by a simple analysis.

5.7.1 Cost Components

Every project cost estimate can be divided into several cost components, according to the type of work. The basic components are labor, materials, equipment, and profits. The following table contains the most used cost components for highway construction and the common percentage of these cost components from the total construction cost:

Item	Typical percent of total
Labor including payroll taxes	17 - 20 %
Materials	53 - 58 %
Rental equipment inc. gas, oil, grease	2.5 - 3 %
Miscellaneous expense	5 - 7 %
Insurance	1.6 - 2 %
Gross profit	12 - 15 %

Table 5.3. Typical cost classification for highway construction projects (Ref 5.11).

The procedure to estimate additional costs owing to accelerated construction consists of increasing the percentage of certain cost classifications in the same proportion as the expected cost increase of that item. For example, if the cost of labor is expected to increase by 50 percent then the percentage of labor as the total cost will also be increased by a factor of 1.5.

Since most of the additional accelerated construction costs stem from increases in labor and/or special materials, the percentages of these items are explicitly used in the equation to estimate additional costs. If the additions come from other items, the increments must be added through the complementary costs, which are those cost items other than labor or materials and equipment. The following are the cost items used in the equation presented in the next chapter:

- Labor (L)
- Materials and equipment (ME)
- Complementary costs (1 - L - ME)

5.7.2 Rehabilitation methods most commonly used

According to a recent survey, the rehabilitation and maintenance methods most used by state departments of transportation are summarized in Table 5.4, including the estimated cost per lane-mile and the average life of each method (Ref 5.12).

Asphalt overlay is the rehabilitation method most often used; however, hot-mix asphalt recycling is becoming popular, since it lasts as long as overlaying, yet costs less according to survey results. Concrete overlays have a higher initial cost than asphalt overlays, but on heavily traveled highways, disruption to traffic as a result of rehabilitation activities means that drivers pay a high cost in annoyance and delays. Moreover, providing a long lasting rehabilitation method such as a concrete overlay, which has an average life of 23.2 years, means avoiding one or more rehabilitation cycles.

Rehabilitation Method	% State Agencies Using	Average Life	Estimated cost/lane mile (1989)
Asphalt Overlay (avg 4 in. thick)	100.0	11.7 yr	\$ 62,790
Hot mix asphalt recycling	58.6	11.8 yr	\$ 42,829
Crack and seat, with overlay	37.9	11.8 yr	\$ 103,940
Concrete grinding	31.0	7.9 yr	\$ 26,339
Cold in-place asphalt recycling	27.3	11.0 yr	\$ 28,555
Concrete undersealing	24.1	6.0 yr	\$ 14,539
Cold mix asphalt recycling	23.5	9.8 yr	\$ 45,400
Asphalt remixing	23.1	8.2 yr	\$ 57,724
Concrete overlay (avg 6 in. thick)	22.8	23.2 yr	\$ 101,250
Maintenance Method			
Asphalt surface treatments	80.1	5.7 yr	\$ 8,229
Concrete joint/slab repair	75.9	8.3 yr	\$ 59,168
Slurry seal	37.9	5.2 yr	\$ 12,255

Table 5.4. Rehabilitation and maintenance methods and costs (Ref 5.12).

The cost figures and average lifetimes summarized above are only guidelines, since they reflect the average value reported by the state agencies. The actual cost of rehabilitation must be assessed for the specific conditions prevailing in the region, and the actual life of any rehabilitation or maintenance method will depend on many factors:

- The way the work is completed
- The quality of the materials used
- The amount and type of traffic
- Weather (freeze/thaw cycles)
- Drainage

5.8 SUMMARY

This chapter was intended to provide further analysis of the innovative contracting practices for the highway construction industry. This new approach for determining project duration and the best bidder basically identifies a value for the time that the normal traffic operations will be disrupted or inconvenienced. Therefore, the awarded contractor is the one who provides the best combination of construction cost and time for completion. Incentives for early completion and disincentives for failure to complete the work within the specified time are other ways to encourage contractors to improve their efficiency. The most common criteria for implementing one of these contracting innovations is the level of congestion in the facility under rehabilitation. Accelerating the rehabilitation project may generate some impacts to the transportation agency, contractors, and the public. Among these impacts are the increased cost of construction, potential reduction in quality during nighttime owing to low visibility, safety and noise problems during night, and loss of productivity owing to extended periods of overtime. An equation was developed to estimate the productivity loss during long periods of scheduled overtime, and the most commonly used rehabilitation methods by the state agencies were reviewed.

5.9 REFERENCES

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CHAPTER 6. ESTIMATING THE EFFECTIVENESS OF ACCELERATED HIGHWAY REHABILITATION

This chapter presents a methodology useful in analyzing the effectiveness of accelerated highway rehabilitation projects in mitigating the adverse impacts of reconstruction on road users and on the environment.

6.1 COST-EFFECTIVENESS ANALYSIS

Highway rehabilitation projects are intended to restore and to provide additional service life to a segment of the infrastructure whose deterioration has caused user operating costs to increase. Many of these projects, however, generate complex impacts, including user delays, additional operating costs, accidents, and emissions from vehicles — all of which are difficult to measure.

Highway economic analyses are routinely used to determine the appropriate level of investment required in a rehabilitation project to obtain specific objectives or to reduce the magnitude of negative impacts. Economic analysis can be divided into two general categories: (1) cost-benefit analysis, and (2) cost-effectiveness analysis (Ref 6.1). The cost-benefit analysis is a quantitative assessment of the economic benefits from different investment alternatives using a common measurement, usually dollars. The cost-effectiveness analysis, on the other hand, sprang from the recognition that transforming all major impact measures into monetary terms in a credible manner is difficult; this analysis suggests that other, more meaningful measures than dollar costs could be used when major social and environmental impacts are involved.

For rehabilitation alternatives that differ in both cost and degree of impacts (i.e., maintaining the maximum number of open lanes to traffic versus minimizing project duration), the effectiveness should be expressed in some standard unit. Using the effectiveness analysis, researchers can obtain a money-based index that is helpful in comparing rehabilitation alternatives that are intended to reach the same type of objective. Such an index might be computed as follows:

$$\text{Cost-effectiveness Index} = \frac{\text{Units that measure consequences}}{\text{Monetary unit in \$}}$$

Cost-effectiveness measures are useful in providing justification for an investment, even if they do not provide explicit measures of return on investment. For example, the

additional investment required for accelerating the rehabilitation can be justified by means of the net benefits from reduced user costs. However, if the cost of expediting the rehabilitation is similar or even greater than the expected benefits to users, other measures of effectiveness may be used to justify the investment, such as the reduction in vehicle emissions or in fuel consumption per dollar invested. No single criterion satisfactorily summarizes the relative cost-effectiveness of different rehabilitation alternatives, and the relative weight of each measure of effectiveness will depend on the local transportation goals.

Below are listed possible measures of effectiveness for evaluating accelerated rehabilitation alternatives:

- 1) Decrease in total vehicle delay time per additional dollar invested
- 2) Decrease in accidents, injuries, and fatalities per additional dollar invested
- 3) Change in air pollution emissions per additional dollar invested
- 4) Decrease in fuel consumption per additional dollar invested

6.2 METHODOLOGY TO ASSESS EFFECTIVENESS OF ACCELERATING HIGHWAY REHABILITATION ACTIVITIES

The basic consideration of this analysis is that the total project cost is the sum of construction plus impact costs to users and the environment. A trade-off exists if there are savings in the total project cost from the money invested in accelerating the rehabilitation activities. Within these parameters, the analysis will compare different construction methodologies and traffic management techniques, and will assess the effectiveness of competing strategies, such as maintaining the maximum number of open lanes during construction versus a shorter construction period with greater delays to motorists.

Quantifiable impacts from highway rehabilitation are measured in user costs. These costs (e.g., travel time, vehicle operating costs, and accidents) are a function of the traffic volumes disrupted by the rehabilitation work. User costs start to increase rather rapidly when hourly volumes reach a value around 1,500 veh/hr/lane on the remaining open lanes, which is the approximate equivalent of the work zone's capacity. Since traffic volumes are not evenly distributed across the day, the existing traffic distribution on the facility in need of

rehabilitation plays a very important role in the amount of additional user costs that certain closure strategies will impose on road users.

Moreover, the capacity of the remaining open lanes on which there is activity is lower than that of lanes having the geometric restriction of the work zone but no activity, owing to a characteristic of human behavior that compels drivers to slow down when they see equipment and crews working on adjacent lanes. Therefore, longer work schedules (i.e., multiple shifts and overtime) will generate even greater impacts to the traveling public. Longer times of restricted capacity and longer exposure to road hazards are the main reasons for the increase in user costs that result from an accelerated construction schedule, especially if the extended work hours disrupt periods of peak traffic demands (afternoon peak of a two-peak traffic distribution). Even though longer work schedules associated with multiple shifts during accelerated construction generate higher rates of user costs per day, which is represented in Figure 6.1 by a steeper slope, the reduction in project duration can reduce the absolute amount of user costs. Figure 6.1 shows a schematic representation of the user costs generated by conventional and accelerated work schedules.

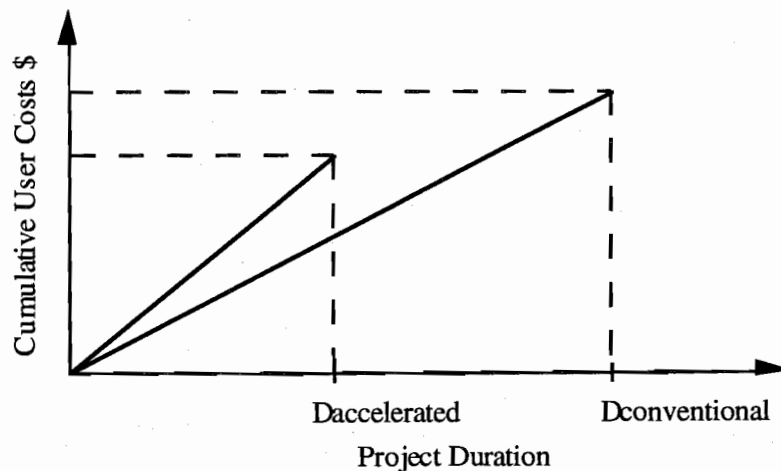


Figure 6.1. Effect of project duration on user costs.

The cost of construction is also affected by project duration because of premium labor charges for overtime and night shifts or the additional costs of special materials or equipment. The cost of construction also increases because productivity and worker morale decrease when scheduled overtime is extended for long periods of time. Figure 6.2 shows the effect of project duration on the cost of construction.

Experience in completed projects undertaken at accelerated rates shows that highway rehabilitation can be completed in approximately half the time required for

conventional construction schedules, with cost increases from 10 to 20 percent of the contract cost (Ref 6.2). Given these experiences, this study proposes a methodology for assessing the effectiveness of accelerated highway rehabilitation in mitigating additional user costs and fuel consumption resulting from the presence of the work zone.

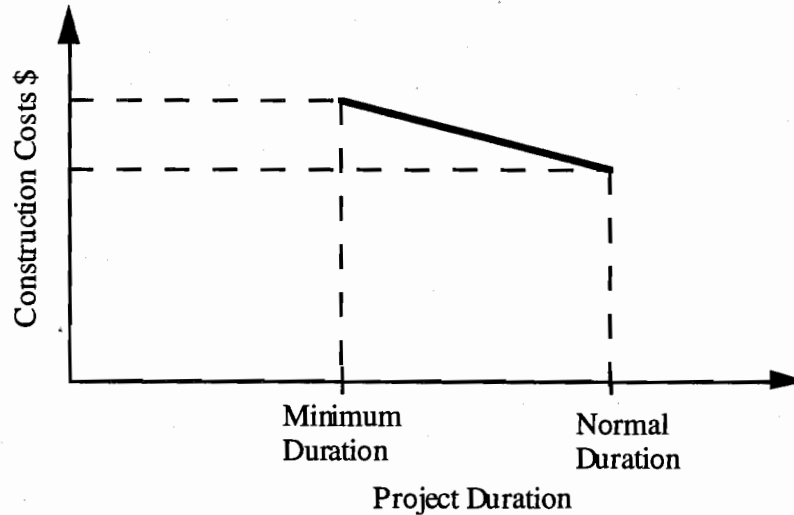


Figure 6.2. Effect of project duration on cost of construction.

6.2.1 Estimating the reduction in project duration

As discussed above and in an earlier chapter, the duration of a rehabilitation project can be reduced if work is conducted at an accelerated rate. An equation is proposed here to estimate the reduction in project duration as a consequence of an accelerated schedule. For estimating the potential reduction in duration, the following project types were considered (Ref 6.2):

Project Classification	Working Period (hr/work week)
Conventional	One shift: 40 - 60
Accelerated	Two shifts: 96
Incentive/Disincentive	Two shifts: 120

The equation is based on the following assumptions:

1. scheduled overtime reduces construction productivity; and
2. using conventional construction, accelerated projects can be completed in half the time required of conventional projects.

Duration of accelerated construction:

$$D_{ac} = \frac{D}{\frac{(\alpha_1 W_1 + \alpha_2 W_2)}{NW}} \geq 1/2 D$$

where:

- D_{ac} = Project duration under accelerated schedule;
- D = Project duration under conventional construction;
- α_1 = Productivity of construction crew under scheduled overtime;
- α_2 = Productivity of construction crew in the 2nd or night shift;
- W_1 = Work hours per week shift 1;
- W_2 = Work hours per week shift 2; and
- NW = Normal week work load.

6.2.2 Estimating Total User Costs

The second part of the analysis consists of estimating the daily amount of additional user costs generated by certain work zone configurations, traffic volumes and work schedule. Using the equations from the QUEWZ Model developed by the Texas Transportation Institute (Refs 6.3, 6.4) and later modifications by de Solminihac (Ref 6.5) and Seshadri (Refs 6.6, 6.7), the daily user costs are estimated given the work zone configuration, work schedule, starting hour of work, and hourly traffic volumes.

For each analysis, the amount of daily user costs generated by the presence of the work zone is computed for the following work scenarios:

- A** Typical weekday traffic distribution for conventional 40-hour week, starting at 8:00 and ending at 16:00.

- B** Saturday traffic distribution without activity. It may also represent Sunday traffic if the two distributions are not significantly different.
- C** Typical weekday traffic distribution for user-specified work schedule to account for accelerated construction.
- D** Saturday traffic distribution with user-specified work schedule to account for weekend construction.

The total user costs are obtained using the following procedure:

1. For conventional construction, a 40-hour week is assumed. Total user costs are computed based on 5 weekdays of construction and 2 weekend days with no activity:

$$\text{TUC} = (5 \cdot \text{Scenario A} + 2 \cdot \text{Scenario B}) \cdot \text{Project Duration} / 5$$

2. For user-specified work schedule with 5-day work week:

$$\text{TUC} = (5 \cdot \text{Scenario C} + 2 \cdot \text{Scenario B}) \cdot \text{Accelerated Project Duration} / 5$$

3. For user-specified work schedule with 6-day work week:

$$\text{TUC} = (5 \cdot \text{Scenario C} + \text{Scenario B} + \text{Scenario D}) \cdot \text{Accelerated Project Duration} / 6$$

4. For user-specified work schedule with 7-day work week:

$$\text{TUC} = (5 \cdot \text{Scenario C} + 2 \cdot \text{Scenario D}) \cdot \text{Accelerated Project Duration} / 7$$

In this fashion, the total user cost could be reduced despite a higher daily rate as a result of accelerated construction not only because the project duration is reduced, but also because more days of work per week are involved.

6.2.3 Estimating Additional Construction Costs

The third part is the estimation of additional construction costs that are generated by the reduction in the number of allocated days for project completion. The cost of construction increases as a consequence of labor premiums for overtime and of incentives for those working on the night shift. Also, the cost of materials can rise if surcharges must be

paid for night deliveries or for overtime in batch plants. If the construction method involves the use of special materials or equipment, the cost will also increase. There are potential savings, however, in the cost of traffic control, which is usually charged on a daily basis. If the total number of days allowed for completion of a certain project is reduced, the total cost of traffic control can be significantly reduced, as well as the time of exposure of motorists and work crews to work zone hazards.

The administrative costs to the transportation agency can increase as a result of the need of site inspection and decision-making personnel for extended schedules, or be reduced as the project duration is reduced. The following is the list of input variables required to estimate the additional costs of accelerated construction:

1. Estimated construction cost using conventional work hours and methods
2. Estimated cost of traffic control per day
3. Project duration under normal conditions
4. Percentage of labor cost from the estimated cost in item number 1
5. Percentage of materials + equipment cost from item number 1
6. Surcharge in labor cost owing to overtime
7. Surcharge in labor cost owing to incentives for night shift
8. Surcharge for using special materials, equipment, or construction method
9. Work load per week for the first and second shifts
10. Construction efficiency while working with scheduled overtime and during night shift

6.2.3.1 Equation to estimate additional construction costs owing to accelerated schedule

This equation computed the daily cost of construction on an accelerated schedule. The following relationships are assumed:

- Labor costs increase in proportion to the overtime hours worked.
- Materials and equipment costs increase only if special materials or equipment are used.
- The cost of traffic control is charged on a daily basis.

The cost of accelerated construction per day will be:

$$CC_{ac} = CC * \left[\left(NS + \phi_1 * \frac{(W_1 - NW)}{NW} + \phi_1 \phi_2 * \frac{(W_2 - NW)}{NW} \right) * L + \beta * ME * \frac{D}{D_{ac}} + \gamma * (1 - L - ME) * \frac{D}{D_{ac}} \right] + TC$$

where:

CC_{ac} = Accelerated construction cost per day;

L = Percentage of labor cost;

ME = Percentage of materials and equipment cost;

TC = Cost of traffic control per day;

ϕ_1 = Surcharge factor in labor due to overtime;

ϕ_2 = Surcharge factor in labor due to night shift;

β = Surcharge factor in materials and equipment for special construction method;

γ = Surcharge factor in the complementary costs;

D = Project duration with conventional construction;

D_{ac} = Project duration under accelerated schedule;

W_1 = Work hours per week shift 1;

W_2 = Work hours per week shift 2;

NW = Normal week work load; and

NS = Number of shifts.

The total cost of construction under an accelerated schedule can be obtained with the following relationship:

$$TCC = (CC_{ac} + TC) * D_{ac}$$

where:

TCC = Total construction cost;

CCac = Accelerated construction cost per day;

TC = Cost of traffic control per day; and

Dac = Project duration under accelerated schedule.

6.2.4 Estimating additional fuel consumption for accelerated construction

The last part of the model computes the additional fuel consumption for both conventional and accelerated construction, that is, compared with no work zone. Longer work schedules during accelerated construction are related to more severe impacts to users in terms of daily rates of delays, operating costs, and fuel consumption. However, by reducing the total number of days allowed for the rehabilitation, fuel can be saved. The purpose of this part is to assess whether there is actually savings in fuel consumption as a result of accelerating the rate of construction.

In order to estimate the total additional fuel consumed during the presence of the work zone, the study used an analysis similar to that used for the total user cost. For each scenario, the amount of daily additional fuel consumed, which is generated by the presence of the work zone, is computed using modified equations from the QUEWZE Model (Ref 6.5).

In this fashion, the total fuel consumed during the rehabilitation can be reduced, despite a higher daily rate generated by accelerated construction, since the project duration is reduced.

6.2.5 Modification of the equations from the QUEWZE Model to report additional fuel consumption

The equations of the QUEWZ Model, developed by TTI (Refs 6.3, 6.4) and modified by de Solminihac (Ref 6.5) to report fuel consumption, and modified further by Seshadri (Refs 6.6, 6.7) to report emissions from vehicles, were used to compute the additional user costs generated by the presence of a work zone. However, the objective of this section of the study was to determine the difference in additional fuel consumption between conventional and accelerated construction.

The equations proposed by de Solminihac (Ref 6.5) to quantify fuel consumption are as follows:

$$\text{CAR FUEL USE} = [(\text{FULps} + \text{XFULps}) * \text{hourly volume} * (1 - \% \text{Trucks})$$

* work zone length/1000] / Cf

TRUCK FUEL USE = [(FULtr + XFULtr)* hourly volume * (%Trucks)

* work zone length/1000] / Tf

where:

$$\log(\text{FULps}) = 4.37555 - 0.036805 s + 0.000493 s^2$$

$$\log(\text{FULtr}) = 5.54162 - 0.038976 s + 0.000422 s^2 + 0.010021 \text{ GVW}$$

$$\log(\text{XFULps}) = -1.82937 + 0.01617 S_b + 0.00928 S_e + 0.95385 \log(\text{DSP})$$

$$\log(\text{XFULtr}) = -0.487983 + 0.014543 S_b + 0.010755 S_e \\ + 1.01086 \log(\text{DSP}) + 0.012024 \text{ GVW}$$

where:

FUL = fuel consumption at speed s, in gal/1000 miles

XFUL = fuel consumption due to speed change cycles, in gal/1000 cycles

S = speed in mph

GVW = gross vehicle weight in kip

S_b = beginning speed change in mph

S_e = ending speed change in mph

DSP = difference between the beginning and ending speeds, in mph

Subscript ps = passenger car weighted average of large, medium, small and pickup

Subscript tr = truck

Observations regarding the equations presented above are summarized as follows:

- a. There is an inconsistency in the units of the elements in the equations for car and truck fuel use. While the FUL component is reported in gal/1,000 miles, the XFUL component is reported in gal/1,000 cycles.

- b. The FUL component of the equation, which reports the fuel consumption as a function of the average speed, must be evaluated for the work zone speed; then the same component evaluated is subtracted from the normal approach speed [FUL(Swz) - FUL(Sap)]. In addition, this equation must be evaluated for the effective length of the work zone, which is a function of the volume-to-capacity ratio.
- c. If a queue develops, the equation must be evaluated for the difference in fuel consumption between traveling in queue and normal approach speed [FUL(Sq) - FUL(Sap)]. This case must be evaluated for the length of the queue.
- d. The equations for car and truck fuel consumption do not need to be divided by the unit cost of fuel, since the consumption rates FUL and XFUL report in gallons.

The following equations are proposed for estimating the additional fuel consumed owing to the presence of a work zone.

Additional Fuel Consumption for passenger cars:

$$\begin{aligned}
 \mathbf{AFCps} = & [\text{FULps}(\text{Swz}) - \text{FULps}(\text{Sap})] * \text{hourly volume} * (1 - \% \text{Truck}) \\
 & * \text{Effective work zone length} / 1,000 \\
 & + [\text{FULps}(\text{Sq}) - \text{FULps}(\text{Sap})] * \text{hourly volume} * (1 - \% \text{Truck}) \\
 & * \text{Queue length} / 1,000 \\
 & + [\text{XFULps}(\text{Sap}, \text{Swz})] * \text{hourly volume} * (1 - \% \text{Truck}) \\
 & * \text{Cycles} / 1,000 \\
 & + [\text{XFULps}(10,0)] * \text{hourly volume} * (1 - \% \text{Truck}) * 3 \\
 & * \text{Queue length} / 1,000
 \end{aligned}$$

Additional Fuel Consumption for trucks:

$$\begin{aligned}
 \mathbf{AFCtr} = & [\text{FULtr}(0.9\text{Swz}) - \text{FULtr}(0.9\text{Sap})] * \text{hourly volume} * (\% \text{Truck}) \\
 & * \text{Effective work zone length} / 1,000 \\
 & + [\text{FULtr}(\text{Sq}) - \text{FULtr}(0.9\text{Sap})] * \text{hourly volume} * (\% \text{Truck})
 \end{aligned}$$

$$\begin{aligned}
& * \text{Queue length} / 1,000 \\
& + [\text{XFULtr}(0.9\text{Sap},0.9\text{Swz})] * \text{hourly volume} * (\% \text{Truck}) \\
& * \text{Cycles}/1,000 \\
& + [\text{XFULtr}(10,0)] * \text{hourly volume} * (\% \text{Truck}) * 3 \text{Queue length} / 1,000
\end{aligned}$$

6.3 MEASURES OF EFFECTIVENESS

Two measures of effectiveness are proposed here to evaluate the relative benefits of conducting rehabilitation at an accelerated pace. Acceleration of rehabilitation by means of different strategies, discussed in earlier chapters, can be achieved at different costs and can generate different degrees of impacts. Moreover, the purpose of this work was to determine the potential reduction in fuel consumption and user costs resulting from accelerating the rehabilitation. Therefore, the measures are the following:

1. Net benefits of quantifiable impacts per additional dollar invested in accelerating the rehabilitation
2. Reduction in fuel consumption per additional dollar invested in accelerating the rehabilitation.

6.4 SUMMARY

This chapter presented a methodology for assessing the effectiveness of accelerated highway rehabilitation projects. The reduction in project duration is first estimated from the assumed accelerated work schedule (96 or 120 hours per week). The total user costs are estimated for the duration of both accelerated and conventional rehabilitation, so that they can be compared. The additional cost of construction is also estimated using an equation developed in this chapter. A modification to the equations that report fuel consumption within the QUEWZ Model is proposed herein to account for the effects of queues and speed change cycles on the additional fuel consumed by motorists during highway rehabilitation. Finally, this chapter proposed some possible measures of effectiveness for mitigation strategies.

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CHAPTER 7: APPLICATION OF THE METHODOLOGY TO ASSESS EFFECTIVENESS OF PROJECT ACCELERATION

This chapter shows the applicability of the methodology, discussed in earlier chapters, that assesses the effectiveness of accelerated highway rehabilitation projects in mitigating adverse impacts on road users. Also, the methodology is intended to identify the best candidates warranting project acceleration. The analysis was further divided into two steps. First, increments in user costs generated by the presence of a work zone were obtained on a daily basis for a range of work zone configurations. The purpose of this part was to characterize the relationship between traffic volumes and user costs at work zones. The second part of the analysis deals with the variation in the total cost of a rehabilitation project when acceleration is implemented.

One of the most sensitive variables determining the magnitude of adverse impacts on road users during highway rehabilitation is the traffic distribution at the work zone. Therefore, the following section analyzes the traffic distributions observed at selected sites on Texas highways.

7.1 TRAFFIC DISTRIBUTIONS

Traffic demand on urban freeways is not evenly distributed throughout the day. A typical weekday traffic distribution has two peak periods, while the weekend distribution spreads traffic into a longer period during evening hours. Variation occurs also by month of year and seasonal fluctuations. Furthermore, traffic does not distribute equally over available lanes or directions (Ref 1). Therefore, the relationship between traffic demands and the reduction in roadway capacity determines the severity of the negative impacts of highway rehabilitation projects.

During rehabilitation projects, peak traffic demands represent the most critical period of operations, owing to reduced capacity on the facility. Congestion is generated by a rehabilitation project when available capacity is less than the expected traffic volumes. Figure 7.1 shows a typical traffic volume distribution for a urban freeway having two peaks during mornings and evenings. Congestion will develop when traffic demands are greater than reduced capacity during rehabilitation.

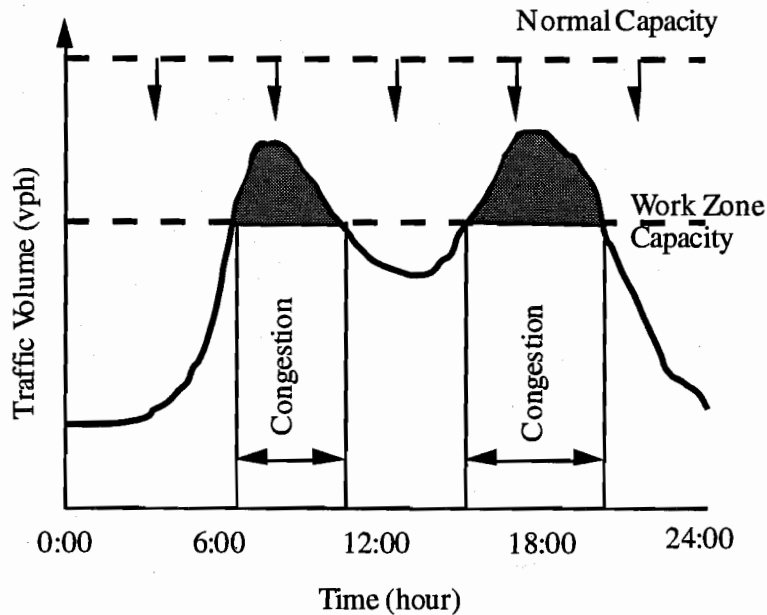


Figure 7.1. Typical traffic distribution in urban freeways.

The shaded area in Figure 7.1 represents the fraction of traffic demand that cannot be processed through the work zone, building long queues upstream of the disrupted section of the freeway. The number of users affected by congestion, however, is the total traffic passing through the work zone, in addition to the traffic idling in the queue. Congestion will last until traffic demands are lower than the restricted capacity of the work zone and queues are dissipated.

Increments in daily volumes will shift down the horizontal lane shown in Figure 7.1, representing the work zone capacity. Consequently, the shaded area of traffic experiencing queues will grow in proportion to the increment in traffic volumes. The portion of the daily traffic affected by congestion, by increased delays and fuel consumption, as well as the duration of such congested periods, also increases in accordance with the increments in traffic volumes using a certain facility under rehabilitation.

Typical hourly traffic distributions for urban areas in Texas were obtained from data gathered by the Permanent Automatic Traffic Recorders (Ref 2) and these distributions were used to estimate the negative impacts on users and on the environment through several daily traffic volumes in a range of work zone configurations. Table 7.1 summarizes the characteristics of facilities selected as typical for urban areas in Texas.

Number of Lanes	Station Number	Location	AADT	% Directn Distribution	K- factor (30th hour)
10	S-126	IH-35E Dallas	180,478	56	8.7
	S-157	IH-610 Houston	163,236	52	9.4
8	S-185	IH-37 San Antonio	117,903	53	10.6
	S-186	IH-410 San Antonio	160,609	50	8.2
6	S-109	IH-35W Ft. Worth	102,707	60	9.2
4	S-122	IH-20 Ft. Worth	52,426	55	10.1

Table 7.1. Characteristics of selected sites for typical traffic distributions in Texas. Source: Ref 2.

Traffic distributions were plotted and expressed as percentages of daily volumes to identify variations owing to location or volumes (ADT). A sample of these plots is presented in Figure 7.2. The complete set of plots is available in Appendix B.

Some conclusions were drawn after reviewing traffic distributions for all selected stations. First, traffic distributions can be classified into two broad groups: weekday and weekend traffic distributions. The former distribution presents two peak periods for morning and afternoon traffic, while the latter presents spread traffic demands.

Secondly, the percentage of daily traffic volumes passing at the peak periods decreases as the average daily traffic increases. As the traffic volume increases, the peaks are less sharp and traffic demands between the two peaks are significant.

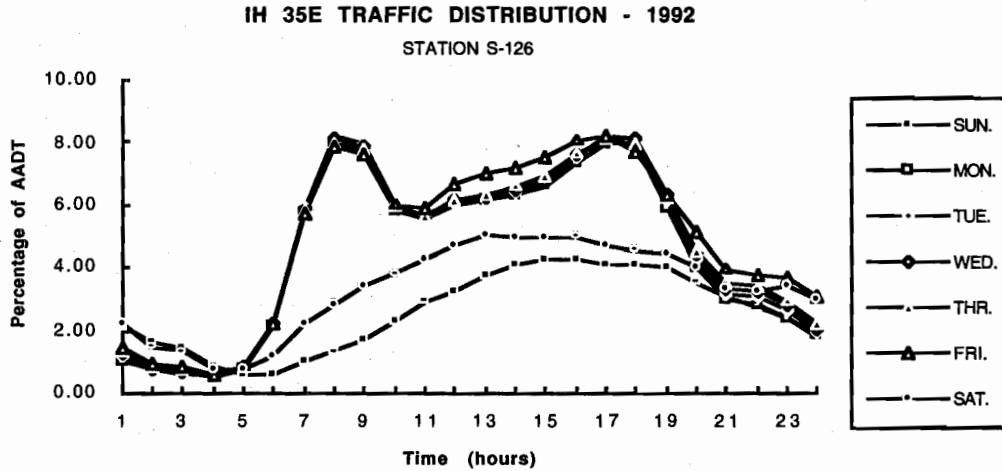


Figure 7.2. Traffic distribution at IH-35E Dallas. Source: Ref 2.

Finally, an average weekday traffic distribution can be used to analyze user costs generated by the work zone, because even if some days are underestimated, using the average distribution, others will be overestimated. For the weekend traffic distribution, the Saturday traffic can be used as the weekend traffic if there is no significant difference with respect to the Sunday traffic distribution. If they differ considerably, then three traffic distributions must be used (one for weekdays, one for Saturdays, and one for Sundays).

A number of work zone configurations can be analyzed by using the traffic distributions from the Permanent Automatic Traffic Recorders (Ref 2). The work zone scenarios selected for analysis in this report are summarized in Table 7.2. They were selected from configurations at representative highway corridors of the largest urban areas in Texas (Dallas, Houston, Ft. Worth, and San Antonio). It was assumed that the heavy traffic using these corridors would prevent the closure of more than two lanes at a given time.

Station Number	Number of lanes	Number of open lanes
S-126, S-157	5	4
S-126, S-157	5	3
S-185, S-186	4	3
S-185, S-186	4	2
S-109	3	2
S-109	3	1
S-122	2	1

Table 7.2. Work zone configurations.

7.2 FACTORIAL DESIGN

Using the traffic distributions analyzed in the last section, the study conducted a factorial experiment to identify changes in user costs and fuel consumption with increasing traffic volumes. Another objective of this experiment was to determine differences between user costs, fuel consumption, and emissions generated by conventional and accelerated construction schedules so that projects warranting acceleration could be identified.

There are several factors affecting user costs, fuel consumption, and emissions during any lane closure strategy. Those factors are identified as follows:

- Traffic distribution and volumes (ADT)
- Total number of lanes in the existing facility
- Number of closed lanes
- Closure time and work schedule
- Vehicle mix (percentage of passenger cars and trucks)
- Work zone length

All but one of the variables were tested using the equations from QUEWZEE Model in order to obtain knowledge on how the variables affect additional user costs, fuel consumption, and emissions during highway rehabilitation projects. Results are given in the following sections.

7.2.1 Traffic distribution and volumes (ADT)

For each work zone scenario under consideration, traffic distributions for the average weekday and Saturday were used to characterize the proportion of hourly volumes passing through. The following table summarizes the station number from which traffic distributions were taken:

Station Number	Location	No. of lanes
S-157	Houston	5
S-185	San Antonio	4
S-109	Ft. Worth	3
S-122	Ft. Worth	2

Table 7.3. Traffic distributions used in the factorial.

Since user costs and fuel consumption at work zones depend largely on the volume to capacity ratio at any given time, it was thought that the range of traffic volumes in the factorial should be expressed as traffic volume per open lane in order to keep a point of comparison between different lane closure strategies and different facilities. In other words, a 4-lane facility that normally carries 45,000 vehicles per day would carry $45,000/3= 15,000$ vehicles per day per open lane if the cross section is reduced to three lanes to accommodate the rehabilitation activities while $45,000/2= 22,500$ vehicles per day per open lane would be carried if the same facility is reduced to two lanes.

The range of traffic volumes at the selected facilities during a major rehabilitation was normalized from 10,000 to 25,000 vehicles per day per open lane for all cases. Therefore, the actual ADT per direction used in the factorial are summarized as follows:

Number of lanes	Number of open lanes	10,000/ open lane	12,500/ open lane	15,000/ open lane	17,500/ open lane	20,000/ open lane	22,500/ open lane	25,000/ open lane
5	4	40,000	50,000	60,000	70,000	80,000	90,000	100,000
5	3	30,000	37,500	45,000	52,000	60,000	67,500	75,000
4	3	30,000	37,500	45,000	52,000	60,000	67,500	75,000
4	2	20,000	25,000	30,000	35,000	40,000	45,000	50,000
3	2	20,000	25,000	30,000	35,000	40,000	45,000	50,000
3	1	10,000	12,500	15,000	17,500	20,000	22,500	25,000
2	1	10,000	12,500	15,000	17,500	20,000	22,500	25,000

Table 7.4. Traffic volumes per direction used in the factorial.

7.2.2 Total number of lanes in the existing facility and number of closed lanes

The number of existing lanes at selected stations listed above ranged from ten to four lanes on divided highways. The work zone configurations proposed in this factorial considered single lane closure and two lane closure for highways having three or more lanes in each direction. In the case of a four-lane divided highway, only the single lane closure strategy was analyzed.

7.2.3 Closure time and work schedule

Lane closures can be classified as short-term and long-term work zones. The first classification applies to those closures that last less than one working day, that is, at the end of the day the lane closure is removed. Usually this type of work zone is conducted during routine maintenance activities. Long-term work zones, on the other hand, are those lane closures that last more than one working day. Rehabilitation of existing highways represents a considerable amount of work that usually extends for several weeks and even months. Therefore, the time of set-up for the traffic control is considered to start at 0 hours and to last 24 hours.

The number of hours taken up by construction activities is an important consideration in this study, for the capacity of the remaining open lanes depends on whether there is activity or not. Since the capacity of the work zone is lower during ongoing construction activities, when compared with lane closures with no work activity, it is expected that longer work schedules associated with accelerated projects will generate higher rates of user costs, fuel consumption, and emissions than conventional work schedules. In order to find out the proportion of such increments, the following work schedules were tested with the model:

- a) Conventional construction. 40 hours a week. One shift
work schedule: 8 hours 5 days a week from 8:00 to 16:00 hours.
- b) Accelerated construction. 96 hours a week. Two shifts
work schedule: 16 hours 6 days a week from 5:00 to 21:00 hours.
- c) Incentive/disincentive contract. 120 hours a week. Two shifts
work schedule: 20 hours 6 days a week from 4:00 to 24:00 hours.

7.2.4 Vehicle mix (percentage of passenger cars and trucks)

The percentage of trucks was used as a constant value of 10 percent, since the main objective was to test the effect of different work schedules.

7.2.5 Work zone length

Highway rehabilitation at urban areas involves a complicated set-up of traffic control devices in order to handle heavy traffic operations while construction is taking place. Therefore, the length of a work zone under rehabilitation must be long enough to allow a

reasonable amount of work to be performed before the traffic control devices are moved to a new location. For this reason, a work zone length of 2 miles was selected in the factorial.

7.2.6 Project duration and cost

The initial cost and duration of rehabilitation projects determine the effectiveness of implementing accelerated work schedules: the cost of expediting the rehabilitation is a function of the base cost of the project. The base duration of the project, on the other hand, determines the magnitude of total user costs and fuel consumption that will be generated because of the rehabilitation project.

Three different types of projects were used for study purposes:

Type of Rehabilitation	Base Duration	Base Project Cost
Minor Rehab	100 Days	\$1,000,000
Medium-Rehab	300 Days	\$10,000,000
Major Rehab	450 Days	\$25,000,000

Table 7.5. Base project duration and costs used in factorial.

The cost of expediting construction is estimated based on the following assumptions:

1. **Estimated project cost.** This is the total cost of the project using conventional contracting practices. Three types of projects are analyzed with a base cost of 1, 10, and 25 million dollars respectively.
2. **Normal project duration.** The number of working days that would be required to finish the project if conventional construction was used. The New Mexico method is used to estimate the duration as a function of project cost.
3. **Normal week workload.** 40 hours a week with one shift.
4. **Construction efficiency during overtime and 2nd shift.** This factor accounts for the loss of efficiency during overtime hours and for the night shift. The

productivity curve shown in Chapter 5 is used. The night shift is assumed to have 90 percent productivity of the day shift.

5. **Percentage of labor, equipment, and materials cost.** The total cost of the project with a conventional contract is divided into 20 percent labor and 65 percent equipment and materials. The rest accounts for profits and miscellaneous expenses.
6. **Surcharge in labor, equipment, and materials owing to overtime.** Increments in labor are assumed as 50 percent for overtime. Increments in equipment and materials owing to working overtime are assumed as 25 percent.
7. **Surcharge in labor, equipment, and materials owing to 2nd shift.** Increments in labor for the night shift are assumed as 30 percent the base rate. Increments in equipment and materials owing to working the 2nd shift are assumed as the same as overtime.
8. **Cost of traffic control.** The daily cost is estimated using the guidelines presented in the FHWA report "Planning and Scheduling Work Zone Traffic Control" (Ref 3) and updated to 1992 dollars. The following formula is used:

$$TC = 2780 + 0.132 * (5280 * WZL - 300)$$

where:

TC = Daily cost of traffic control for freeways/expressways

WZL = Work zone length, in miles.

7.3 ANALYSIS OF RESULTS

The first part of the analysis consists of determining the relationship between daily user costs at work zones and traffic volumes. The following measurements were obtained from the output of the QUEWZEE Model for each of the work zone configurations and work schedules:

- a) Additional User Costs generated by the lane closure (DlIs/day)
- b) Additional Truck and Car fuel consumption (Gal/day)

- c) Additional emissions of carbon monoxide (CO), hydrocarbons (HC) and oxides of nitrogen (NOx) from vehicles traveling through the work zone (Kg/day)

The outputs of the model showed the following behavior:

7.3.1. User Costs

User costs increased as a function of traffic volumes with an exponential curve. User costs increased rather rapidly when traffic volumes (ADT) reached a value around 20,000 vehicles per day per open lane, except for a 3-lane freeway with only one lane open where sharp increments were observed after traffic demand reached 17,500 vehicles per day per open lane. Figure 7.3 shows a sample of user costs as a function of traffic volumes at work zones. Graphs for other work zone configurations are available in Appendix C.

Even though the absolute traffic volumes were different for each configuration studied, the shape of the user costs curves were very similar for the same amount of traffic per open lane. This means that the severity of traffic impacts is similar because similar volumes per open lane represent similar values of the volume to capacity ratio in any work zone configuration. Also, the value of 20,000 vehicles per open lane is consistent with the criterion that uses hourly volumes of 1,500 vehicles per lane as the threshold because 20,000 multiplied by the K- factor, usually 8 percent, gives around 1,600 vehicles per hour per lane during peak periods.

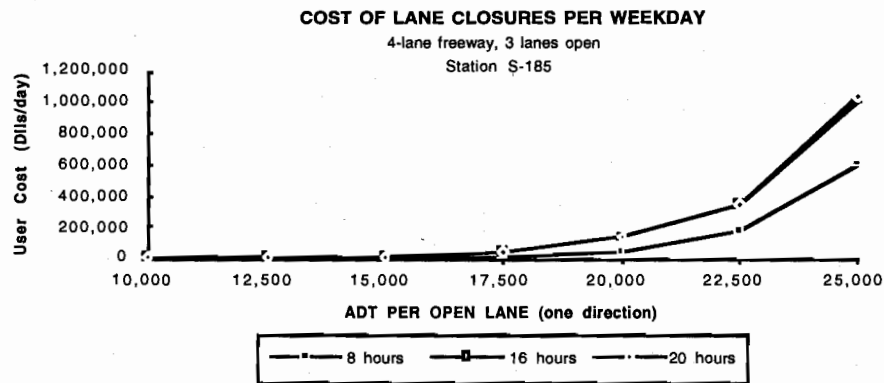


Figure 7.3. User costs per day generated at a work zone.

As the number of existing lanes increases, the effect of a lane closure over traffic passing through the work zone decreases. On the other hand, as the number of closed lanes increases, the effects of the lane closure over the traffic stream passing through the work zone increase.

Another important observation was that longer work schedules generated greater values of user costs, when compared with a conventional 8 hours work schedule. The difference between a 16 hours and a 20 hours work schedule, however, was not significant. Again, when traffic volumes reached a value of 20,000 veh/open lane, the difference in user costs generated by a conventional schedule and an accelerated schedule was significant.

7.3.2. Fuel Consumption

Fuel consumption by trucks and cars also varies proportionally to traffic volume. In this case, results from the QUEWZE Model were compared with the results obtained from the modified equations proposed herein.

As stated earlier, the equations to estimate fuel consumption within the QUEWZE Model depends mostly on the number of vehicles traveling through the work zone, instead of the traffic conditions at the work zone. The variation in fuel consumption as a function of traffic volume is rather a flat curve and no provisions are made to subtract the amount of fuel consumed without the presence of the work zone. Also, the amount of fuel consumed at the queue is not properly modeled. Using the QUEWZE model, the study found that fuel consumption for an accelerated work schedule was slightly higher than a conventional 8 hours schedule, but the difference was not as dramatic as in the case of total user costs.

The modified equations for reporting fuel consumption produced a curve that better reflects the traffic conditions at work zones. As shown in Figure 7.4, fuel consumption also varies exponentially as a function of traffic volume. This is explained by the fact that queues will appear after traffic volumes reach 20,000 vehicles per open lane, and fuel consumption starts to increase rapidly for vehicles that are traveling through growing queues.

Even though excess fuel consumption per day was greater for accelerated work schedules, the difference in fuel consumption for a 16 hours and a 20 hours work schedule is not significant. Finally, the contribution of fuel consumption to total user costs decreases as traffic volume increases. This happens because the delay cost contribution to total user costs increases more rapidly, as congestion appears at the work zone, than fuel consumption and vehicle operating costs.

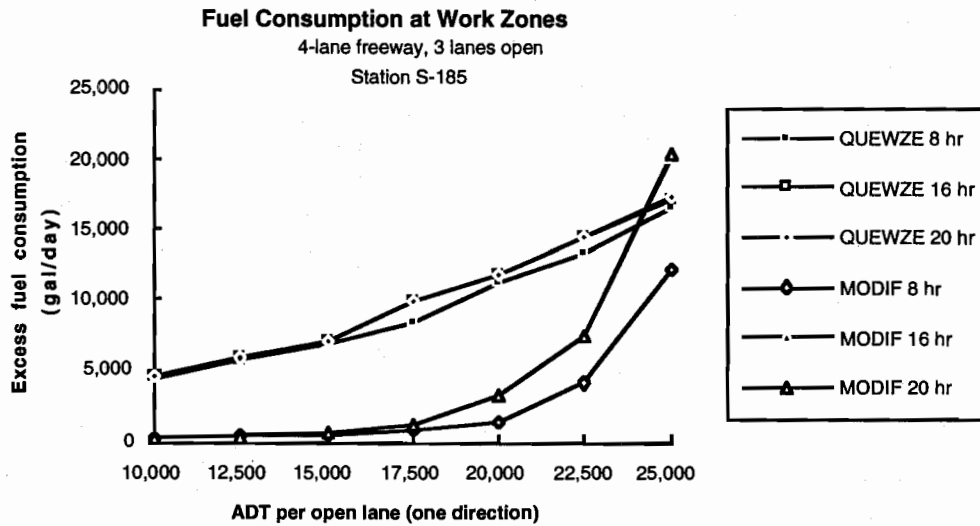


Figure 7.4. Excess Fuel Consumption per day at Work Zones.

7.3.3 Emissions of carbon monoxide (CO), hydrocarbons (HC) and oxides of nitrogen (NOx)

Emissions from vehicles traveling through the work zone vary in proportion to traffic volume. The variation is exponential and follows a similar behavior as the total user cost curve. Emissions are directly related to the degree of congestion, expressed as the volume to available capacity ratio for the work zone in consideration.

The rate of emissions from vehicles also increased rapidly when traffic volumes reached a value of 20,000 vehicles per open lane. Again the effect of a lane closure on the rate of emissions decreases as the number of existing lanes increases. Also, the emission rate increases when the number of closed lanes increases.

The difference in emission rates between a conventional 8 hours work schedule and an accelerated work schedule is significant, but not as critical as the case of total user costs. This difference increases as traffic volumes increase; accelerated schedules produce two to four times the emissions as conventional schedules. Figures 7.5 to 7.7 show the behavior of tailpipe emissions as a function of traffic volumes within the work zone.

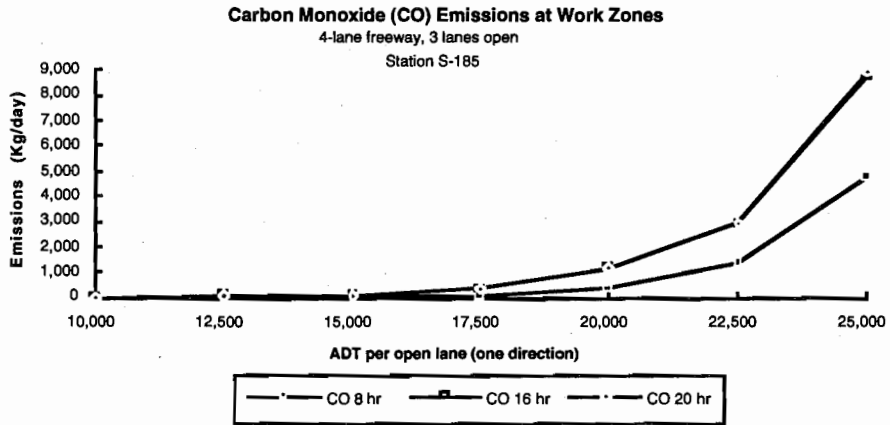


Figure 7.5. Carbon Monoxide emissions at work zones.

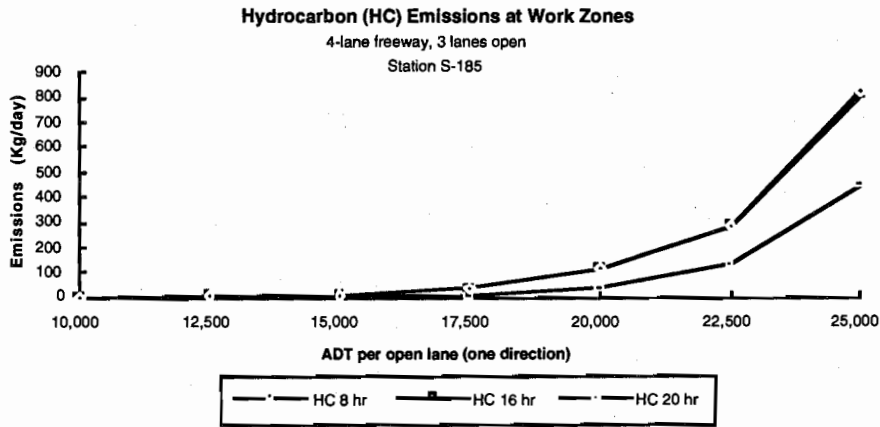


Figure 7.6. Hydrocarbon emissions at work zones.

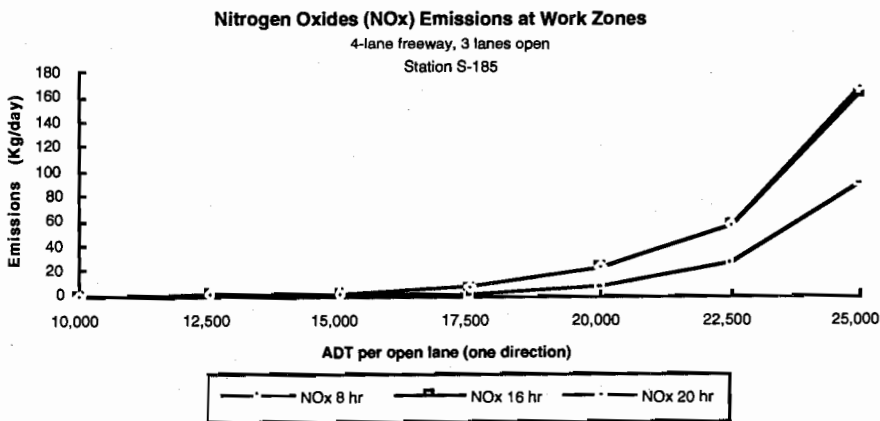


Figure 7.7. Nitrogen Oxides emissions at work zones.

The first part of the analysis determined that the daily rates for user costs at work zones were higher for the longer work schedules of accelerated projects. However, the reduction in the total number of days resulting from project acceleration may produce net savings in the total project cost.

The second part of the analysis consisted of determining, on the total cost of the project, the aggregated effect of accelerating the rehabilitation. This total cost comprises the sum of both construction and user costs. User costs are then divided into travel time and vehicle operating costs. The objective of this analysis was to determine whether the total cost of the project will be reduced by implementing the accelerated schedule, that is, compared with conducting the same job with conventional 40 hours work schedules. The methodology of the analysis was modeled into a computer spreadsheet in order to facilitate calculations. A sample of the input and output tables are presented below.

Table 7.6 contains a sample of input values for fuel, oil, tires, maintenance, and depreciation unit prices for passenger cars and trucks. It also contains the average gross vehicle weight for trucks that is used in some of the regression equations that estimate vehicle operating costs for trucks.

Unit prices	Unit	Pass. cars	Trucks
Fuel =	\$/gal	\$1.00	\$0.61
Oil =	\$/gal	\$3.19	\$1.52
Tires =	\$/tire	\$67.86	\$479.00
Maintenance =	\$/100 mi	\$69.94	\$224.50
Depreciable value =	Veh	\$10,057	\$77,445
Gross Vehicle Weight =	Kip		62.5

Table 7.6. Unit Costs Input table.

Table 7.7 contains a sample of the input values that determines the geometric configuration of the work zone, traffic conditions (volume and vehicle mix), the duration and starting time of work activity, and the value of time for cars and trucks. The case showed in Table 7.7 is for a 4-lane highway with 2 lanes open carrying 25,000 vehicles per day per open lane.

Number of Lanes =	4
Number of Open Lanes =	2
Work Zone Length (mi)=	2
Work load weekdays(hrs)=	20
Starting hour weekdays =	4
Work load Saturdays (hrs)=	20
Starting hour Saturdays =	4
AADT/Open lane =	25,000
Percentage of trucks =	10%
Factor to update costs =	1.00
Car value of time (\$/hr) =	\$12.64
Truck value of time (\$/hr) =	\$23.09

Table 7.7. Geometric and Traffic input table.

Table 7.8 contains a sample of the parameters that determine the increase in the cost of construction owing to an accelerated work schedule, including the base project cost and duration, the percentage of labor, equipment and materials cost from the total and their respective increase owing to acceleration, the cost of traffic control per day of construction, and the total number of work hours per week.

Estimated construction cost =	\$25,000,000
Normal project duration (workdays) =	450
Normal work load per week (hrs/week) =	40
Construction efficiency w/overtime =	70%
Construction efficiency w/overtime for 2nd shift =	63%
Percentage of LABOR cost =	20%
Percentage of EQUIP. AND MATERIALS cost =	65%
Cost of TRAFFIC CONTROL per day =	\$4,126
Surcharge LABOR overtime =	1.5
Surcharge LABOR 2nd shift =	1.3
Surcharge EQUIP. & MATERIALS for overtime =	1.35
Number of shifts =	2
Work load per week shift 1 =	60
Work load per week shift 2 =	60
Number of workdays per week =	6

Table 7.8. Project cost input table.

Table 7.9 shows a sample of the output table that clearly summarizes the potential reduction in the total cost of the project resulting from accelerating the rehabilitation project. According to this example, even though the cost of construction increased as a result of accelerating the rehabilitation, the savings in user costs offset the amount of money invested in project acceleration. In this particular example the cost/benefit ratio was 6. This means that from each dollar invested in accelerating the rehabilitation, six dollars were obtained in net benefits to road users.

OUTPUT VALUES	Conventional	Accelerated
Hours of work per week =	40	120
Project duration (Work days) =	450	226
User Costs per weekday =	\$328,341	\$574,591
User Costs per weekend day w/activity =		\$12,226
User Costs per weekend day no activity =	\$8,354	\$8,354
=		
Total User Costs =	\$149,257,215	\$108,779,413
Average cost of construction per day =	\$59,682	\$144,716
Cost of accelerated construction =	\$26,856,844	\$32,642,685
Cost of expediting =	\$0	\$5,785,841
% of expediting as constr. cost =	0%	22%
Total project cost =	\$176,114,059	\$141,422,098
Net benefits =		\$34,691,961
COST-EFFECTIVENESS (DLLs benefits/DLLs invested)=		\$6.00

Table 7.9. Total project cost output table.

Table 7.10 illustrates an example of the output table for estimating the amount of fuel saved when conducting the rehabilitation at an accelerated pace compared with the conventional rehabilitation methods. The amount of fuel saved is only the difference between the fuel actually consumed and the amount of fuel that would have been consumed if the conventional rehabilitation was used.

OUTPUT VALUES	Conventional	Accelerated
Project duration (Work days) =	450	226
Car fuel per weekday (gal/day) =	3,529	5,783
Car fuel per weekend day w/activity =		168
Car fuel per weekend day no activity =	153	153
Additional Car fuel consumed =	1,615,841	1,318,320
Truck fuel per weekday (gal/day) =	3,851	6,075
Truck fuel per weekend day w/activity =		428
Truck fuel per weekend day no activity =	341	341
=		
Additional Truck fuel consumed =	1,794,192	1,400,966
Net Savings in Car Fuel (gallons) =		297,521
Net Savings in Truck Fuel (gallons) =		393,226
Total Savings in Fuel (gallons) =		690,747

Table 7.10. Additional fuel consumption output table.

For the three types of rehabilitation studied, the cost of construction was greater than the magnitude of user costs when low traffic volumes were present. Therefore, acceleration did not produce many benefits because the reductions in user costs were similar to or less than the increases in construction costs. See Figure 7.8 for a graphic comparison of total project costs between conventional and accelerated rehabilitation.

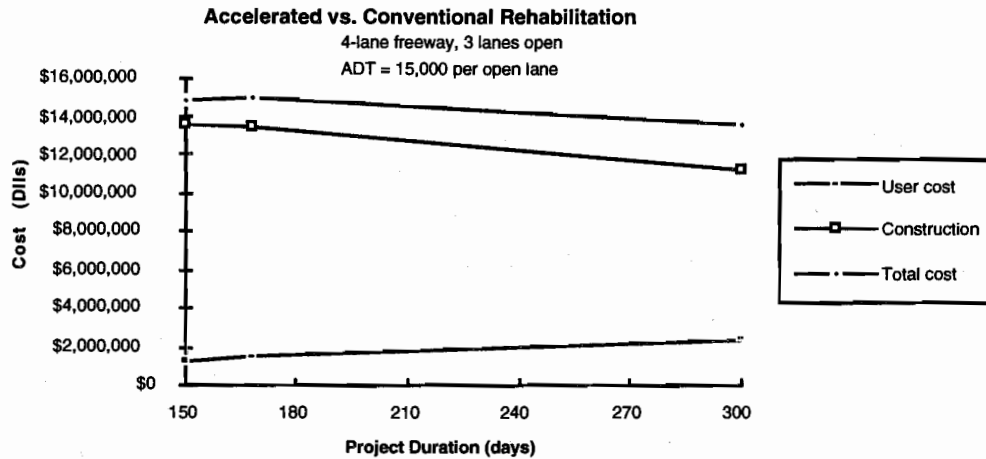


Figure 7.8. Project base cost and duration: \$ 10,000,000 and 300 days.
 ADT = 15,000 per open lane.

As traffic volumes increased, acceleration produced benefits because the reductions in user costs were greater than the increases in construction costs. See Figure 7.9 for a graphic comparison of conventional total project cost and accelerated rehabilitation total project cost during a major rehabilitation with heavy traffic volumes. Savings in user costs were greater than the cost of accelerating the project.

According to results from this part of the analysis, the number of 20,000 vehicles per day per open lane again was found to be the threshold for expediting highway rehabilitation projects. Therefore, in those facilities where traffic volumes are greater than this number, the cost of accelerating the project would be negated by the amount of savings in user costs.

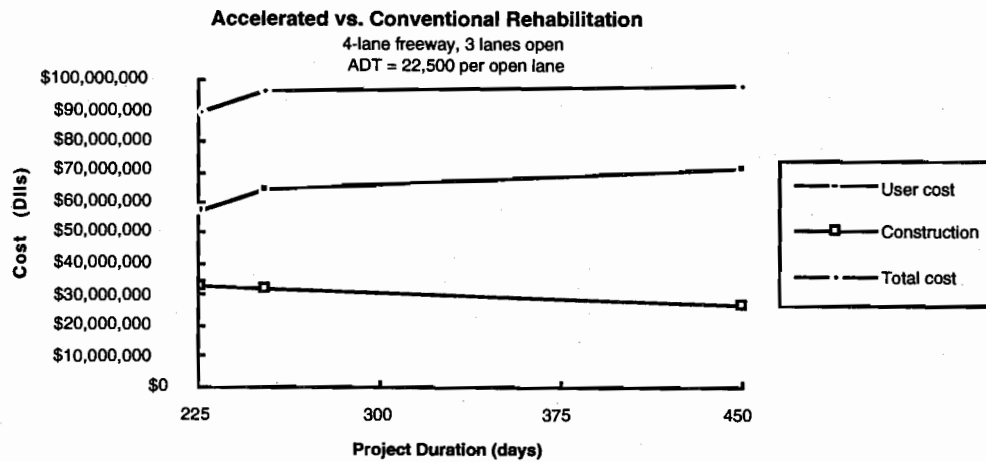


Figure 7.9. Project base cost and duration: \$ 25,000,000 and 450 days.
ADT = 22,500 per open lane.

The following table summarizes the findings of this study by providing the minimum traffic volumes warranting acceleration of highway rehabilitation projects for a number of work zone configurations.

No. of open lanes	No. of lanes				
	6	5	4	3	2
1	20,000	20,000	20,000	17,500	20,000
2	40,000	40,000	40,000	40,000	
3	60,000	60,000	60,000		
4	80,000	80,000			
5	100,000				

Table 7.11. Recommended minimum traffic volumes per direction warranting acceleration of rehabilitation projects.

7.4 SUMMARY

The methodology for assessing the effectiveness of accelerated highway rehabilitation was applied to a factorial experiment in order to develop some guidelines for projects warranting acceleration. Different work zone configurations and traffic volumes were used to estimate the total user costs. Three different base project duration and cost were also used to analyze the effect on the additional cost of construction. It was found that acceleration is feasible when traffic volumes are greater than 20,000 vehicle per day per open lane.

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CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

8.1 SUMMARY

The purpose of this research report was to develop guidelines for identifying highway rehabilitation projects warranting acceleration within Texas. Reduction in the total number of days allocated for project completion is recommended if savings in user costs are greater than the additional costs of accelerating the project. Throughout this report, the short-term impacts to road users and the environment were analyzed, and methods for quantifying user costs were reviewed. Also, potential consequences of accelerated rehabilitation projects were presented, and a methodology to estimate additional construction costs was developed to assess the effectiveness of accelerated construction schedules. Finally, recommendations are made to identify candidates for expediting highway rehabilitation by means of threshold traffic volumes warranting project acceleration.

8.2 CONCLUSIONS

Highway rehabilitation projects in highly trafficked corridors generate short-term negative impacts to road users and the economy. Additional fuel consumption is only one of a number of adverse impacts derived from highway rehabilitation. Increased travel times, operating costs, and tailpipe emissions, as well as temporary reduction in revenue earnings by adjacent businesses are among these negative impacts.

There are existing methodologies to quantify additional travel time costs and vehicle operating costs generated by rehabilitation projects, although there are uncertainties about the increases in accident rates and severity owing to the presence of work zones. The social cost of air pollution is hard to estimate because damage to human health and materials are due to a combination of socio-economic and environmental factors. Loss of revenue by adjacent businesses cannot be credibly quantified since reasons other than the rehabilitation projects may affect the level of sales and property value.

The economic analysis of alternative rehabilitation methods and work schedules must account for the cost of quantifiable negative impacts when selecting the best alternative. Therefore, the total project cost comprises the sum of construction and user costs. Although accelerating rehabilitation increases the cost of construction, and longer work schedules generate a greater number of impacts to road users per day of operation, savings in the total

cost of the project are possible by means of the reduction in the total number of days allocated for project completion.

Project acceleration creates a number of consequences for the state or federal transportation agency, the contractor, and the road user. The increase in construction cost is by far the most important effect of acceleration. Problems with quality, low visibility, accidents, low productivity, low worker morale, fatigue, safety, and noise at night are among the impacts resulting from accelerated construction schedules.

The cost of acceleration, however, can only be justified if the amount of traffic volumes passing through the work zone is such that the magnitude of the savings in additional user costs are similar to or greater than the cost of accelerating the project. The minimum traffic volumes warranting accelerated rehabilitation were identified as 20,000 vehicles per day per open lane in the direction under consideration. Once a facility is carrying higher volumes, the additional cost of accelerating the rehabilitation can be negated by the amount of savings in user costs.

Even though project acceleration has yielded benefits for highly trafficked corridors, there are other mitigation measures available to transportation agencies, which do not include reducing the number of days available for project completion. Improved design practices and innovative construction methods and equipment may help in reducing the time required to produce transportation services by the contractors. Innovative contracting practices and project management techniques may be the most effective means of accelerating rehabilitation projects. Traffic management both on-site and off-site of the work zone may help with reducing demands and hazards along the facility by redistributing traffic through the existing capacity of the surrounding network during rehabilitation. Transportation systems management may also contribute in reducing demands by changes in modal splits or travel patterns and behavior. Public information campaigns may reduce negative impacts by raising the tolerance of the public to the temporary inconveniences. Two-way communication may improve coordination between traffic operations and construction activities and build public support. All these mitigation strategies should be applied together in order to get the most benefit from the money invested.

8.3 RECOMMENDATIONS

Further research in the area of quantification and cost allocation of accident costs, environmental costs, and abutting businesses and property is needed to credibly estimate the impacts of rehabilitation projects. The better those impacts are understood and quantified, the easier and more reasonable it will be to justify additional expenditures for mitigation measures during highway rehabilitation.

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**APPENDIX A: EQUATIONS FOR ESTIMATING ADDITIONAL USER COSTS
DURING HIGHWAY REHABILITATION**

ADDITIONAL USER COSTS FROM HIGHWAY WORK ZONES

The procedures and equations contained in the QUEWZ model and later modifications –QUEWZE (energy) and QUEWZEE (energy and emissions)– are presented in this section.

1. WORK ZONE CAPACITY ESTIMATION

The linear equations shown in Figure 1 are used to identify the risk associated with a certain value of the work zone capacity for a given lane closure strategy. If the actual value for the work zone capacity is lower than the assumed value, the analysis will tend to underestimate the length of queues caused by the work zone lane closure.

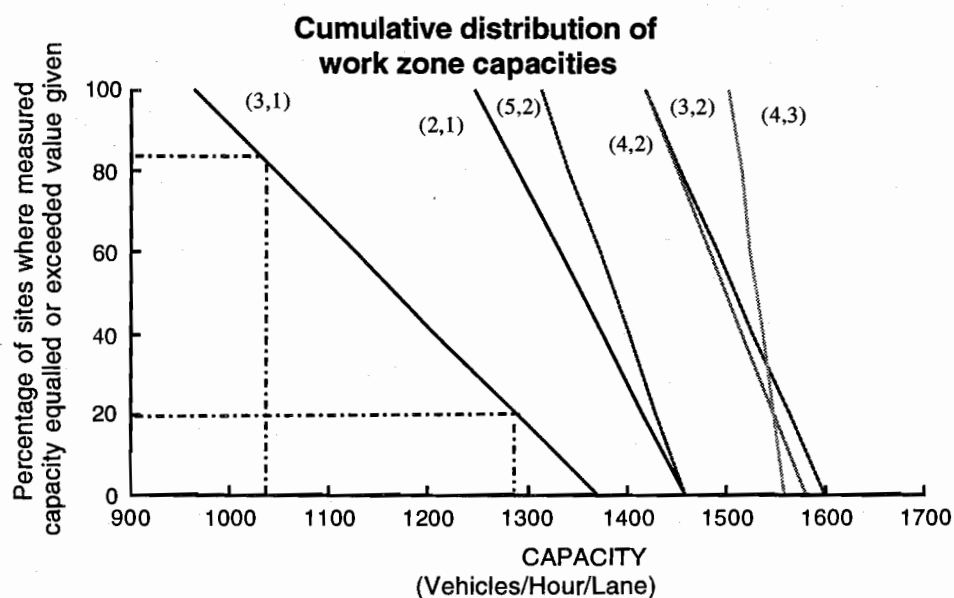


Figure 1. Work zone capacities and associated risk of the assumed value .

The estimated capacity is calculated with the following equation

$$\text{CAPW} = a - b (\text{CERF})$$

where:

CAPW is the restricted capacity during work zone activity hours
CERF is the capacity estimate risk factor or probability that the estimated capacity will be less than or equal to the actual capacity.

a and b are coefficients obtained by regression analyses of capacity data

The values for coefficients a and b are listed in Tables 1 and 2.

Normal No. of Open Lanes in one direction	No. of Open in		Lanes Through One	Work Zone Direction	
	1	2	3	4	5
2	1,460				
3	1,370	1,600			
4	1,200	1,580	1,560		
5	1,200	1,460	1,500	1,550	
6	1,200	1,400	1,500	1,550	1,580

TABLE 1. Restricted Capacity Coefficients During Work-Zone Activity Hours: Intercept Term (a).

Normal No. of Open Lanes in one direction	No. of Open in		Lanes Through One	Work Zone Direction	
	1	2	3	4	5
2	2.13				
3	4.05	1.81			
4	0.00	1.60	0.57		
5	0.00	1.46	0.00	0.00	
6	0.00	0.00	0.00	0.00	0.00

TABLE 2. Restricted Capacity Coefficients During Work-Zone Activity Hours: Slope Term (b).

2. SPEED REDUCTION ESTIMATION

The procedure to estimate the average approach speed is based on this speed-volume relationship using three speed parameters along with two volume parameters to define the shape of the curve as shown in Figure 2:

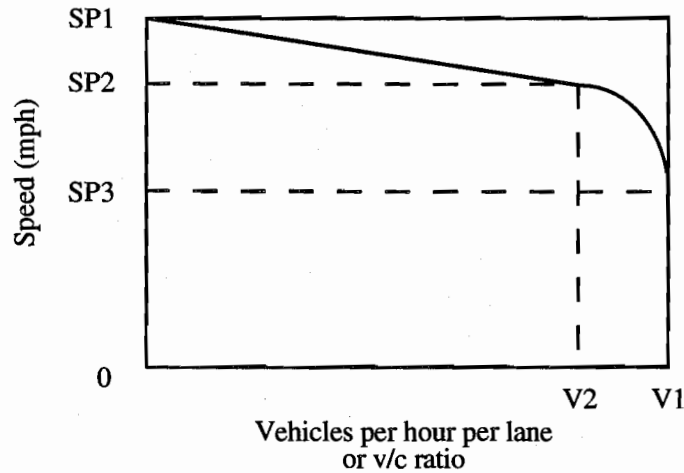


Figure 2. Hourly speed-volume curve .

The Highway Capacity Manual gives guidance for speed and volume parameters to be used in the speed-volume relationship shown above. These parameters vary according to the number of freeway lanes and the peak-hour factor, which is the ratio of the peak-hour traffic volume and the maximum 5 minute rate of flow within the peak-hour. A peak-hour factor of 0.91 is recommended for large metropolitan areas with over a million people, 0.83 for metropolitan areas with 500,000 to 1,000,000 people, and finally a peak-hour factor of 0.77 is recommended for areas below 500,000 inhabitants. Table 3 shows the values for speed and volume parameters suggested by the Highway Capacity Manual.

6 lanes Parameters:	Peak-hour factor			
	1.00	0.91	0.83	0.77
SP1	60	60	60	60
SP2	37	39	41	43
SP3	30	30	30	30
V1	2000	2000	2000	2000
V2	1800	1650	1500	1400

Table 3. Recommended Speeds and Volumes for 6-lane freeways of Various Peak-hour Factors.

The hourly traffic volume is converted into a volume-to-capacity ratio (V/C), and the approach speed in miles per hour is calculated using the following equations:

If $V/C < V_2/V_1$,

$$SP = SP_1 + \left[\frac{V_1 * (SP_2 - SP_1)}{V_2} \right] * (V/C)$$

If $V_2/V_1 < V/C < 1$,

$$SP = SP_2 + (SP_2 - SP_3) * \left\{ 1 - \left[\frac{(V/C) - (V_2/V_1)}{1 - (V_2/V_1)} \right]^2 \right\}^{1/2}$$

If $V/C > 1$ or a queue is present,

$$SP = SP_3 [2 - (V/C)]$$

with the speed constrained to the following range: $20 < SP < SP_3$

The average speed through the work zone (SP_{wz}) is calculated from the same speed equations using the V/C ratio of the work zone area. The higher V/C ratio accounts for the lower average speeds.

The minimum speed reached by a vehicle approaching the work zone is somewhat lower than the average speed through the work zone since several vehicle maneuvers are involved such as decelerating, merging, etc. The minimum speed is also dependent on the traffic conditions at the work site reflected in the volume/capacity ratio. Therefore, the minimum speed can be estimated using the following equation:

$$SP_{mn} = SP_{wz} - 2.3 - 25.7(V/C_{wz})^2$$

If there is a queue, then $SP_{mn} = 0$.

3. USER DELAY COST ESTIMATION

3.1 Cost of delay through the lane closure

The distance over which vehicles travel at a reduced speed through a work zone is not always the entire distance of restricted capacity. Adjustment to the length of reduced speeds is required when traffic volume is light for vehicles that tend to slow down only when passing the paving machine or other major work activity. The following equations are used to estimate the effective length of closure of reduced average speeds:

$$CLL = 0.1 + (WZd + 0.1) * (V/Cwz)$$

where:

CLL = Effective length of closure (miles)

WZd = Length of restricted capacity (miles)

V/Cwz = Volume to restricted capacity ratio.

If $WZd \leq 0.1$ or if $V/Cwz > 1$ then:

$$CLL = WZd + 0.2$$

The dollar delay cost of going through the work zone at a reduced speed (CDWZ) is calculated with:

$$CDWZ = CLL * \left[\frac{1}{SPwz} - \frac{1}{SPap} \right] * (VL) * (CUF) * \left(PTC * VLTc + \frac{PTT * VLTt}{0.9} \right)$$

where:

SPap = Approach speed (mph)

SPwz = Work zone speed (mph)

VL = Hourly vehicle volume (vph)

CUF = Factor to update cost calculations

PTC = Percentage cars

PTT = Percentage trucks

VL_{Tc} = Value of time for cars (\$/hr)

VL_{Tt} = Value of time for trucks (\$/hr)

3.2 Cost of delay during deceleration/acceleration cycles

Additional delay costs are due to vehicles slowing down and returning to the approach speed. The distance traveled during the speed-change cycle (DSC) is a function of the V/C ratio through the work zone as follows:

$$DSC = 0.5 + 0.25 * (V/Cwz), \quad DSC \leq 0.75$$

Assuming that the speed is reduced and increased at an approximately constant rate, then:

$$CDSC = DSC * \left[\frac{2}{SP_{ap} + SP_{mn}} - \frac{1}{SP_{ap}} \right] * (VL) * (CUF) * \left(PTC * VL_{Tc} + \frac{PTT * VL_{Tt}}{0.9} \right)$$

3.3 Cost of delay in queue

The average delay for each hour a queue is present is the average of the accumulated vehicles in queue at the beginning and the end of the hour, assuming the vehicles have arrived at a constant rate during the given hour. The following formula is used to compute the average queue delay:

$$DQUE_i = \frac{ACUM_{i-1} + ACUM_i}{2}$$

where:

$$ACUM_i = ACUM_{i-1} + VL_i - CAPW_i$$

and

DQUE_i = Average delay in vehicle hours

ACUM_{i-1} = Accumulated vehicles in the queue at the beginning of hour i

$ACUM_i$ = Accumulated vehicles in the queue at the end of hour i
 $CAPW_i$ = Restricted capacity through work zone (vph) for hour i
 VL_i = Vehicle demand during hour i

Figure 3 is a graphical representation of the queue delay estimation, where the area between the demand curve and the work zone capacity represents the vehicles in the queue.

If the queue dissipates during hour i , the delay calculation must be modified by the proportion of the hour that a queue was present (PQUE):

$$DQUE_i = \frac{ACUM_{i-1} + ACUM_i}{2} * PQUE_i$$

where:

$$PQUE_i = \frac{ACUM_{i-1}}{CAPW_i - VL_i}$$

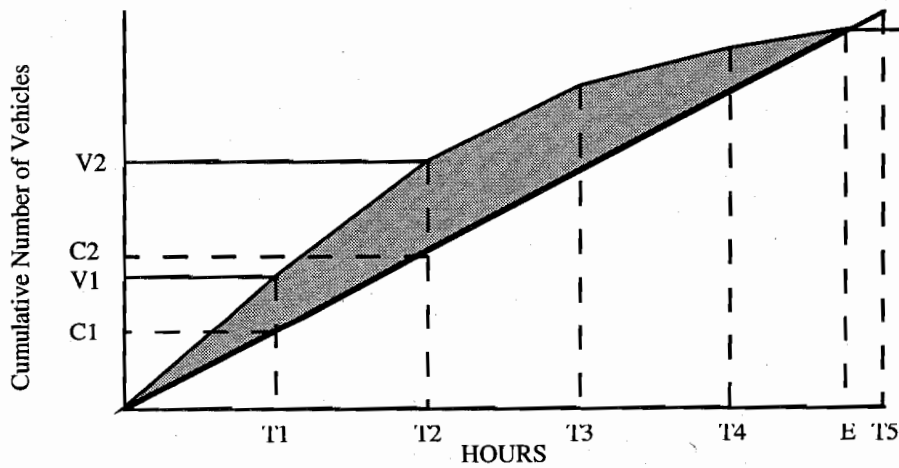


Figure 3. Calculation of Queue Delay.

The cost of delay (CQUE) is calculated as:

$$CQUE_i = (DQUE_i) * (CUF) * (PTC * VLT_c + PTT * VLT_t)$$

4. CHANGES IN VEHICLE OPERATING COSTS WHILE TRAVELING AT A REDUCED SPEED

Vehicle running costs are estimated as a function of speeds as follows:

Passenger Vehicles:

$$f(sp) = FULps * Cf + OILps * Co + \frac{TIRps * Ct * 4}{100} + \frac{MRPps * Cm}{100} + \frac{DEPps * Cd}{100}$$

$$\ln(FULps) = 4.37555 - 0.036805 SP + 0.000493 SP^2$$

$$\ln(OILps) = 2.24911 - 0.605472 \ln(SP) + 0.000138 SP^2$$

$$\ln(TIRps) = -2.64126 + 0.026311 SP + 0.000179 SP^2$$

$$\ln(MRPps) = 3.79730 + 0.007514 SP + 0.000038 SP^2$$

$$\ln(DEPps) = 0.141111 - 0.025357 SP + 0.000184 SP^2$$

Trucks:

$$g(sp) = FULtr * Tf + OILtr * To + \frac{TIRtr * Tt * 18}{100} + \frac{MRPtr * Tm}{100} + \frac{DEPtr * Td}{100}$$

$$\ln(FULtr) = 5.54162 - .0038976 SP + .000422 SP^2 + 0.010021 GVW$$

$$\ln(OILtr) = 1.73804 - 0.054478 SP + 0.00058 SP^2 + 0.01972 GVW$$

$$\ln(TIRtr) = -1.29336 + 0.033594 SP - 0.365299 \ln(GVW)$$

$$\ln(MRPtr) = 3.75972 + 0.011918 SP - 0.006733 GVW + 0.000094 GVW^2$$

$$\ln(DEPtr) = 0.785579 - 0.416221 \ln(SP) - 0.025701 GVW$$

where:

FUL = fuel consumption, in gal/1,000 miles

OIL = oil consumption, in quart/1,000 miles

TIR = tire wear, in percent of wear/1,000 miles

MRP = maintenance and repair, in percent of average cost/1,000 miles

DEP = depreciation, in percent depreciable/1,000 miles

SP = speed, in mph

GVW = gross vehicle weight, in kip

Subscript ps = cars, weighted ave. of large, medium, small and pickup

Subscript tr = truck

Ci = unit price for cars

Ti = unit price for trucks

f = fuel, o = oil, m = maintenance and repair, t = tires, d = depreciation

Changes in operating costs are estimated by the difference between operating costs at normal and reduced speeds:

Changes in operating costs for cars:

$$\mathbf{VOC_{pc} = f(SP_{wz}) - f(SP_{ap})}$$

Changes in operating costs for trucks:

$$\mathbf{VOC_{tr} = g(0.9SP_{wz}) - g(0.9SP_{ap})}$$

Changes in operating costs at the work zone:

$$\mathbf{OC = (VL/1000) * CUF * CLL * (PTC * VOC_{ps} + PTT * VOC_{tr})}$$

If queue is formed, the average speed through the queue is a function of the reduction in capacity:

$$\mathbf{SP_q = \frac{S_1}{2} * \left[1 - \left(1 - \frac{C_{wz}}{Cap} \right)^{\frac{1}{2}} \right]}$$

where:

Cap = normal capacity, vph

Cwz = work zone capacity, vph

S1 = free flow speed, miles

Changes in operating costs are estimated as follows:

Changes in operating costs for cars if queue develops:

$$QVOC_{pc} = f(SP_q) - f(SP_{ap})$$

Changes in operating costs for trucks if queue develops:

$$QVOC_{tr} = g(SP_q) - g(0.9SP_{ap})$$

Changes in operating costs at the work zone if queue develops:

$$OCQ = (VL/1000) * CUF * QUEL * (PTC * QVOC_{ps} + PTT * QVOC_{tr})$$

5. CHANGES IN VEHICLE OPERATING COSTS DUE TO SPEED CHANGE CYCLES

Vehicle operating cost from speed change cycles are estimated as a function of the initial and ending speeds as follows:

Passenger Vehicles:

$$SPCC = XFUL_{ps} * Cf + XOIL_{ps} * Co + \frac{XTIR_{ps} * Ct * 4}{100} + \frac{XMRP_{ps} * Cm}{100} + \frac{XDEP_{ps} * Cd}{100}$$

$$\ln(XFUL_{ps}) = -1.82937 + .01617 Sb + .00928 Se + .95385 \ln(DSP)$$

$$\ln(XOIL_{ps}) = -7.08574 + .000165 Sb^2 - .00433 Se + .785289 \ln(DSP)$$

$$\ln(XTIR_{ps}) = -4.21757 + .009618 Sb + .014043 Se + 1.12544 \ln(DSP)$$

$$\ln(XMRP_{ps}) = -3.98097 + .014714 Sb + .017072 Se + 1.13136 \ln(DSP)$$

$$XDEP_{ps} = 0.001121 + .000003 Sb^2 - .000205 Se + .001204 \ln(DSP)$$

Trucks:

$$SPCT = XFUL_{tr} * Tf + XOIL_{tr} * To + \frac{XTIR_{tr} * Tt * 18}{100} + \frac{XMRP_{tr} * Tm}{100} + \frac{XDEP_{tr} * Td}{100}$$

$$\ln(XFUL_{tr}) = -0.487983 + .014543 Sb + .01755 Se + 1.01086 \ln(DSP) \\ + .012024 GVW$$

$$\ln(XOIL_{tr}) = -5.90401 + .000244 Sb^2 - .00431 Se + .718207 \ln(DSP) \\ + .025511 GVW$$

$$\ln(\text{XTIRtr}) = -3.90082 + .008921 \text{ Sb} + .014405 \text{ Se} + 1.13969 \ln(\text{DSP}) \\ - .006515 \text{ GVW}$$

$$\ln(\text{XMRPtr}) = -4.49595 + .022254 \text{ Sb} + .019257 \text{ Se} + 1.10363 \ln(\text{DSP}) \\ + .004409 \text{ GVW}$$

$$\ln(\text{XDEPtr}) = -7.93292 + .000055 \text{ Sb}^2 + .000103 \text{ Se}^2 + .999303 \ln(\text{DSP}) \\ - .011838 \text{ GVW}$$

where:

XFUL = fuel consumption, in gal/1,000 cycles

XOIL = oil consumption, in quart/1,000 cycles

XTIR = tire wear, in percent of wear/1,000 cycles

XMRP = maintenance and repair, in percent of average cost/1,000 cycles

XDEP = depreciation, in percent depreciable/1,000 cycles

Sb = beginning speed change, in mph

Se = ending speed change, in mph

DPS = difference between the beginning and ending speeds, in mph

GVW = gross vehicle weight, in kip

Subscript ps = cars, weighted ave. of large, medium, small and pickup

Subscript tr = truck

Ci = unit price for cars

Ti = unit price for trucks

f = fuel, o = oil, m = maintenance and repair, t = tires, d = depreciation

Changes in operating costs owing to speed change cycles are estimated as follows:

$$\text{CSPC} = (\text{VL}/1000) * \text{CUF} * (\text{PTC} * \text{SPCC} + \text{PTT} * \text{SPCT})$$

If queue is formed, every vehicle will experience approximately 3 speed change cycles from 10 to 0 mph for every mile of queue. The length of queue if estimated is as follows:

$$QUEL_i = \frac{40 * DQUE_i}{5280 * TL}$$

where:

QUEL = length of queue, miles

TL = number of lanes upstream the work zone

Changes in operating costs if there is a queue are estimated as follows:

$$CSPCQ = (VL/1000)*CUF*3*QUEL*[PTC*SPCC(10,0) \\ +PTT*SPCT(10,0)]$$

The numbers in parenthesis indicate beginning and ending speeds

6. EMISSION RATES

Tailpipe emission rates are estimated for carbon monoxide, hydrocarbons and nitrogen oxides. They are modeled for each mode of operation, including cruising, acceleration and deceleration, as a function of speed, acceleration, and idle emission rates. The emission rates are estimated as follows:

Carbon Monoxide (CO)

1. Cruise Emission Rate (gm/hr)=[16mph MOBILE Scenario Rate] *(16.2mph) * (0.494 + 0.000227S²)
2. Acceleration Rate (gm/hr)= MOBILE Scenario Rate*S*[0.182 - 0.00798(AS) + 0.000362(AS)²]

Equivalent Model:

$$\text{Pass cars} = 111.4 - 9.05 S + 0.84 S^2 - 0.493 S^3 + 0.00729 S^4$$

$$\text{Trucks} = 20.125 + 8.5985 S - .37135 S^2 + 6.1456E^{-3}S^3 - 2.9472E^{-5}S^4$$

3. Deceleration Rate (gm/hr)= 1.5 * idle emission rate (gm/hr)

Hydrocarbons (HC)

1. Cruise Emission Rate (gm/hr)= idle emission rate (gm/hr)

2. Acceleration Rate (gm/hr)= MOBILE Scenario Rate*S*[0.018+5.226E⁻⁴(AS)
+ 6.1296E⁻⁶(AS)²]

Equivalent Model:

Pass cars=5.8127 -.141735 S +1.4535E⁻²S² -3.443E⁻⁴S³ +2.894E⁻⁶S⁴

Trucks =0.1672 +.21664 S -7.7947E⁻³S² +1.216E⁻⁴S³ -6.4191E⁻⁷S⁴

3. Deceleration Rate (gm/hr)= idle emission rate (gm/hr)

Nitrogen Oxides (NOx)

1. Cruise Emission Rate (gm/hr)= idle emission rate (gm/hr)

2. Acceleration Rate (gm/hr)= MOBILE Scenario Rate * S * [0.00386
+ 8.1446E⁻⁴(AS)+ 6.1296E⁻⁶(AS)²]

Equivalent Model:

Pass cars= 0.2963 +.1544 S - 4.577E⁻³S² + 6.19E⁻⁵S³

Trucks = -0.69458 +1.46 S -3.3855E⁻²S² +4.859E⁻⁴S³

3. Deceleration Rate (gm/hr)= MOBILE Scenario Rate * S * [0.00143
- 1.7005E⁻⁴(AS)]

Equivalent Model:

Pass cars= -8.1618E⁻³ + 3.774E⁻² S - 4.809E⁻⁴S² - 1.3859E⁻⁶S³
+ 1.3574E⁻⁷S⁴

Trucks = -0.211 + 0.3125 S - 1.1E⁻²S² + 1.4347E⁻⁴S³

**APPENDIX B: TRAFFIC DISTRIBUTIONS ON
SELECTED
TEXAS HIGHWAYS**

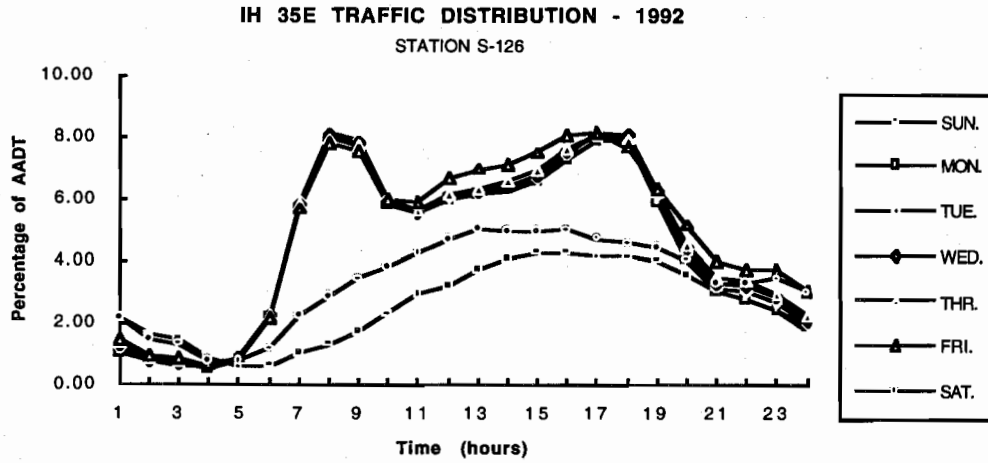


Figure 1. Traffic Distribution at IH-35E Dallas Station S-126.

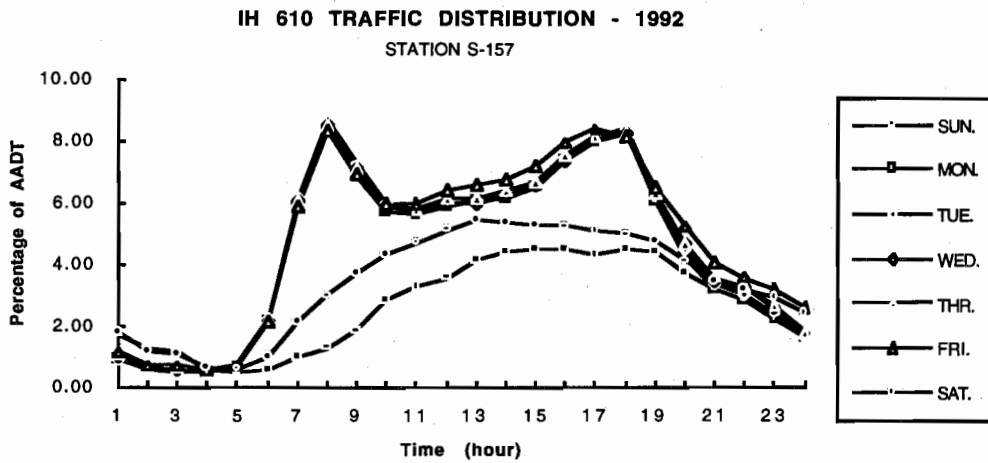


Figure 2. Traffic Distribution at IH-610 Houston Station S-157.

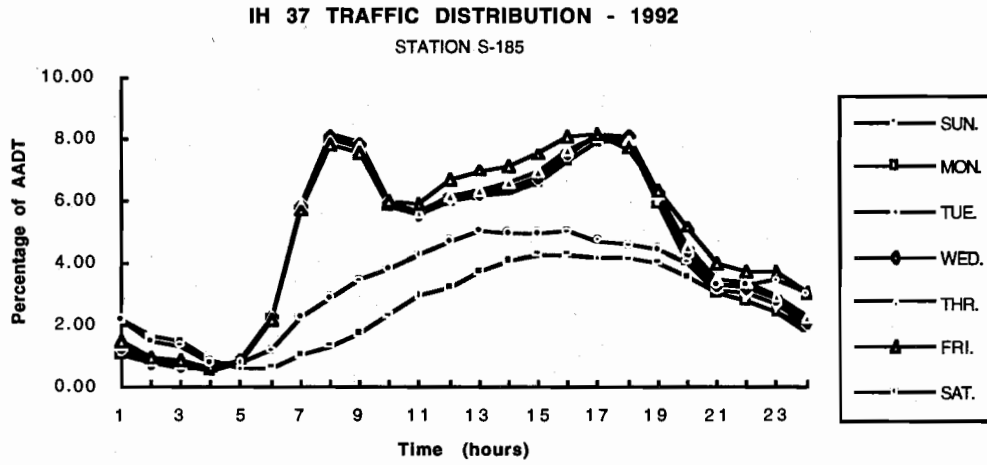


Figure 3. Traffic Distribution at IH-37 San Antonio
Station S-185.

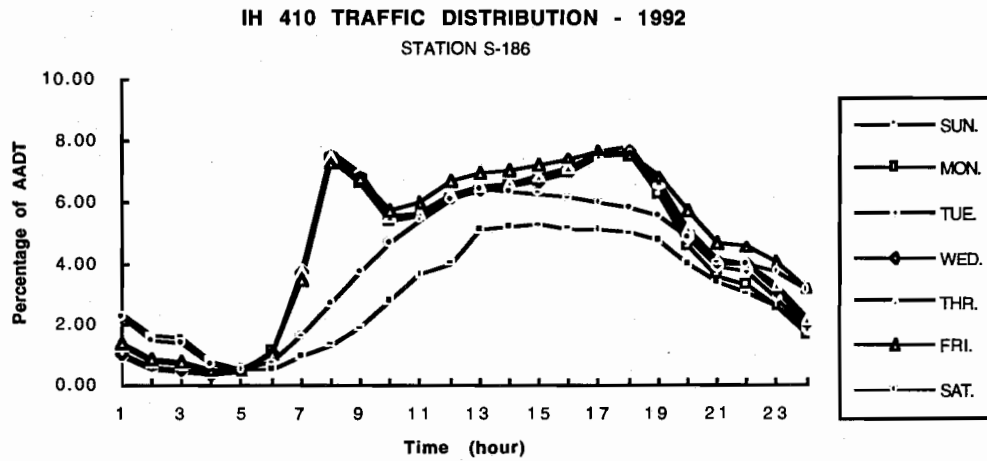


Figure 4. Traffic Distribution at IH-410 San Antonio
Station S-186.

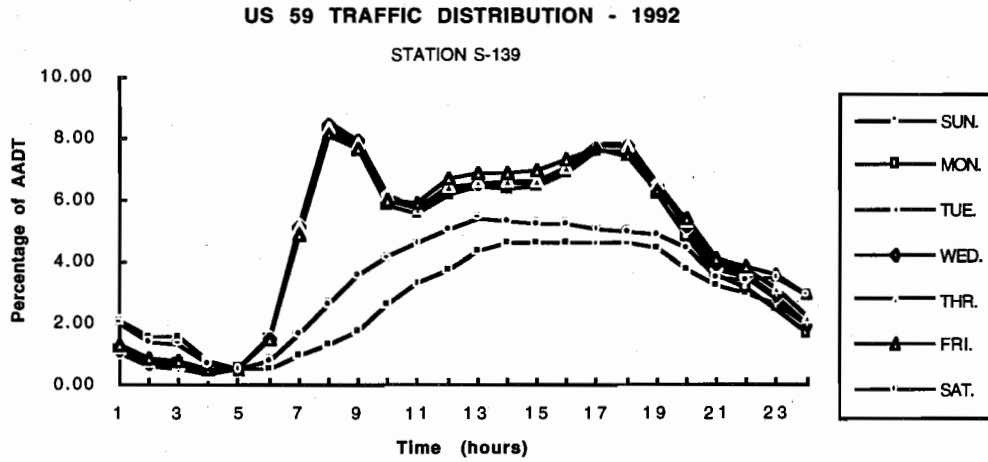


Figure 5. Traffic Distribution at US-59 Houston Station S-139.

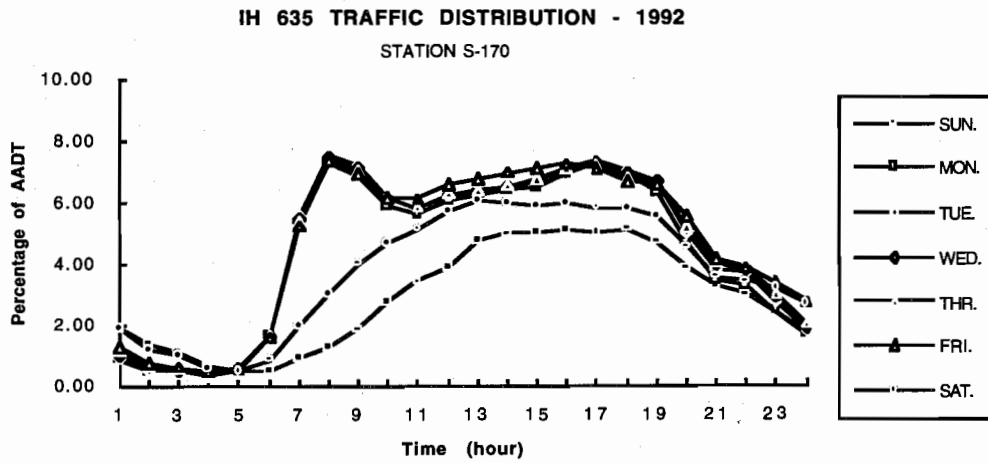
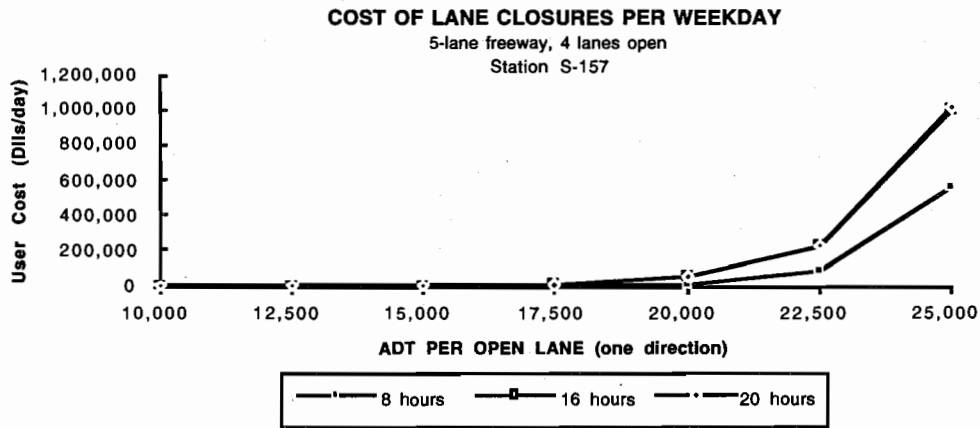
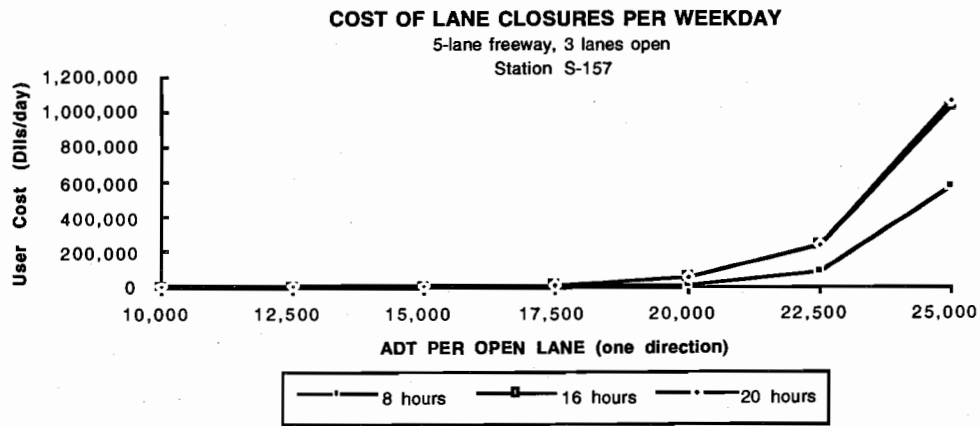


Figure 6. Traffic Distribution at IH-635 Dallas Station S-170.

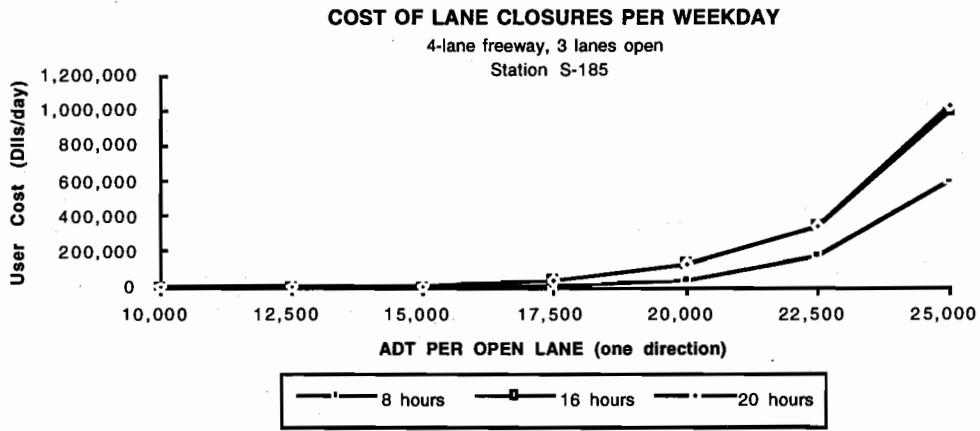
**APPENDIX C: USER COSTS GENERATED AT WORK ZONES
PER DAY OF CLOSURE**



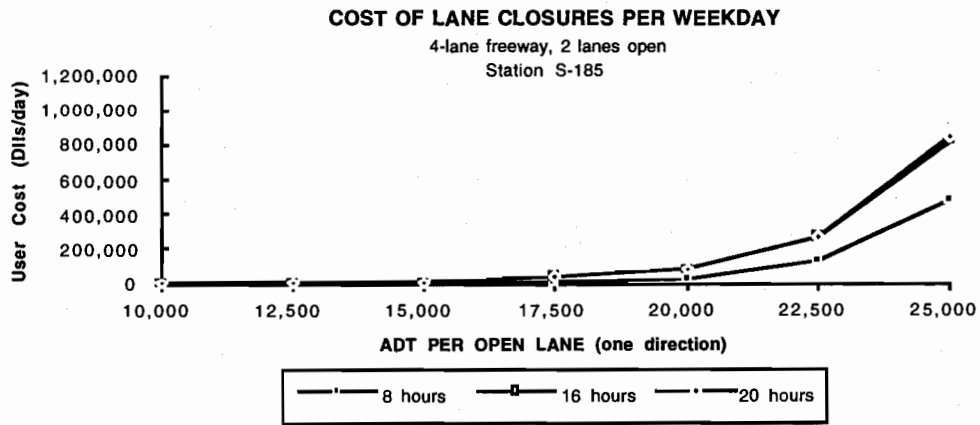
*Figure 1. User Costs at a 5-lane freeway
4 lanes open.*



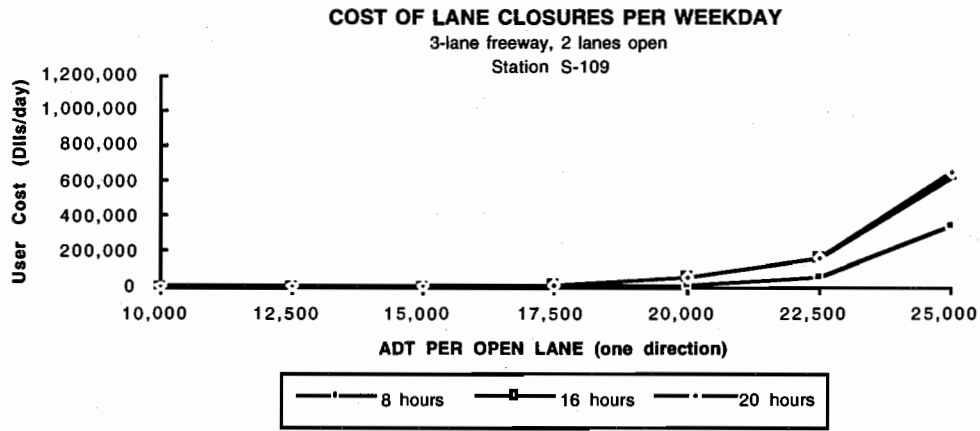
*Figure 2. User Costs at a 5-lane freeway
3 lanes open.*



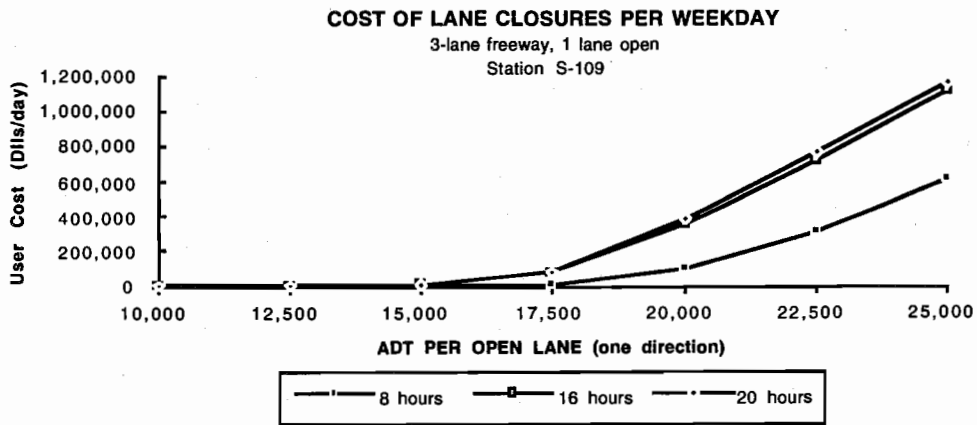
*Figure 3. User Costs at a 4-lane freeway
3 lanes open.*



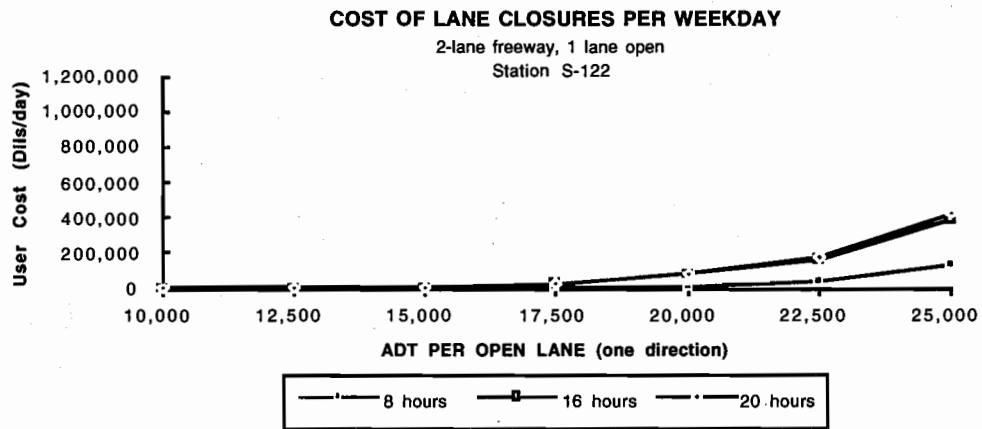
*Figure 4. User Costs at a 4-lane freeway
2 lanes open.*



*Figure 5. User Costs at a 3-lane freeway
2 lanes open*



*Figure 6. User Costs at a 3-lane freeway
1 lane open.*



*Figure 7. User Costs at a 2-lane freeway
1 lane open.*

**APPENDIX D: COST COMPARISON BETWEEN ACCELERATED AND
CONVENTIONAL HIGHWAY REHABILITATION PROJECTS**

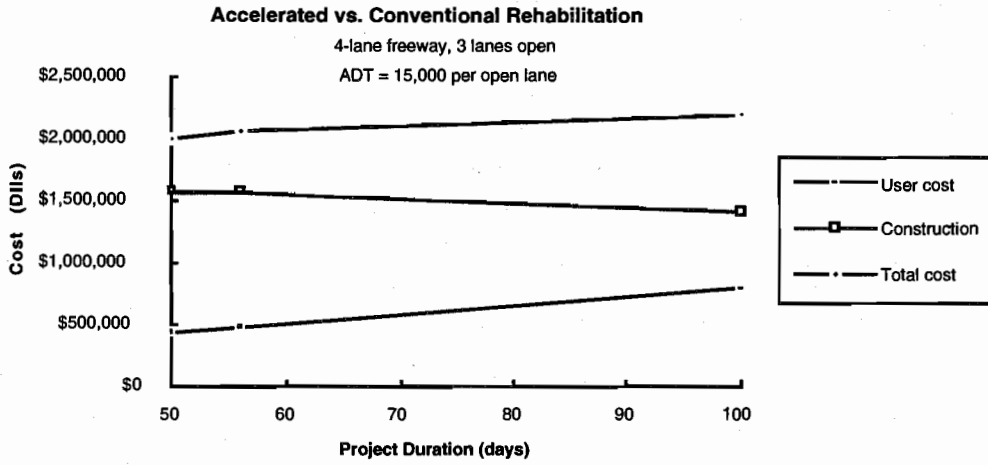


Figure 1. Project base cost and duration: \$ 1,000,000 and 100 days.
ADT = 15,000 per open lane.

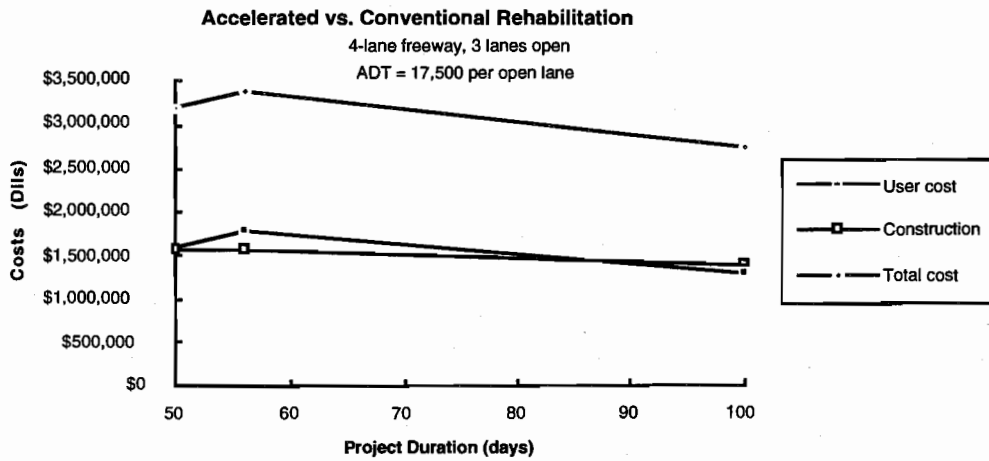


Figure 2. Project base cost and duration: \$ 1,000,000 and 100 days.
ADT = 17,500 per open lane.

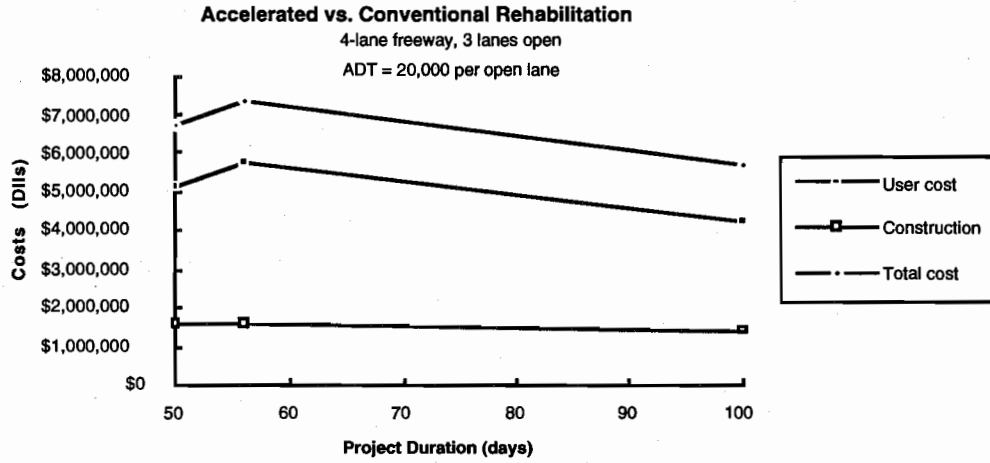


Figure 3. Project base cost and duration: \$ 1,000,000 and 100 days.

ADT = 20,000 per open lane.

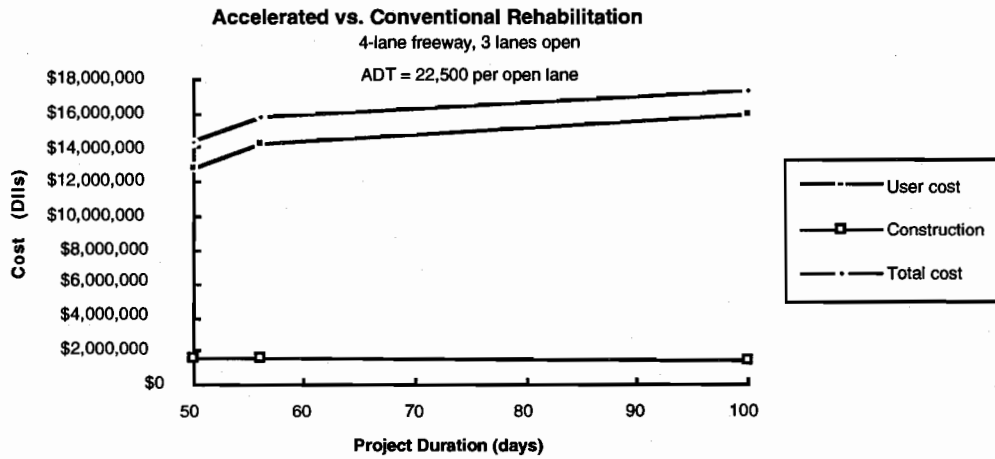


Figure 4. Project base cost and duration: \$ 1,000,000 and 100 days.

ADT = 22,500 per open lane.

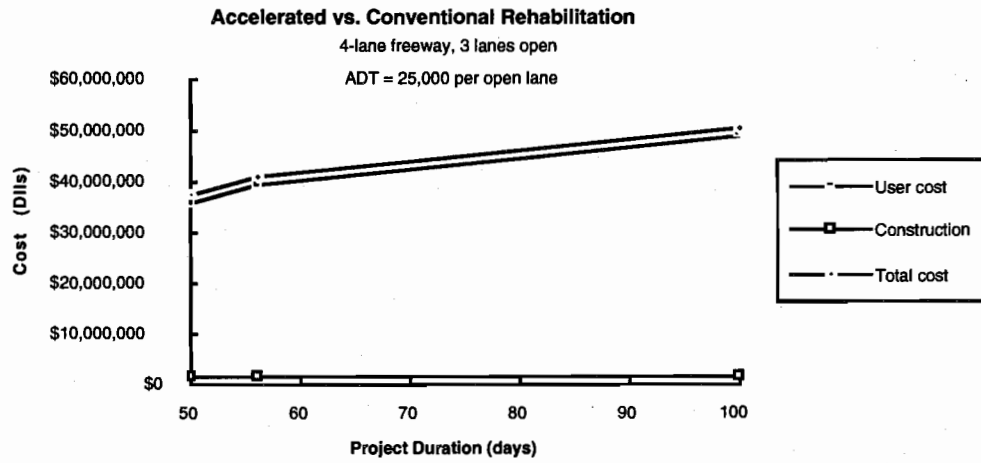


Figure 5. Project base cost and duration: \$ 1,000,000 and 100 days.
 ADT = 25,000 per open lane.

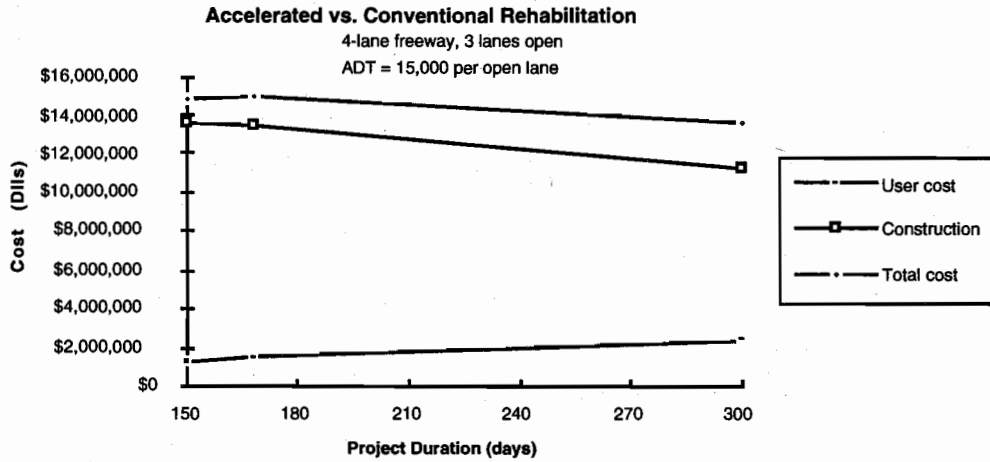


Figure 6. Project base cost and duration: \$ 10,000,000 and 300 days.
ADT = 15,000 per open lane.

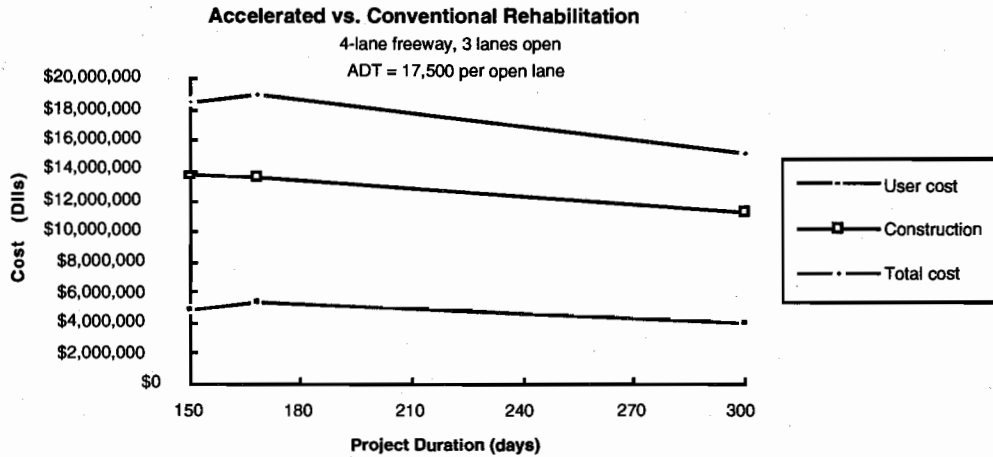


Figure 7. Project base cost and duration: \$ 10,000,000 and 300 days.
ADT = 17,500 per open lane.

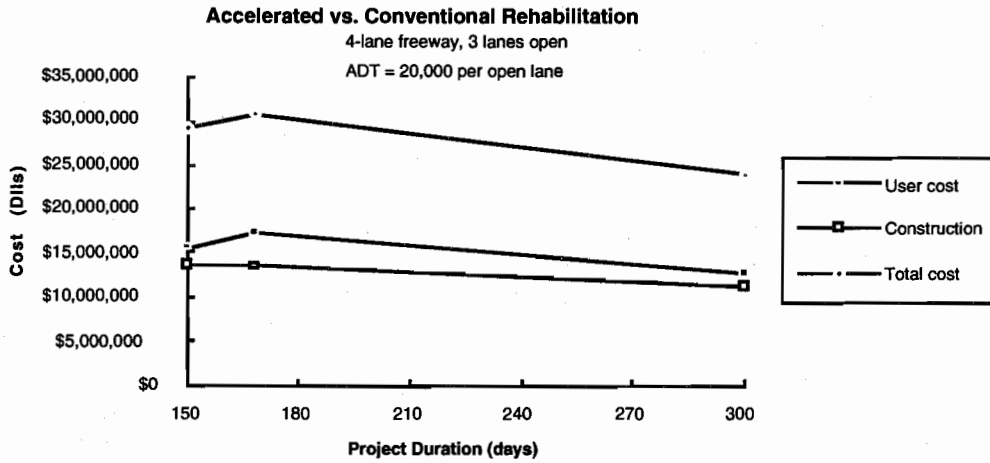


Figure 8. Project base cost and duration: \$ 10,000,000 and 300 days.
ADT = 20,000 per open lane.

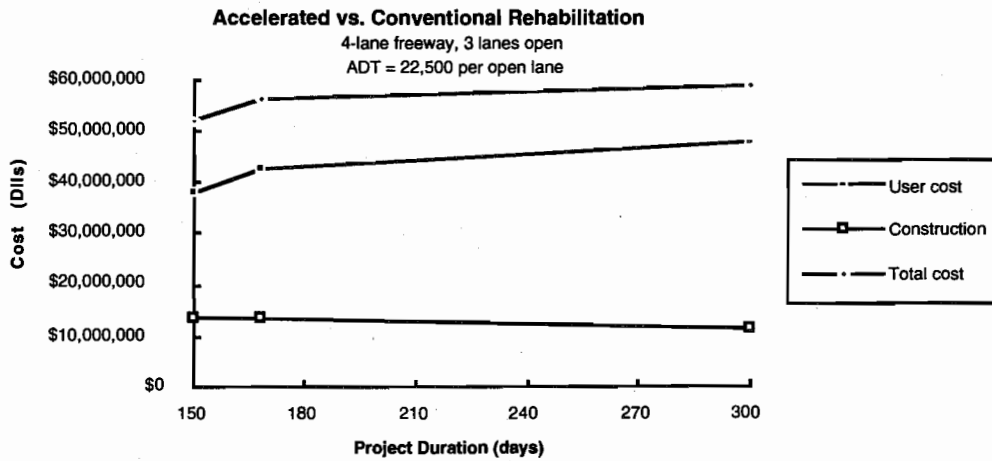


Figure 9. Project base cost and duration: \$ 10,000,000 and 300 days.
ADT = 22,500 per open lane.

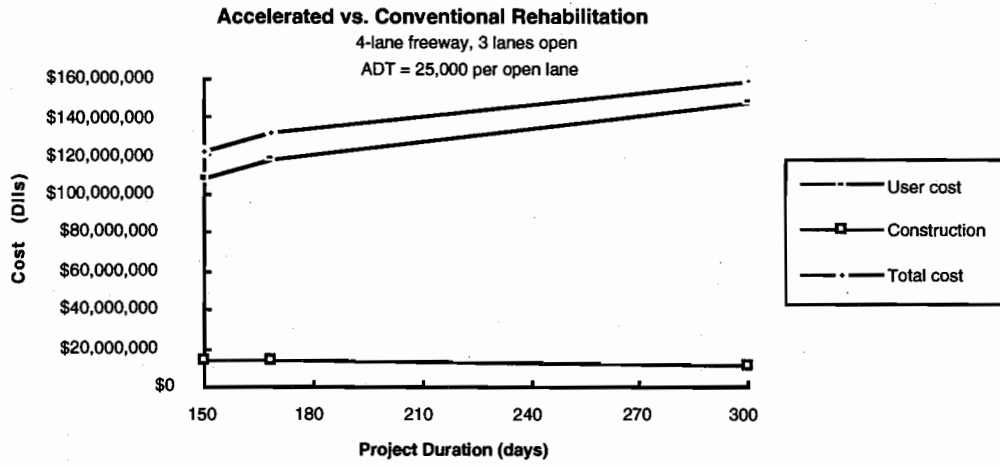


Figure 10. Project base cost and duration: \$ 10,000,000 and 300 days.
 ADT = 25,000 per open lane.

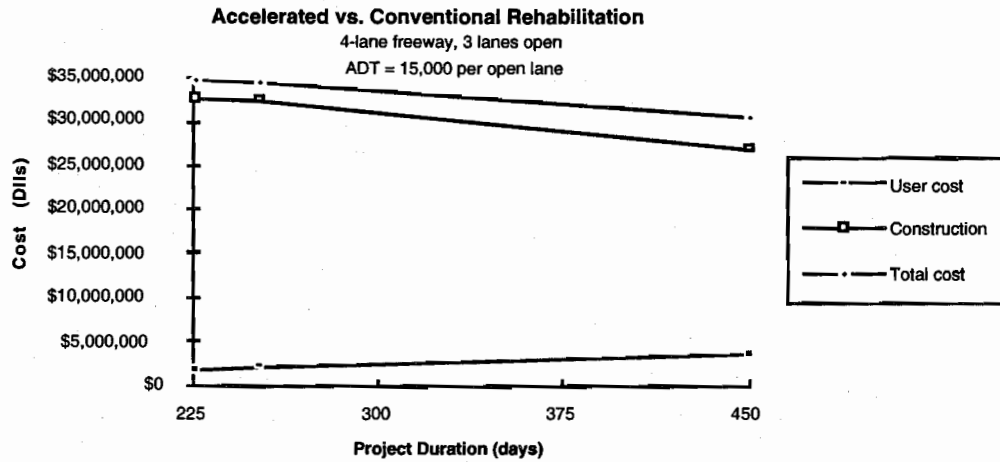


Figure 11. Project base cost and duration: \$ 25,000,000 and 450 days.
ADT = 15,000 per open lane.

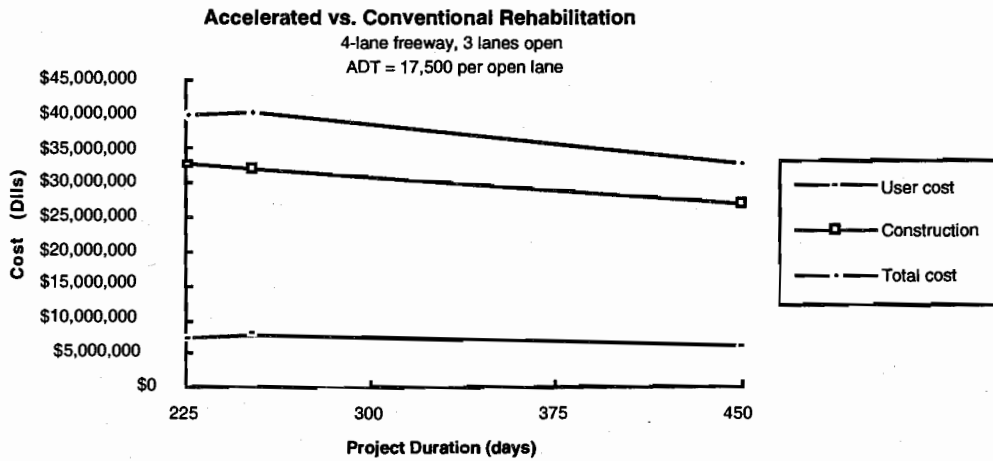


Figure 12. Project base cost and duration: \$ 25,000,000 and 450 days.
ADT = 17,500 per open lane.

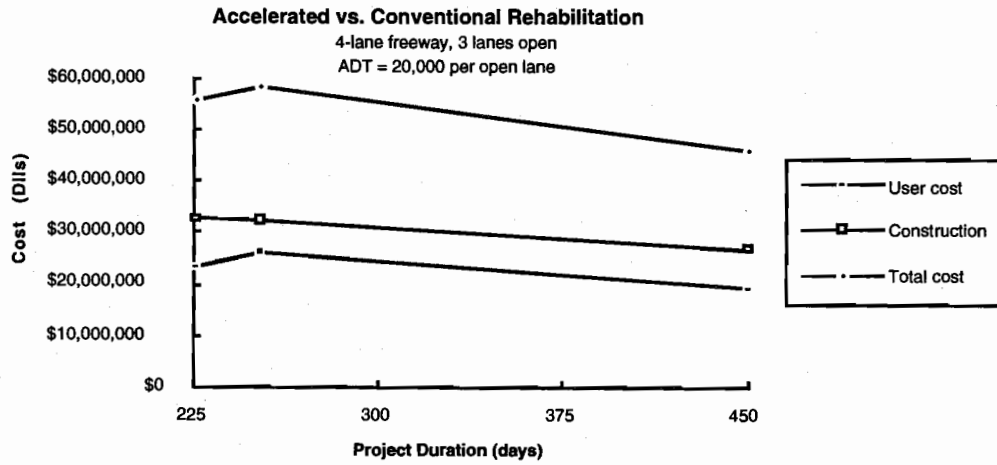


Figure 13. Project base cost and duration: \$ 25,000,000 and 450 days.
ADT = 20,000 per open lane.

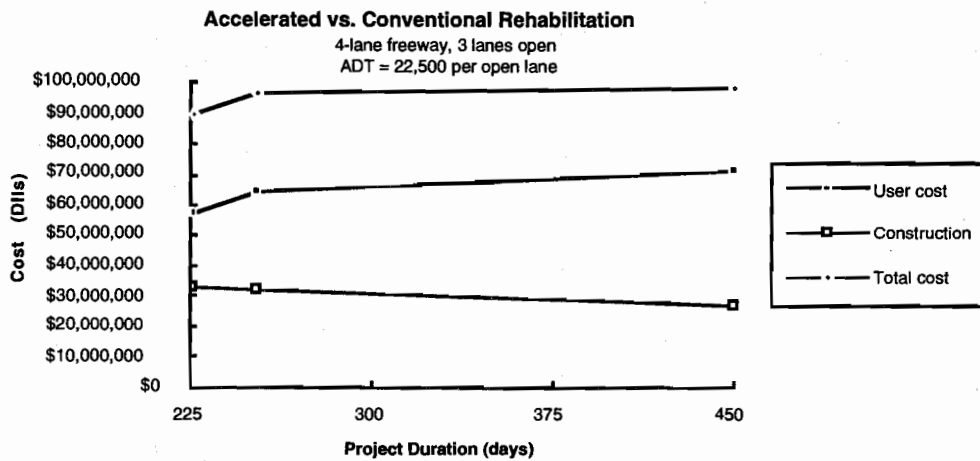


Figure 14. Project base cost and duration: \$ 25,000,000 and 450 days.
ADT = 22,500 per open lane.

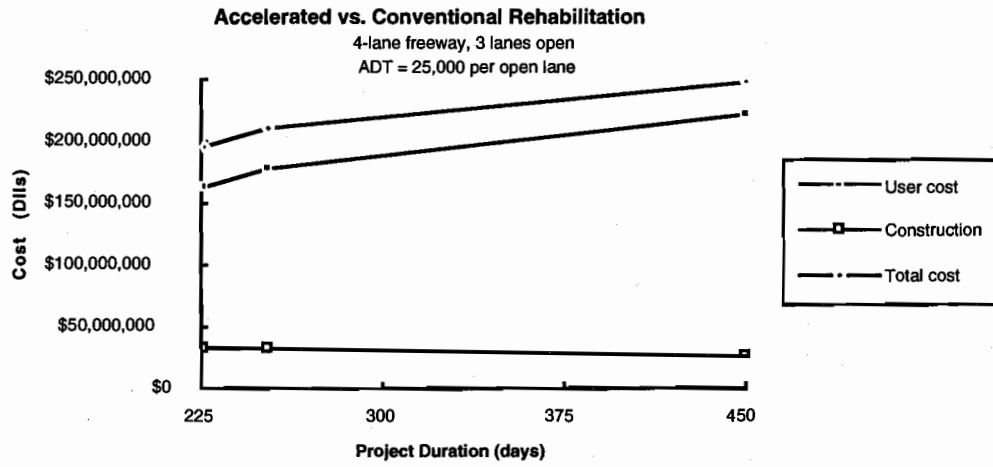


Figure 15. Project base cost and duration: \$ 25,000,000 and 450 days.
 ADT = 25,000 per open lane.