NCHRP

REPORT 475

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

A Procedure for Assessing and Planning Nighttime Highway Construction and Maintenance

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A Procedure for Assessing and Planning Nighttime Highway Construction and Maintenance

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SUBJECT AREAS
Maintenance

Research Sponsored by the American Association of State Highway and Transportation Officials
in Cooperation with the Federal Highway Administration

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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The project that is the subject of this report was a part of the National Cooperative Highway Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council. Such approval reflects the Governing Board's judgment that the program concerned is of national importance and appropriate with respect to both the purposes and resources of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration, U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical committee according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

To save time and money in disseminating the research findings, the report is essentially the original text as submitted by the research agency. This report has not been edited by TRB.

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FOREWORD

By Staff
Transportation Research Board

This report presents a decision process to assist highway agencies in evaluating night work alternatives against other work schedules. It provides a comprehensive, quantitative basis for selecting the most cost-effective plan for ensuring the safety of the public and workers, maintaining capacity, minimizing the impact on the community, and getting the work completed on schedule. This report will be of particular interest to engineers responsible for scheduling construction and maintenance work.

Work zones pose safety problems for both motorists and workers. Although work zones result in significant amounts of congestion and associated delay, lead to accidents and related losses, cause adverse impacts on communities and businesses, and increase driver frustration, the need to construct new highway facilities, preserve existing roadways, and perform maintenance make work zones unavoidable. Growth in traffic volumes has led many agencies to defer roadwork activities to off-peak hours to avoid congestion. Nighttime work, however, raises additional safety problems.

The objectives of NCHRP Projects 17-17 and 17-17(2) were to (1) develop guidelines for nighttime road work to improve safety and operations and (2) formulate procedures to facilitate making decisions about undertaking nighttime work. This report presents procedures to assist highway agencies in determining whether to perform nighttime construction or maintenance. *NCHRP Report 476* contains the guidelines for design and operation of nighttime traffic control for highway construction and maintenance.

A research team from The Last Resource, Inc., was selected to undertake this research. The structured decision process presented in this report encourages a systematic comparison of alternative traffic control strategies, including traffic control plans, traffic management plans, and work schedule alternatives. It provides a comprehensive, quantitative basis for selecting the most cost-effective plan for ensuring the safety of the public and workers, maintaining capacity, minimizing the impact on the community, and getting the work completed on schedule. Although the original intent of this research was to provide a means of evaluating night work alternatives against other work schedules, there is no reason why the process could not be applied to evaluating alternative traffic control strategies incorporating work schedules for any time of day.

PREFACE

Increasingly, it is becoming necessary to conduct construction and maintenance on operational highways while the highway continues to carry its normal traffic volume, or close to its normal volume. The public and community often expect that such work will result in little or no disruption to normal travel patterns and not limit access to land use along the highway corridor. There is also increasing concern for the safety of the traveling public and workers at highway work sites. In addition, highway agencies are under increasing pressure to complete the work in a manner that addresses quality, cost, and scheduling criteria, enabling construction and repair workers to "get in, get out, and stay out."

Whether the work entails routine maintenance activities such as patching potholes and sealing cracks and joints, more extensive rehabilitation such as setting pavement overlays and conducting bridge deck repairs, or major reconstruction, activities that involve work in the travel lanes result in some measure of disruption to normal travel patterns. Such work also poses increased safety risks and makes it more difficult to meet construction quality, cost, and scheduling goals.

When traffic volumes are well below the capacity of the highway, at least for a sizeable portion of the day, a number of options are normally available to accommodate both the normal traffic flow and the work activity within the existing roadway. These options typically consist of such techniques as closing lanes, shifting traffic onto the shoulder, or operating two-way traffic on one roadway of a divided highway while the work proceeds in the other roadway.

When traffic volumes approach the capacity of a highway section, especially when volumes remain at or close to capacity for most of the normal work day, reducing the total number of lanes available to traffic may result in delays, congestion, and overall unacceptable conditions in terms of congestion and community impact. In many cases, traffic congestion and delays also closely correlate with or lead to problems in terms of safety and adequate access to the work site. When such conditions arise, it usually becomes necessary to examine alternate traffic control strategies that can accommodate the traffic demands on the highway section and permit the work activities to proceed in a manner that reduces the adverse effects on all three traffic control objectives (i.e., safety, traffic and community impact, and constructability).

Except for very minor efforts, a traffic control plan (TCP) is normally prepared for most construction or maintenance activities. The TCP focuses on work zone traffic control, specific detour routes, and construction procedures. Traffic demand on the facility under construction is accommodated either within the roadway or (by establishing detours to carry traffic) around the work area. Traditional TCPs consist of sharing the roadway between traffic and construction or rerouting traffic onto other facilities using conventional traffic control devices and setups. Nontraditional TCPs typically may add contractual requirements to accelerate the work, introduce techniques to reduce the work space and time needed to complete the work, or shift the work to periods with less traffic (i.e., nights or weekends).

A conceptual framework for a TCP can be developed following the concepts discussed in this volume. If the decision is made to work at night, a detailed TCP must be developed following the principles of the Manual on Uniform Traffic Control Devices (MUTCD) and the guidelines provided in Sections 1, 2, and, to some extent, 3 of Volume II, which will be published separately as *NCHRP Report 476* and which is referred to herein as the Guidelines. Once the detailed TCP is finalized, an operational plan will be developed that will address the issues of staffing, training, oversight, accessibility of site, setup and takedown, and emergencies and contingencies. The development and implementation of an operational plan for night work is the subject of Section 3 of Volume II.

Depending upon the complexity of the TCP that develops, the need for a transportation management plan (TMP) often arises. The scope of a TMP is much broader than that of a TCP, often involving numerous agencies and concerning itself with traffic management and alternative transportation methods over a wide geographic area **(1)**.

The TCP is concerned with maintaining capacity and protecting workers and the public while getting the work completed efficiently, whereas the TMP considers the impact of the project throughout a corridor and sometimes beyond. However, since the TMP may be used to reduce the impact of a TCP, the TMP must be considered in the development of the TCP. This being said, this volume focuses on the development of a preliminary TCP, but with the understanding that TMP concepts may also be necessary on complex projects to meet the traffic control objectives. Principles for developing the TMP may be found elsewhere. The reader is referred to National Highway Institute Course No. 13355 for this purpose **(1)**.

It is the intention of this volume to provide a structured decision process that encourages a systematic comparison of alternative traffic control strategies, including TCPs, TMPs, and work schedule alternatives. This volume provides a quantitative basis for selecting the most cost-effective plan for ensuring the safety of the public and workers, maintaining capacity, minimizing the impact on the community, and getting the work completed on schedule. While the original purpose of this volume was to provide a means of evaluating night work alternatives against other work schedules, there is no reason why the method provided could not be applied to evaluating alternative traffic control strategies incorporating work schedules for any time of day.

The structured process offered in this volume is not without precedence. The process has its origins in the work of Abrams and Wang **(2)** and the National Highway Institute Course 13355 **(1)**. These sources provided the material from which Elrahman and Perry **(3)** produced their report, which included eight steps in a process for evaluating night versus day construction. New York State Department of Transportation (DOT) has implemented this process as the DOT's standard procedure for assessing the feasibility of night work **(4)**. The eight steps are encompassed in the structured process developed in this volume. The intent of this volume is to build on the earlier work and provide more quantification and subjective scaling with the goal of providing a reliable and valid procedure. Reliability in this situation is achieved if different people in an agency can take the same project and arrive at the same decision weighing the same alternative plans. Validity is achieved if the procedure results in choosing a TCP that, when implemented, results in achieving all of the desired effects with respect to capacity, safety, social and environmental parameters, work efficiency, and cost.

CONTENTS

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1. Introduction

As a means to assess the value of alternative traffic control strategies that involve night work, this procedure encourages a thorough and critical review of all traffic control options that adhere to essential traffic control standards and that are consistent with the work to be performed. This would include the consideration of the most advantageous traffic control plan (TCP) for daytime work as well as any additional options that become viable if the work can be done at night. Familiarity with the objectives of temporary traffic control and the variety of traffic control strategies available is essential to make effective use of these procedures and arrive at a valid decision. This introduction provides a brief overview of this subject along with a discussion of the conditions needed for night work to be effective, including factors to consider when beginning to evaluate night work options.

1A Temporary Traffic Control

Managing traffic through a highway construction or maintenance work area is an integral part of the overall management of the work. To plan, design, and operate the temporary traffic control used in highway work activities, it is essential to first understand the goal of temporary traffic control. This can normally be stated in terms of three specific objectives:

Objectives of traffic control

- Provide a high level of safety for workers and the public.
- Minimize congestion and community impact by maintaining levels of service at close-to-preconstruction levels.
- Provide adequate access to the roadway to complete the work efficiently while meeting the quality requirements for the completed product.

Principles of work zone traffic control

Part VI of the Manual on Uniform Traffic Control Devices (MUTCD), which establishes seven fundamental principles of work zone traffic control, is designed to ensure that the above objectives are satisfied **(5)**. These principles are summarized here:

1. Traffic safety in temporary traffic control areas should be an integral and high-priority element of every project from planning through design and construction. Plans should be developed in sufficient detail to provide safety for motorists, pedestrians, workers, and enforcement/emergency personnel and equipment.

2. Traffic movement should be inhibited as little as possible.

3. Drivers and pedestrians must be guided in a clear and positive way. Positive guidance emphasizes the proper path rather than areas that are to be avoided. Existing traffic

control devices should be removed if not appropriate or, in short-term work zones, other devices should be used that clearly emphasize the intended path.

4. Inspection of the traffic controls must be done on a frequent and regular basis. Accidents and other incidents should be analyzed to determine if changes in the TCP are necessary.

5. Measures should be taken to ensure a safe roadside. The roadside is of particular concern in work zones because of materials and equipment that are often stored on the roadside, thereby increasing the number of hazards. There are also a number of traffic control devices that can become hazards if struck. Sidewalks and pedestrian pathways must also be protected.

6. All persons involved with the selection, placement, or maintenance of work zones should be trained in safe traffic control practices. This includes designers as well as field personnel.

7. It is necessary to maintain good public relations. Although public relations is not a primary concern of the TCP designer, special efforts can be required in the contract document, and many agencies have policies that require notice in the media prior to beginning a project.

In addition, the MUTCD points out that laws are necessary to provide the traffic regulations needed in the work zones. These laws must permit sufficient flexibility to alter traffic control to fit changing conditions in a work zone.

All of the principles listed above are addressed in the second volume of this set, which will be published separately as NCHRP Report 476: *Guidelines for Design and Operation of Nighttime Traffic Control for Highway Maintenance and Construction*. However, the second principle, "Traffic movement should be inhibited as little as possible," is the focus of this volume, as nighttime work must often be considered as a method of limiting restrictions on traffic flow that would otherwise be incurred during daylight operations.

Traffic control options

Numerous techniques are available to manage traffic in highway work zones. The techniques may be used in conjunction with various transportation systems and transportation demand management techniques to reduce or divert traffic demand to alternate facilities, or to increase the capacity of the corridor where the work is to occur. References are available to provide an overview of these techniques, along with specific details on the planning, design, and operation **(5,6)**. A brief overview of these techniques is provided in Appendix A at the end of these procedures.

1B When Should Night Work Be Considered?

Whenever an acceptable balance among the three basic objectives of work zone traffic control (high level of safety, minimum congestion, and access to work area) cannot be achieved through traditional TCPs for daytime work, the feasibility of night work should be evaluated along with other traffic management strategies. However, the two basic conditions that must normally be met in order for night work to offer any advantage in terms of meeting the basic objectives are reduced traffic volumes and easy setup and removal of the traffic control pattern on a nightly basis.

Low volume, short work duration, and easy setup and removal

Shifting work activities to night hours, when traffic volumes are lower and normal business is less active, may offer an advantage in some cases, as long as the necessary work can be completed and the work site restored to essentially normal operating conditions to carry the higher traffic volumes during nonconstruction hours. In order for night work to provide a viable option, it is essential that the highway can easily be reconfigured from the normal traffic condition to the construction condition, and then returned to normal at the end of the night. If the construction operation must occupy the roadway for more than several hours each night, or if the temporary traffic pattern requires too great an effort to deploy and remove, no advantage is gained, and normally the night work option should not be considered further.

1C Factors Impacting Nighttime Work

While the basic conditions discussed above must generally be satisfied for night work to provide a feasible traffic control option, there are a number of other factors that also impact the feasibility and suitability of night work. Grouped into six major categories, these factors include the following:

- Traffic
- Construction
- Social
- Economic
- Environmental
- Other

While some factors may be readily quantified, others must be assessed primarily in terms of qualitative attributes **(1,3)**. See Section 5 (Conduct Cost-Effectiveness Analysis) for an in-depth discussion of these factors.

Traffic-related factors

The traffic-related factors that must be considered include congestion, safety, and traffic control. Congestion is the primary motivation to consider night work, as any reduction in capacity during the day often results in unacceptable queues and delays. While reduced traffic volumes at night result in less congestion and fewer delays, the negative impact of night work on safety may be a serious concern. Not only does reduced visibility make the driving and work tasks more difficult, but drivers, pedestrians and workers are generally all less alert. The incidence of impaired drivers and pedestrians is often higher, as are traffic speeds. Compared with daytime work zones, enhanced traffic controls are generally required at night to compensate for these factors. These enhancements may ensure an acceptable level of safety, but at an increase in project cost and duration. As mentioned earlier, the complexity of setup and removal of the traffic control system may make night work unfeasible if the work cannot be completed and the traffic control pattern cannot be returned to normal for day operations.

Construction-related factors

Productivity and quality are the two construction-related factors that must be considered. Reduced visibility and greater difficulty communicating with supervisors and/or technical support staff are two of the night-related factors that may have a negative effect on both the productivity and the quality of the work. Another factor that may have a negative effect on productivity is the longer setup/takedown times for traffic controls and lighting. There may, however, be some positive effects. The reduced interference from traffic and the longer work shifts that may result from lower night traffic volumes can be expected to produce greater productivity. Also, cooler night temperatures may enhance the quality of concrete placed and finished at night.

Social factors

Social factors that must be considered include those that affect workers and those that affect drivers. These factors can have a negative effect on safety and, in the case of workers, on productivity as well.

Working at night may disrupt normal sleep patterns and result in either sleep deprivation or a poor quality of sleep. Normal family and social activity is also disrupted, and the inability to attend community activities or family events may create serious domestic problems. Driver anger and frustration may be reduced because of fewer traffic delays; however, fatigue and impairment may be a greater concern at night.

Economic factors

The economic factors to consider may be divided into construction costs, user costs, and accident costs. Construction costs are theoretically more expensive because of overtime and night-premium pay, lighting expense, added traffic control costs, and increased material costs. These increases may be offset by decreased highway user costs and increased productivity. Operational efficiencies result when there is less traffic interference with construction operations.

Accident experience on individual projects suggests that accident costs may be either higher or lower at night, depending upon traffic conditions. On the one hand, poor visibility, higher speeds, and traffic control options that increase exposure to hazardous conditions increase the likelihood of an accident. Lower volumes, on the other hand, may offset some of the dangers involved in night work.

User costs are reduced because of fewer delays, which result in lower vehicle operating costs and substantial time savings. The economic impact on local business is usually lower at night because of the lower level of business activity.

Environmental factors

Air quality and fuel consumption are the two principal environmental factors to consider. Air quality is improved by night work because vehicle emissions are typically reduced because of reduced congestion, shorter delays, and fewer stops. Likewise, lower fuel consumption is associated with these improvements in traffic flow. Reduced emissions and lower fuel consumption both result in an environmentally friendlier alternative, which may be especially important in areas already having marginal or poor air quality.

Other factors

Other factors that must be addressed include public relations, scheduling, lighting, availability of material, and labor. To enhance the success of night work, the work hours should coincide with the lowest periods of traffic flow and should allow operations to be completed in time for traffic patterns to be returned to daytime conditions prior to the start of the morning peak. Effective public relations efforts are also essential to keep motorists and residents informed regarding traffic plans and impacts on the community. Community concerns associated with night work include noise, glare from work lights, and changes in traffic patterns that impact residential neighborhoods. These concerns may be partially offset by improved traffic flow and reduced congestion compared with daytime work. Adequate lighting is essential, both to ensure work quality and productivity and for the safety of workers and travelers. Finally, it must be ensured that materials, equipment, repairs, supervision, and special support services can all be obtained at night as necessary to support the work activities.

1D Overview of the Assessment Procedure

The sections that follow provide a structured procedure to assess the night work option compared with more traditional day work options for traffic control. This procedure consists of four distinct tasks and is applicable to the assessment of the full range of traffic control alternatives, not just night work. When night traffic volumes are markedly lower <u>and</u> the work site can be restored to essentially normal operating conditions during the higher volume daylight hours, night work becomes one of the options to be evaluated using this procedure. The four tasks in the procedure, displayed in Figure 1-1, are the following:

1. Gather Information
2. Develop Traffic Control Options
3. Evaluate Volume/Capacity
4. Conduct a Cost-Effectiveness Analysis

Gather information

One begins the procedure by determining the nature and extent of the work to be performed, traffic demands on the work site, and the availability of potential diversion and detour routes. The task also involves acquiring a variety of additional information needed to develop alternative traffic control schemes.

Develop traffic control options

The second task is intended to develop a listing of feasible options for traffic management control. It is at this point that a traffic management plan (TMP) should be initiated if applicable, and the entire corridor should be considered.

Evaluate volume-capacity

The third task requires an examination of the traffic volume/capacity relationships for the listed options. The purpose is to determine which of the options provide acceptable levels of congestion and delays. If none of the options being considered provide acceptable levels, the previous tasks should

be repeated until one or more acceptable options are identified.
Case studies conducted during this research confirm that many highway projects are limited to a single option that can meet all three traffic control objectives given various constraints and limited capacity of the highway system in the project vicinity.

Conduct a cost-effectiveness analysis

For projects where more than one traffic control option appears to meet the project objectives, the fourth and final task consists of a comparative analysis to select the preferred option for detailed planning and design. This preferred option will be the option that, for a given cost, is most effective in meeting the specific objectives established for it. The methodology presented here utilizes a cost-effectiveness analysis, which is comprised of five distinct steps:

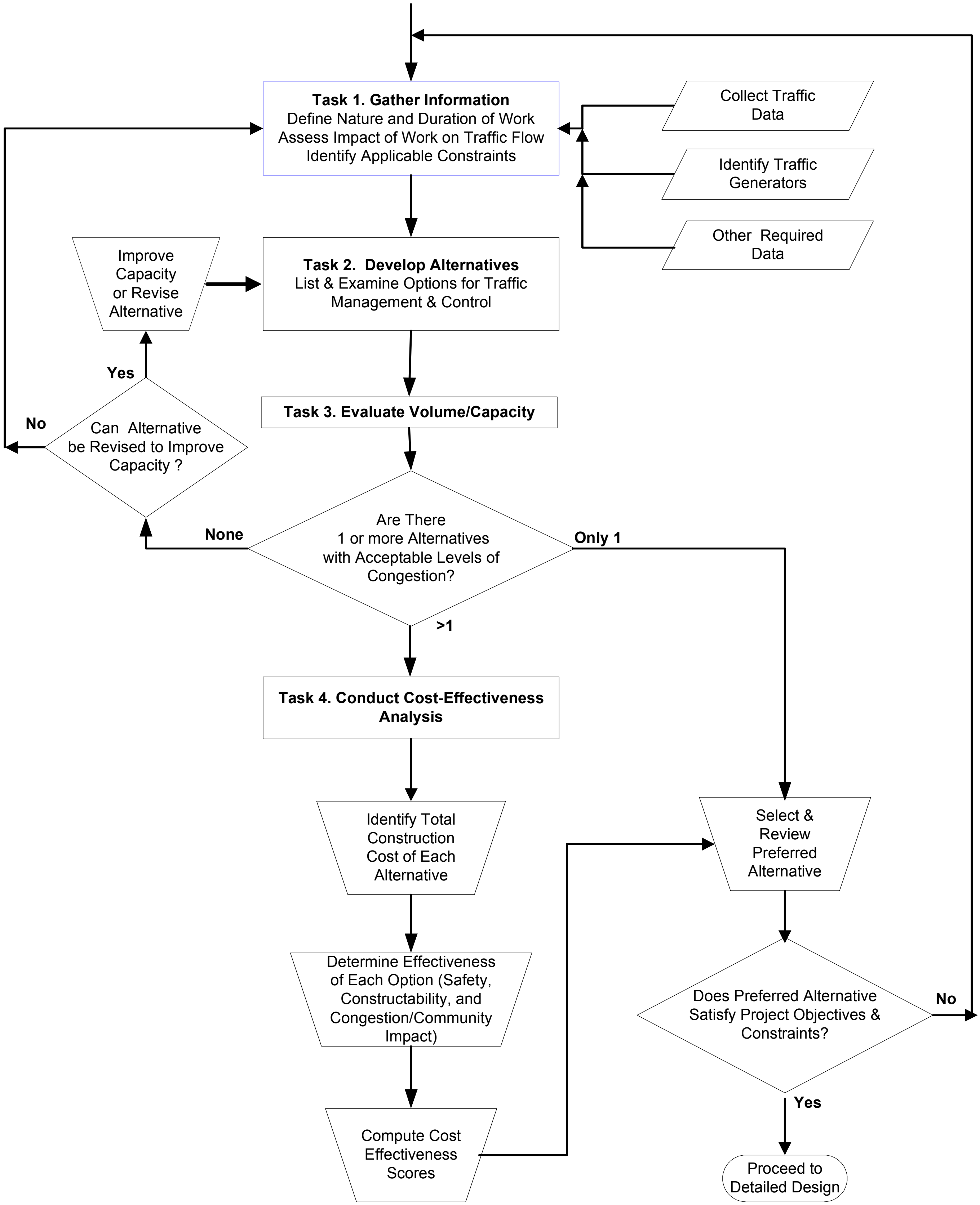
1. Identify Costs
2. Determine Effectiveness
3. Determine Weights for Objectives
4. Compute Cost-Effectiveness Scores
5. Select Preferred Option

The factors impacting the project costs are identified and quantified as accurately as possible. A qualitative assessment of each option is made to determine the effectiveness of the traffic control option in meeting the three primary objectives of work zone traffic control. Relative weights are then assigned to each of the three primary objectives on the basis of local considerations associated with the particular project.

The cost-effectiveness assessments are then used to develop a cost-effectiveness rating for each option considered. Options resulting in high qualitative effectiveness ratings, but with low costs, will be the preferred options. In some cases, it may be necessary to evaluate several options with similar and acceptable cost-effectiveness ratings and to base the final choice on project-specific constraints.

Following presentation of the step-by-step details of each task in the procedure, a number of examples are presented to illustrate the procedure's application. Throughout the procedural steps, appendices are referenced that provide specific guidance on the detailed analyses needed to complete the evaluation.

Figure 1-1 - Procedural Steps to Analyze Traffic Control Options Including Night Work



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2. Gather Information (Task 1)

This section describes the first task of the assessment procedure. Before the traffic control options can be identified, it will be necessary to compile a significant amount of relevant data. These data will be needed to develop each of the traffic control options that can carry the expected traffic volumes through or around the site while meeting other demands dictated by the community, the work itself, and other constraints. Like the development of any other work zone traffic control strategy, planning for night construction starts with the basic need to compile information concerning the work to be accomplished, the traffic demands that must be accommodated during the work, and the impacts the planned work activities will have on traffic flow and on the community in general. The National Highway Institute (NHI) Course, *Developing Traffic Control Strategies* **(6)**, and the MUTCD **(5)** provide details of the information needed for this purpose. The sections that follow provide a brief discussion of information that should be considered when developing traffic control options, including the option of working at night.

2A Nature and Duration of Work

The starting point in developing traffic control options is the definition of the work to be performed. The NHI Course, Developing Traffic Control Strategies **(6)**, lists several essential project characteristics that affect the selection of traffic control schemes. These include the following:

- Description and type of work (overlay, total pavement reconstruction, joint repair, bridge deck replacement, etc.)
- Roadway encroachment required, including buffers, storage, loading, and unloading areas
- Project work limits
- Tentative schedule (consider required time to complete, start time, and necessity of seasonal work through winter)
- Time periods and days of week that the roadway will be occupied
- Location of utilities and how they will be impacted
- Work vehicle entrances and exits required

Section 1B identified the two basic conditions under which night work may offer an advantage over other traffic control options: reduced traffic volumes at night that make it easier to accommodate traffic demand, and a work site that can be restored to essentially normal conditions in daylight to carry the normal traffic volumes during nonconstruction hours. The types of projects that may be good candidates for night work are activities such as pavement overlays and repairs, bridge work that can progress in nightly increments, and other activities that encroach on the travel lanes, but that can be started and stopped on a nightly basis. Certain other activities such as bridge deck replacement or full-depth pavement reconstruction typically require extended work periods. However, night work may also be advantageous for such activities when sufficient lanes can be left open to satisfy peak travel demands, with additional lanes closed at night to provide contractor access to the work space.

2B Impact of Work on Traffic Flow

Once the nature and duration of the work to be performed is defined, it is also necessary to define the level of roadway encroachment and the extent to which work activities will interfere with normal traffic flow on the facility. This, in effect, is the initial assessment of roadway capacity. Section 6-G of the MUTCD discusses several levels in which the planned work may encroach on the travel lanes, thus interfering with normal traffic flow:

All work beyond the shoulder. Impact on traffic is minimal, and traffic control is normally limited to alerting traffic to the activity on the roadside and protecting work traffic entering and exiting the traffic stream. If pedestrian paths are affected, it may become necessary to provide alternate pedestrian routes.

Work on shoulder. Depending on the nature of the work, impact on the travel lanes will vary considerably. Traffic control may range from a shoulder closure with little traffic impact to a full lane closure.

Within traveled way of two-lane, two-way roadway. This level of activity will have a significant effect on travel and will require either some means of controlling alternating one-way flow or rerouting one or both traffic streams.

Within traveled way of multilane roadway. Because one or more lanes must be closed, either traffic from that lane must merge with lanes that remain open or lanes must be shifted or relocated.

Work within intersections or interchanges. These locations are likely the points of lowest capacity and often represent the greatest impact on traffic flow. One must relocate traffic through the work area while still maintaining the ability to accommodate turning, crossing and merging traffic.

In addition to identifying the extent of interference, this analysis should consider the length of the occupied roadway on any given night, the number of days to complete the project, and the number of hours each day the roadway will be occupied.

Before beginning to identify specific traffic control options that may apply, a considerable amount of information is needed that describes the specific constraints to which any traffic control option must be responsive. One can identify these constraints by acquiring information concerning local traffic, generators, and the characteristics of the community in which the project is planned.

2C Identify All Applicable Constraints

The NHI Course, *Developing Traffic Control Strategies* **(6),** lists traffic data that are essential for traffic control development. They include the following:

Traffic data

- Speed data (design, legal and running)
- Twenty-four-hour volume counts (hourly or peak counts will be essential if night work is to be considered)
- Possible alternate routes (traffic data will be needed for these options as well)

- Other nearby projects and activities that may impact traffic
- Daily and seasonal volume variations
- Intersection/interchange turning movements
- Signal timing data
- Truck volume
- Bus traffic and stops
- Accident data
- Pedestrian and bicycle volumes and routes
- Railroad crossings and train schedules

Identify traffic generators and patterns

In addition to these data, major traffic generators should be identified, along with their traffic characteristics. These may include major commercial/retail centers, sports and entertainment sites, large educational institutions, and major employers. Any sites that may generate dramatic traffic peaks, such as the end of a sports event or the end of a work shift at a large employer, may have a significant impact on traffic volumes through a project. These sites need to be considered for night work options as well as for typical daytime operations. Extremely high traffic peaks, even for a relatively short duration, may result in unacceptable queuing and delays for traffic control schemes that appear acceptable on the basis of average traffic volumes over the entire work shift.

Other required data and agency contacts

While traffic data for the project and possible alternative routes are essential, other information concerning the project locale will also be essential to develop, evaluate, and implement traffic control options. Additional information needed includes the following:

- Business access and parking facilities, especially on-street parking that may be impacted by work operations
- School bus routes and stops, and school and recreational pedestrian crossings
- Fire districts and locations of fire stations
- Hospitals, ambulance services, and other emergency medical responders and services
- Public transportation routes, stations, etc.
- Restrictions on noise and lights
- Police agencies that may be available to assist with traffic control
- Policies or restrictions on worker or motorist safety
- Traffic restrictions on possible alternate or detour routes
- Trucking industry input on potential impacts on trucking operations

In addition, it will be necessary to establish contacts with government jurisdictions involved to gain approval for the various options, to obtain additional information as necessary, and to gain cooperation in implementing the plan finally selected.

Finally, several other characteristics of the project site and the surrounding community may impact not only traffic demands, but the viability of traffic control options as well. It is therefore essential to also consider the following points:

- Special events or holidays that may require special traffic handling for a short period.
- Environmental impacts or restraints on or adjacent to the project.
- Property owner and general public reaction to the proposed project, or to specific traffic control options.
- Wetland, archaeological, or historical sites that may require special treatment or further limit potential traffic control options.

3. Develop Traffic Control Options (Task 2)

The second task of the assessment procedure is to identify all viable options for traffic control. Appendix A provides a brief discussion of the traffic control alternatives that are available for consideration in developing a specific option for a project. Suitable options for night work must be able to carry the reduced nighttime traffic volume at an acceptable level of service, while permitting the roadway to be reconfigured to carry the higher daytime volumes. Options that may meet these requirements for night work include the following:

- Close lanes or shoulders during work hours.
- Shift traffic onto shoulders or temporary lanes adjacent to the permanent lanes.
- Shift traffic across the median, carrying both directions of travel on one roadway.
- Divert part of the traffic to alternate facilities, while carrying the remaining traffic through the project using the options listed above.
- Close the roadway through the project, detouring traffic to alternate or parallel routes or service-frontage roads.
- Divert through traffic, while permitting local traffic through the project, but restrict to fewer lanes.

Often, a combination of these options may be necessary to provide adequate contractor access to the roadway, while maintaining adequate traffic capacity. For example, it may be necessary to close the outside two lanes of a six-lane undivided highway for paving. Traffic on the opposing direction could be restricted to two lanes, while traffic on the affected direction is carried on the one remaining lane of that direction and one lane of the opposing side. A moveable traffic barrier may be added to separate the opposing traffic flows, depending on site considerations discussed in the design guidelines.

Using the traffic control concepts discussed above and listed in Appendix A, a list of options should then be developed based on the project requirements, traffic demands, and other information compiled in the previous task. Because night work entails a number of inherent disadvantages, as discussed in Section 1C, other options that can successfully address project needs should be fully explored before considering night work options.

The normal starting point in developing traffic control options is to determine the number of traffic lanes that will be needed to handle the expected traffic demand, as well as any other traffic demands such as pedestrian or bicycle traffic or other special demands. Table 3-1, taken from the 1997 Highway Capacity Manual, provides approximate lane capacities that may be appropriate for initial estimates of the number of traffic lanes that will be required **(7)**. This early check of available roadway capacity is critical because the vast majority of additional delay due to a work zone occurs if the traffic demand exceeds the available capacity for any appreciable length of time.

Table 3-1 - Lane Capacities

Number of Lanes		Average Capacity (vphph)	Capacity provided in 85 percent of cases
Normal	Open during construction		
3	1	1170	1020
2	1	1340	1270
5	2	1370	1340
4	2	1480	1440
3	2	1490	1450
4	3	1520	1490

The Highway Capacity Manual provides a wide range of capacity values that may be more appropriate to a particular case than the values in Table 3-1. Unfortunately, little reliable information is available on how capacity changes between day and night construction. Agencies could use the capacity provided in 85 percent of cases, as shown in Table 3-1, to be fairly sure that the actual capacity value they experience is higher than planned.

In addition to addressing basic traffic capacity requirements, the various traffic control options listed must also satisfy the requirements and constraints identified in Section 2C. Section 5 provides a detailed cost-effectiveness analysis to assess the various options developed here. However, before proceeding to this formal analysis, an initial screening is important to determine that the list of options to be evaluated at least appear capable of meeting traffic and other requirements and constraints for the project. Each of the potential options listed in this step should therefore be evaluated to ensure that it reasonably addresses these requirements. Options that obviously cannot meet one or more requirements should be dropped, and those remaining should progress to formal evaluation using the cost-effectiveness analysis discussed in Section 5.

4. Evaluate Volume/Capacity (Task 3)

Under Task 2 of this procedure, basic traffic control options were listed to meet the traffic demands of the planned work, and those options were screened to determine whether they met the requirements and constraints imposed by the project conditions. In this third task of the procedure, the options that survive the initial screening are evaluated in depth.

4A Determine Traffic Volume/Capacity Relationships

This in-depth evaluation requires determining the traffic capacity of the various traffic control options identified in the preceding section. The capacity characteristics of each option are then compared with the traffic volumes expected to use the facility, including the various diversion or detour routes that may be included in that option. For traffic control options that will be installed and removed on a daily basis, such as night work, the volume/capacity relationship must be examined on an hourly basis.

If volume exceeds capacity for any of the alternatives for more than a brief period of time, queue lengths, queue durations, and resulting delays may grow large and must then be calculated. Appendices B and C provide an overview of references addressing capacity and the analysis of queues and delays. Since one of the basic objectives of work zone traffic control is to minimize the impact on travelers and the community in general, this analysis is directed toward evaluating the congestion resulting from project activities for the various traffic control options and determining whether any resulting delays and queues are acceptable.

Evaluate congestion relative to local conditions

There is no widely accepted definition of "unacceptable" congestion. It is often not the same among urban and rural areas, and even among different areas within the same state. "Unacceptable" congestion must therefore be determined by local norms. Typically, the determination of whether congestion is unacceptable on a given project involves consideration of changes in level of service during construction, queue length/duration and resulting delay, and disruption of access to businesses and to travel pattern throughout the community. Another critical consideration is whether a queue grows so large that it blocks other intersections or interchanges. This is called 'spillback' and often has large negative delay and safety consequences that the profession cannot calculate at this time. The agency responsible for the work must determine what level of congestion and delay is unacceptable for each project on the basis of the impact of the project on the community.

For facilities with little or no congestion prior to the start of the work, a drop in the level of service to level E or F from preconstruction levels of A or B are likely to be considered unacceptable. Likewise, for facilities with preconstruction levels of service already in the E/F range, a 50-percent increase in average delay per vehicle over preconstruction conditions may be considered unacceptable. While these guidelines are suggested by one agency **(4)** as defining "unacceptable" congestion, each agency must select appropriate values for its own use.

4B Identify Acceptable Options or Improve Capacity

If the analysis determines that one or more of the options identified in Task 2 (Section 3) results in acceptable levels of congestion, those options should be subjected to the remaining steps of the assessment procedure to select the preferred option. If all of the options result in unacceptable congestion, the process should return to the second task (Section 3) to revise one or more of the options by increasing capacity, reducing demand, or otherwise reducing congestion. Increasing capacity usually requires adjustments to the TCP, while demand can be reduced by methods that require adjustments to the TMP such as trip diversions to other corridors or the use of high occupancy vehicle (HOV) lanes. In rare cases, it may not be possible to identify any options that satisfy all of the requirements of the project without resulting in at least some periods of unacceptable congestion. In such cases, those options offering the least congestion should be moved forward into the remainder of the assessment procedure.

For many projects in urban areas, and some projects involving rural expressways and arterials, high traffic volumes make it impossible to work during daytime without unacceptable traffic impacts, and alternate routes are not available to divert traffic around the project. Constraints identified in Task 1 may eliminate some potential traffic control options that may otherwise address capacity needs. In such cases, night work often emerges as the only viable option. If other project objectives can be met and other constraints addressed, working at night then becomes the preferred choice. In this situation, Task 4 is unnecessary, unless there is a need to choose between significantly different night work options.

5. Conduct Cost-Effectiveness Analysis (Task 4)

Cost/benefit vs. cost-effectiveness

The remainder of these guidelines are concerned with implementing a cost-effectiveness model as an aid to making a selection among two or more alternative traffic control strategies. The model suggested is based upon the procedure suggested in the NHI Course, *Developing Traffic Control Strategies* **(6),** and later modified by Elrahman and Perry **(3)**. While the terms cost/benefit and cost-effectiveness are often used interchangeably, the distinction between them generally rests on whether the benefits of the options being evaluated can be stated in the same terms as the costs (typically dollars). Cost/benefit analysis is most appropriate when the decisionmaker needs to see a positive return on an investment (i.e., the benefits should equal or exceed the costs). As one example, cost/benefit analysis would be appropriate if one were trying to decide whether a new road should be constructed. In this situation, the benefits of the new road (access, reduced congestion, etc.) should offset the costs of land and construction over some reasonable period of time.

The cost-effectiveness method was selected for these guidelines as opposed to cost/benefit analysis since the evaluation of whether to work at night requires the consideration of numerous factors that provide no easily quantified monetary benefit. While it is true that everything has a price, and methods do exist to assist in quantifying seemingly subjective factors, it is likely that the cost and accuracy of doing so makes a cost-effectiveness analysis most appropriate. The decision to be made about whether to work at night concerns only the relative effectiveness of different methods and not any expected benefits. The benefits will be derived from building or repairing the road in the first place; the methods of construction do not affect these benefits, but only the effectiveness of the method of getting the job done.

Cost-effectiveness: a tool, not an answer

While cost-effectiveness analysis is offered as a method to choose among alternative solutions to a single construction or maintenance problem, it must be remembered that this analysis is only an aid to the decision-making process and does not replace "experiment, experience, intuition, and judgement" **(8)**. The quantification and systematization of cost-effectiveness analysis can, however, add to the likelihood that the decision is good. Although cost-effectiveness analysis cannot ensure that a particular option is best beyond any reasonable doubt, the method can make a systematic and efficient use of information and, if nothing else, eliminate really bad alternatives. It should be clear that cost-effectiveness analysis does not yield decisions, but improves the likelihood that a decision is good by sharpening the intuition and judgement of the decisionmaker.

5A Identify Total Construction Cost of Each Option

There is an undisputed consensus that construction costs include both the costs of traffic control and any upgrades to detour routes as well as the basic costs of project construction **(1,3)**. There appears to be less agreement as to whether various user costs should be considered as a cost or a measure of effectiveness. Elrahman and Perry combine user and construction costs and compare them with various qualitative measures of effectiveness or utility. Traffic delay and vehicle operating costs are considered costs, while the costs associated with safety, environmental impact, etc. are considered a measure of utility **(3)**. For the purpose of a cost/benefit analysis, the NHI Course, *Developing Traffic Control Strategies*, combines user costs with the cost of accidents and business loss to derive an overall benefit in dollars. The cost element of the equation includes only construction and traffic control costs. For the purpose of a cost-effectiveness analysis, the NHI course includes an effectiveness rating that is based upon user costs, accidents, and other qualitative measures **(6)**.

These guidelines follow the model of Elrahman and Perry and include user costs together with the costs of traffic control, project construction, road upgrades, etc. in the cost estimate of construction. However, it should be noted that user costs are not paid for out of an agency's operating budget, and, therefore, an agency may choose not to include them. If they are not included as a cost, but their existence is likely to affect public reaction to the project, they should be considered in the effectiveness ratings discussed below. If, on the other hand, user costs are added to the total project costs, they should not influence the effectiveness ratings. In other words, they should be counted only once, either as an increase in costs or as a reduction of effectiveness, and this must be done the same way for each option being evaluated.

Table 5-1 - Sample Cost Identification Worksheet

Objective	Factor	Cost		
		Option 1	Option 2	Option 3
Traffic Control	Setup/Takedown			
	Device Rental			
	Maintenance			
	Pedestrian Accommodation			
	Enforcement			
	Detour Upgrade			
Lighting	Planning			
	Hardware Rental			
	Maintenance			
Constructability	Labor			
	Labor Premiums			
	Incentive Clauses			
	Materials			
	Equipment			
User	Traffic Delay Costs			
	Vehicle Operating Costs			

A worksheet similar to that shown in Table 5-1 should be used to identify as many costs as accurately as possible.

It should also be noted that these guidelines do not account for accidents in the total cost estimate, but do allow any judgement of accident potential to affect the safety component of effectiveness (see discussion below). Should data become available that would allow one to estimate accident costs for different traffic control schemes, accident costs would be included in the same way as user costs. The only exception would be that some accident costs would be incurred by the agency and some by the user.

Use local data

Whenever possible, an agency should use cost data based upon its own local experience in estimating each of the component costs that must be included in the analysis. When local data are not available, it may be possible to obtain "ball park" cost estimates from local contractors. Sources for obtaining estimates of user costs are discussed in Appendix C.

5B Determine Effectiveness of Each TCP/Option

Factors that reflect the effectiveness of each alternative solution will be evaluated in this step, and the output of these evaluations will be used to develop an overall effectiveness rating. The three global objectives of traffic control for construction and maintenance (high level of safety, minimal congestion, and access to work area) have been clearly stated in Section 1A, and it is clear that any measure of effectiveness should reflect how well these objectives have been satisfied.

Identify factors that reflect the effectiveness of each option

One begins the second step in implementing the cost-effectiveness analysis by listing the factors that determine how well each traffic control option satisfies the objectives of community and traffic impact, safety, and constructability. Section 1C included a discussion of factors that may typically impact the feasibility or suitability of night work and other traffic control options. Section 2 described information needed to identify the constraints to which any option must be responsive and to define the factors on which each of the options should be evaluated. Not every individual factor has relevance to every project. It is essential for the agency conducting the assessment to select those factors that are considered relevant to the project being considered. For example, it would rarely be necessary to consider the impact of business and pedestrian concerns for a project on a rural freeway, although these concerns may be very relevant on an urban arterial project. Factors typically grouped under each of the three objectives are discussed below.

Community/traffic impacts

While community and traffic impacts are grouped under the same general objective, traffic impacts may normally be quantified while the impact on the community is normally subjective. Local conditions and attitudes will determine the perceived importance of noise from construction, glare from work lights, the impact and inconvenience of traffic detours, congestion, interference with access, environmental impacts, and overall community acceptance of the traffic control strategy.

Safety

The qualitative rating of safety should reflect the hazard potential of the option and its ability to minimize the level of risks of all operations. This rating must include safety with regard to the public, traffic control, and workers. Traffic control and safety must include the level of risk associated with the setup and takedown of the system, maintenance of the devices, and modifications to the system. Rating the risk level of workers should consider numerous factors, including the visibility level of workers, the availability and size of a buffer zone, and the effectiveness and clarity of the traffic control system. If accident cost estimates are available for either traffic or workers, these costs may either be added to the cost of the traffic control option or be used to rate the effectiveness of the option for safety. Whatever method is used, it should be used consistently for all options being evaluated. If accident costs cannot be estimated for all options, they should be estimated only to rate the effectiveness of the option with regard to safety.

Constructability

The effectiveness rating for constructability should reflect the contractor's access to the work site, the relative efficiency of the work operations, the relative quality of the completed work under the various options, and the ability of both the contractor and the owner agency to manage and oversee the work. The construction costs that were assessed quantitatively in the previous step should not be considered in rating constructability.

Table 5-2 illustrates a sample worksheet that can be used to decide which factors should be considered in the evaluation. Factors not relevant to the proposed project should be deleted. Additional factors should be added as necessary for local conditions. Additional factors taken from the illustrations contained in Section 6 include construction quality, seasonal consider-

Table 5-2 Sample Effectiveness Rating Worksheet

Objective	Factor	Cost		
		Option 1	Option 2	Option 3
Community/Traffic Impact	Business impact			
	Pedestrian/Bicycle impact			
	Emissions and other environmental concerns			
	Public transit			
	Emergency services			
	Noise effect on residences or hospital			
	Effects of lighting and glare			
	Reaction to off-site traffic in local neighborhood			
	Impact on off-site traffic			
	OVERALL RATING			
Safety	Traffic accidents			
	Construction accidents			
	Maintenance			
	OVERALL RATING			
Constructability	Experience of contractor with night work			
	Suitability of temperatures for operations			
	Supervision			
	Worker efficiency at night			
	Quality of lighting plan			
	Materials/equipment availability			
	OVERALL RATING			

ations, residential impact, air quality, and school impact. Anyone using these procedures must determine which factors are most relevant for consideration in the analysis.

Complete qualitative assessment of effectiveness

Space is also included on the sample form to note the numerical assessment score given to each relevant qualitative factor. In order to calculate a numerical effectiveness score for each objective, it is now necessary to rate each of the factors affecting each of the objectives on a numerical basis. The following scale is suggested to develop a numerical rating for each factor:

(4) The objective can be achieved without any noticeable adverse impact.
(3) Small, but normally accepted adverse construction impact, based on agency norms.
(2) Substantial negative impacts, borderline acceptable for this objective.
(1) Unacceptable impact, objective not achieved at an acceptable level.

Any of the factors that have been quantified in some way may also be easily converted to this rating scale.

Overall rating

Because more than one factor is usually considered under each objective, it will be necessary to combine the ratings of all factors to come up with an overall rating for each objective. At the completion of this step, effectiveness ratings for each of the primary traffic control objectives should be estimated for each of the options using the qualitative assessment of the various factors.

The combined score for each objective may be obtained by simply computing a numerical average of all factors included, or simply assigning the score of the poorest rating on any factor. For example, if an important factor is rated as "2," or "borderline acceptable," the entire traffic control option may be only borderline acceptable in terms of that objective. In most cases, any option that receives an "unacceptable" rating, or "1," on any relevant factor would not survive the initial screening in Task 2, and thus would not remain under consideration in Task 4. It is therefore essential to first determine a score for each factor, and then determine the overall rating for the objective by considering the specific ratings given to each factor that relate to that objective.

5C Determine Relative Weights of Traffic Control Objectives

The third step of the cost-effectiveness evaluation of the traffic control options is to determine the relative importance of each objective, and to assign a numerical weight to that importance. While it is essential to maintain a reasonable balance between objectives, some situations may indicate the need to place higher importance on satisfying one or more specific objectives. For example, if a project is the first of a series of projects planned to complete an overall corridor improvement, and there is strong community concern about the impact of the projects, it becomes imperative to minimize adverse traffic and other impacts on the community to avoid increased opposition to future projects. In this case, the community impact factor may be rated higher than the other two. Two alternative methods of scaling are provided below.

Ordinal scaling

The simplest weighting system uses weights from 1 to 3 as follows:

(1) This is the baseline weight and is normally assigned to each objective.

(2) Assigned to objectives with factors that are especially relevant to the project for identifiable reasons or concerns.

(3) Assigned to objectives with factors that are absolutely critical to the project.

Magnitude estimation

An alternative weighting system that may be used is a variation of a technique known as magnitude estimation. If all objectives are equally important, they should be given the same weight (e.g., 1). If one or more objectives are more important than another, give the least important objective a weight of 1. Next consider the objectives that are more important and compare these with the least important objective. If the second objective is twice as important, it gets a weight of 2; three times as important, it gets a weight of 3. If it is just slightly more important, it might be given a weight of 1.5.

All things being equal, a weight of 1 should be assigned to each of the three objectives. If one objective is seen as very critical, and another objective not critical, the very critical objective is given a weight of 3, the least critical objective a weight of 1 and the remaining objective a weight of 2. At the completion of this step, all of the information is available to proceed to the cost-effectiveness analysis and select the preferred traffic control option.

5D Compute Cost-effectiveness Scores

In this step, the cost-effectiveness scores are computed for each option, and the preferred option (or multiple preferred options, if more than one has similar scores) is evaluated in terms of meeting each of the constraints previously set. The previous steps of this procedure defined the nature and extent of the work to be completed, along with the traffic demands and community constraints to be addressed. Options that clearly did not meet one or more of the constraints identified in Task 1 were discarded in Task 2 or 3. Traffic control options were listed and evaluated against traffic demands and community constraints, and options that survived were examined for traffic congestion. Factors associated with each option were then listed and examined in terms of either project costs or the effectiveness of the traffic control option in meeting the objectives. The effectiveness rating was determined for each of the primary objectives: safety, community impact, and constructability. Weighting factors were then assigned for each. In this final step, the option to be moved forward to detailed design is selected after a final comparison of two or more options with the highest cost-effectiveness scores to determine which ones most consistently meet the traffic control objectives with the least cost.

Once the quantitative and qualitative assessments are completed and weights are assigned for each of the objectives, results are compared to select the preferred option or options. Input to the cost-effectiveness analysis consists of the following information for each option:

- Quantitative construction and user costs

- Qualitative effectiveness rating by objective

- Relative weight for each traffic control objective

The cost-effectiveness score actually consists of the ratio of effectiveness to cost for each option. The higher the effectiveness of an option compared with its cost, the better that option in terms of satisfying the traffic control objectives. The following substeps define the process:

- An overall effectiveness score for each option is computed by multiplying the weight for each objective by its qualitative rating, and then summing the three objectives to obtain a single effectiveness rating for each option.

- The effectiveness rating for each option is divided by its quantitative cost to obtain the effectiveness-cost ratio. The option having the highest ratio is considered the preferred option.

To simplify the procedure, and to facilitate comparison of the various options, a tabular worksheet such as the one shown in Table 5-3 is suggested for this step. This table lists the objectives with their assigned weights and the effectiveness rating from Table 5-2 for each option. The total effectiveness rating is summed for each option and divided by its total costs obtained from Table 5-1 (and entered at the top of each column) to obtain the effectiveness-to-cost ratio.

5E Select Preferred Option By Cost-Effectiveness Analysis

In this example, Option 2, with its significantly lower ratio of effectiveness to cost, is clearly unacceptable. The option with the highest effectiveness/cost ratio (Option 3 in this example) is the preferred option. However, Options 1 and 3 have nearly identical effectiveness/cost ratios, and further analysis will be necessary to choose between them. When two or more

Table 5-3 - Cost-Effectiveness Analysis Worksheet

		Option 1		Option 2		Option 3	
		$4.4 M		$6.0 M		$5.5 M	
OBJECTIVE	**Weight**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Community/Traffic Impact	2	3	6	2	4	4	8
Safety	1	2	2	3	3	3	3
Constructability	1	3	3	2	2	3	3
Effectiveness Rating			11		9		14
Effectiveness / Cost			2.5		1.5		2.55

options have similar overall scores, it becomes important to examine not only the overall effectiveness/cost ratio, but the individual ratings for the traffic control objectives. In this example, each of the objectives is met by Option 3 with no adverse impact or only a small adverse impact. Option 1, however, is rated as "borderline acceptable" in terms of safety. Therefore, Option 3 may be the preferred choice.

In addition to examining the three basic objectives, it is also important to examine other constraints. In this example, Option 1 enjoys a considerable cost advantage over Option 3. If most of that differential comes from a savings in construction cost, and the agency is faced with a tight budget for the project, this may indicate a preference for Option 1, even though it is "borderline acceptable" in terms of meeting the objective of safety.

Before making a final decision and moving ahead with a detailed design for a "preferred" traffic control option, it is essential to review that option one more time to ensure that it meets each of the project constraints listed in Task 1. While options that failed to meet the basic constraints should have been deleted in Task 2 or 3, this final check may reduce the risk that the preferred option will be rejected at a later stage in the design process. In addition to ensuring that the preferred option falls within the project budget constraints, several other factors should be reviewed:

- Noise and light impact on local communities for any night work options

- Neighborhood traffic impacts for detours, diversions, or night work

- Adverse business impact from traffic congestion

- Known community resistance to specific alternatives

The preferred option is then forwarded for a detailed design, following the guidelines in Volume II. As detailed traffic control design progresses, it is essential to revisit the basic assumptions used during the cost-effectiveness analysis to ensure that all of the key constraints are actually satisfied. If specific design details change those assumptions, it may be worthwhile to recalculate the cost-effectiveness score for the option originally selected. If it no longer compares favorably with other options rejected, it would then become desirable to identify an alternate traffic control option and forward it for detailed design. In effect, this becomes a reiterative process that may require more than one iteration to develop a TCP that meets all of the constraints initially identified and that closely matches the assumptions used in the cost-effectiveness analysis. The better the information compiled in the preliminary steps of the procedure, the more likely it is that the preferred option selected in the first iteration will actually remain the preferred option at the completion of the detailed design.

6. Illustrative Examples

Four sample problems are presented in this section to illustrate the assessment procedure. A number of assumptions relating to the impacts of the various evaluation factors are made in these problems. For actual project assessments, it will be essential for the designer to compile as much information as possible concerning the proposed project and the impact of the various traffic control options on safety, community impact, and constructability.

For simplicity, only three options are described for each of the sample problems. For actual projects, a greater number of traffic control options are typically considered. However, in many cases, some of those options will drop out in the initial assessment stage because one or more of the project constraints or traffic control objectives cannot be satisfied at an acceptable level.

6A Problem #1

This sample project involves a six-lane urban, high-speed freeway that is to be resurfaced using a three-course asphalt-concrete overlay. The project length is approximately 6 miles, with no interchanges within the length of the project.

Traffic volume information

- Peak volumes - 1800 - 2600 vehicles per hour (vph) - peak and nonpeak directions - these volumes reverse morning and evening.

- Daytime off-peak volumes - 1000 - 1400 vph - varies between 9 AM and 3 PM depending on hour and direction.

- Night volume - 400 - 800 vph - varies with hour and direction, lowest from 9 PM until 6 AM.

- Lane capacity - per Highway Capacity Manual - one lane open - 1170 vph (1020-car capacity for 85 percent of cases); two lanes open - 1490 vph per lane (1450-car capacity for 85 percent of cases).

Other factors

- Past experience with similar projects on other sections of this facility have shown substantial increases in rear-end accidents during construction, as well as occasional intrusions into the work space resulting in injuries to travelers and workers.

- This facility traverses a heavily populated suburban residential area for most of its length. Residents of the area are organized to oppose any perceived impacts on the tranquility and environmental quality of the area. Previous proposals for highway expansion projects have met stiff political opposition.

Traffic control options

Based on an analysis of traffic demands on the project and characteristics of the highway, three options have been developed for further analysis:

- Option #1 - This option involves closing one lane at a time for paving on each roadway. Traffic will be maintained in the remaining two lanes. Lane and shoulder widths are sufficient that traffic can be shifted a few feet to provide a lateral buffer between the travel space and work space. Paving the center lane in each direction will require a traffic split, using the two outer lanes to carry traffic. Paving can be scheduled for a full 10-hour day while still meeting traffic demands. The estimated construction cost is $10M, and user costs are estimated at $0.6M, associated with traffic delays during center lane paving because of the traffic split. The total cost is $10.6M.

- Option #2 - Two lanes will be closed for paving, with traffic maintained in one lane. To minimize traffic congestion, paving will be restricted to 7 hours per day during off-peak hours, although the allowable work times are not the same in each direction. Even with the work hour restrictions, considerable delays are expected during part of the work day. Estimated construction cost is increased to $10.5M, reflecting the inefficiencies of working in a single lane and the shortened work day. User costs are estimated at $1.2M because of the increased delays associated with the double-lane closure. Total cost is $11.7M.

- Option #3 - Paving will be performed at night, with two lanes closed between 9 PM and 6 AM. Traffic will be maintained in the one open lane. Based on wage premiums, lighting costs, increased traffic control, and other costs of working at night, the estimated construction cost is $11.5M, but no user costs are expected because traffic delays will be minimal. The total cost is thus $11.5M.

Weights for traffic control objectives

Based on expected community concern over this project, the weight for the congestion/community impact objective is increased to “2.” The weights for the other factors remain at the normal value of “1.”

Evaluate options

Quantitative costs for construction and user delay costs were estimated during development of each of the options and were stated above. Because sufficient accident histories were not available, qualitative ratings, rather than cost estimates, were assigned for the safety factors.

Based on the characteristics of this project and consideration of project constraints and evaluation factors, the following rating worksheet was developed, with qualitative ratings assigned for each factor of each option. Where more than one factor was included under an objective, a simple numerical average was computed to obtain an overall effectiveness rating for that objective.

Table 6-1 - Rating Worksheet for Assessment Factors

Objective	Factor	Rating		
		Option 1	Option 2	Option 3
Community/Traffic Impact	Noise and glare	4	4	2
	OVERALL RATING	4	4	2
Safety	Traffic accidents	2	3	3
	Construction accidents	3	4	2
	OVERALL RATING	2.5	3.5	2.5
Constructability	Construction quality	3	4	3
	Lighting	4	4	3
	Supervision	4	4	3
	Materials/equipment availability	2	4	2
	Seasonal completion	4	3	4
	OVERALL RATING	3.4	3.8	3

Following completion of the quantitative and qualitative assessments, the resulting costs and overall effectiveness ratings are entered on the following cost-effectiveness analysis worksheet, along with the relative weights for each objective. The weighted ratings for each option are calculated and the effectiveness rating obtained by summing these weighted scores. The ratio of effectiveness to cost is then obtained by dividing the effectiveness rating by the cost of each option.

Table 6-2 - Cost-Effectiveness Analysis Worksheet

		Option 1		Option 2		Option 3	
		$10.6 M		$11.7 M		$11.5 M	
OBJECTIVE	**Weight**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Community/Traffic Impact	2	4	8	4	8	2	4
Safety	1	2.5	2.5	3.5	3.5	2.5	2.5
Constructability	1	3.4	3.4	3.8	3.8	3	3
Effectiveness Rating			13.9		15.3		9.5
Effectiveness / Cost			1.31		1.31		0.83

Select preferred option

In this sample problem, the night work option rates well below the daytime options, primarily because of concern over opposition from the community about the impact of construction noise and lighting glare at night. In this analysis, this concern outweighed the traffic congestion costs that would occur during daytime work. For this example, the two daytime options scored about the same. To select the preferred option, it would be necessary to further consider the factors associated with each. In this case, Option #2 has higher construction and user delay costs, but because of the freer traffic flow and probability of higher speeds, safety concerns are greater for Option #1. Unless construction budget restrictions are a major concern, Option #2 may become the preferred choice because of a lower safety risk during paving.

6B Problem #2

This sample project involves a pavement overlay for a four-lane rural freeway. The project length is 10 miles, and a three-course asphalt concrete overlay will be placed on the travel lanes and shoulders. There are no interchanges within the length of the project, but interchanges are located within a few miles of each end of the project.

Traffic volume information

- Peak volumes - 1800 - 2400 vph - during morning and evening peaks. Peaks reverse morning and evening.
- Daytime off-peak volumes - 1200 - 1500 vph between 9 AM and 3 PM.
- Night volumes - 400 - 800 vph from 8 PM until 6 AM.
- Truck traffic - approximately 15 percent of total traffic at all times. Truck traffic consists of heavy long-haul trucks.
- Lane capacity - per Highway Capacity Manual - 1340 vph for a single lane open (1270-car capacity for 85 percent of cases).

Other factors

- Contractors and trade unions have both expressed concern regarding the safety of working at night on high-speed freeways.
- Two local communities located on the state highway under consideration as a detour have expressed concern about increased traffic, especially truck traffic.
- The route under consideration as a detour has marginal alignment, including several steep grades and sharp curves. The detour will add an additional 12 miles to travel distance, all of it on a two-lane state highway.

Three options have survived the initial screening and will be subjected to further analysis:

- Option #1 - One lane of each roadway will be closed for an 8-hour work day, while paving proceeds in the closed lane. The estimated construction cost is $7M. Because extensive delays are expected during much of the day, user delay costs are estimated at $1.5M, for a total cost of $8.5M.
- Option #2 - All truck traffic will be detoured onto a state route that goes through two communities. Car traffic will be maintained in one lane, while paving is done in the closed lane. It is expected that some car traffic will also choose to use the detour to avoid the construction. Travel distance on the detour is increased by 12 miles, but congestion will be minimal because volumes are low. However, travel speeds will be low on several steep grades because of the truck traffic. Construction cost is lowered to $6.8M because work hour restrictions will not be nec-

essary, and the contractor will have better site access. User costs include $1M for the increased truck travel distance. In addition, $1M in improvements will be necessary on the detour route. Total cost of this alternative is $8.8M.

• Option #3 - All work will be done at night. One lane will be closed, with paving in the closed lane. A 10-hour shift will be allowed, with no traffic congestion expected. Construction costs increase to $7.5M because of wage differentials and other added costs at night. An additional $0.5M is estimated for lighting and traffic control, for a total cost of $8M.

Weights for traffic control objectives

A weight of "2" is assigned to safety on the basis of concerns expressed over night work and the concern for truck traffic on the detour. A weight of "2" is also assigned to congestion/community impact on the basis of opposition to the truck detour through two communities. The constructability weight remains at "1."

Evaluate options

Based on the project considerations, the following worksheet was developed to evaluate each of the effectiveness factors using the same general procedure as in Problem #1.

Table 6-3 - Rating Worksheet for Assessment Factors

Objective	Factor	Rating		
		Option 1	**Option 2**	**Option 3**
Community Congestion	Congestion/business impact	4	2	4
	Residential impact	4	2	4
	Air quality	2	3	4
	OVERALL RATING	3.3	2.3	4
Safety	Traffic accidents	3	2	3
	Construction accidents	3	3	2
	OVERALL RATING	3	2.5	2.5
Constructability	Construction quality	3	3	3
	Lighting	4	4	3
	Supervision	4	4	3
	Materials/equipment	3	3	3
	OVERALL RATING	3.5	3.5	3

Compute cost-effectiveness scores

The following worksheet was developed to compute the cost-effectiveness ratios using the same procedure as in Problem #1.

Table 6-4 - Cost-Effectiveness Analysis Worksheet

		Option 1 $8.5 M		Option 2 $8.8 M		Option 3 $8.0 M	
OBJECTIVE	**Weight**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Community/Traffic Impact	2	3.3	6.6	2.3	4.6	4	8
Safety	2	3	6	2.5	5	2.5	5
Constructability	1	3.5	3.5	3.5	3.5	3	3
Effectiveness Rating			16.1		13.1		16
Effectiveness / Cost			1.89		1.49		2

Select preferred option

In this case, Option 3, working at night, offers a higher cost-effectiveness score than either of the daytime options. It also provides the lowest construction and user costs. The only evaluation factor not satisfied at a high level is the concern for worker safety at night, and that concern is based primarily on lack of familiarity with night work rather than actual adverse work histories. The detour option (Option 2) has major concerns associated with the proposed detour, both in terms of traffic safety and community impact. Option 1 is expected to result in objectionable traffic congestion, as expressed in the high user costs, and is also expected to adversely affect air quality because of the traffic congestion. Given all of these considerations, the night work option is the preferred choice for this project.

6C Problem #3

This sample project entails the replacement of bridge decks on a pair of twin bridges on a four-lane divided suburban expressway. The width of each bridge is 32 ft curb-to-curb. Median width is 30 ft, and alignments are parallel for each roadway.

Traffic volume information

- Traffic volumes and other congestion considerations are such that it is mandated to maintain two lanes open in each direction from 6 AM to 10 PM.

Other factors

- Construction considerations dictate that the bridge decks may be reconstructed in two segments, placing approximately half of the deck in each of two stages.

- Ten-foot-wide travel lanes are considered to be acceptable through the project. However, it is considered essential to maintain positive barrier separation between opposing traffic flows at all times.

- Alternate routes are not available to divert traffic from this facility because of other projects that will reduce the capacity of other facilities at the same time that this project will be underway.

Traffic control alternatives

Based on site characteristics, traffic demands, safety considerations, and construction requirements, the following options have been proposed for initial screening:

Option # 1 - A median crossover will be constructed, and the eastbound roadway will be reconfigured into two 10-ft lanes eastbound and one westbound, separated by a temporary concrete barrier. The westbound roadway will carry one 10-ft travel lane separated from the work space by a temporary concrete barrier. Although the westbound traffic will be split, two lanes will be maintained in each direction. Variations on this pattern will be used in several stages to replace all of the bridge decks.

Option # 2 - The same pattern as in Option #1 will be used. In addition, it is proposed to close the remaining westbound lane from 10 PM until 6 AM, permitting the contractor improved access to the work space, as well as providing a third work shift to speed project completion.

Option # 3 - A temporary structure will be constructed in the median between the existing structures to carry two lanes of traffic. Each existing bridge will be closed, one at a time, for reconstruction, while traffic for the closed roadway is carried on the temporary structure.

Screening of options

A detailed screening of the proposed options reveals that Option 2, night work, does not completely satisfy the basic conditions necessary for night work to be advantageous. Adequate work space can be provided during the daytime while still maintaining adequate traffic capacity. Closing the extra lane at night provides improved access to the work space, but this added access provides little advantage in terms of completing the project within the desired time frame. Considering effort necessary to reconfigure the TCP at the start and end of each night shift, and the short 8-hour shift available, little or no advantage would be provided by working at night.

Both Options 1 and 3 appear to provide adequate traffic capacity with little or no congestion problems. Both also provide adequate access for a contractor to complete the work in a satisfactory, timely manner. Additional analysis will be required to select between these options. However, because there is no added advantage for night work, Option 2 should be dropped at the conclusion of the initial screening.

6D Problem #4

This project consists of reconstructing an arterial street running through the central business district of a small urban area. The existing roadway consists of two lanes in each direction plus a two-way left turn lane in the center. This project will replace existing curbs, build new sidewalks, install new storm drainage, and resurface the traffic lanes with an asphalt-concrete overlay.

Traffic information

- Traffic volumes - approximately 1400 - 1800 vph in each direction throughout the day, and continuing at this level until 9 PM.

- Night traffic volume - range from 600 vph after 9 PM, quickly dropping to less than 300 vph in each direction later in the evening.

- Truck traffic - truck traffic is about 10 percent of total traffic throughout the day. At night, trucks are limited to occasional deliveries to businesses throughout the project.

Other factors

- Congestion during construction will have a significant negative impact on the local business community.

- Several emergency service providers are located within the project limits. Traffic congestion will have a negative impact on their ability to respond.

- Two public schools are located within the project. Maintaining safe pedestrian access for school children will be a major concern.

- A good street grid parallels the arterial street, providing an acceptable detour/diversion opportunity in each direction. However, these streets pass through residential neighborhoods, and residents are expected to be opposed to heavy traffic volumes on these detours.

- Because of numerous intersections, heavy traffic volumes on these routes would also cause safety concerns.

Traffic control alternatives

- Option #1 - Four lanes of traffic will be maintained at all times, although they will be narrowed somewhat. A single-lane work space will be available to complete the work in stages. Construction cost for this option is estimated at $8M, with an additional $2M in user delay costs for a total of $10M.

- Option #2 - The curb lanes will be closed one at a time to permit curb and sidewalk replacement and drainage work, with traffic maintained in the other four lanes. After the curb lanes are rebuilt, local traffic will be permitted on the curb lanes. The three interior lanes will be closed together for repaving, with through traffic detoured through the residential streets. Construction cost is reduced to $7.8M by the improved work site access during paving, and user delay costs are reduced to $1M by the partial detour. However, added traffic control costs of $0.4M bring the total cost of this option to $9.2M.

- Option #3 - The roadway will be closed to all traffic except local deliveries after 9 PM, with traffic detoured through the residential streets. Essential local traffic, emergency responders, etc. will be maintained on one lane that will operate in one direction only under flagger control. Improved site access offsets wage premiums, lighting costs, etc., resulting in an estimated construction cost of $8M. While there are no user delay costs, added traffic control costs associated with the detour and the one lane for local access within the project add $0.7M, bringing the total for this option to $8.7M.

Weights for traffic control options

Because of the potential impact on both the business community and residential neighborhoods, the congestion/community impact objective will be assigned a weight of "2." The weights for safety and constructability will remain at "1."

Following the same procedures as in the previous examples, the following worksheet was developed, providing qualitative ratings for the various evaluation factors identified for the project.

Table 6-5 - Rating Worksheet for Assessment Factors

Objective	Factor	Rating		
		Option 1	Option 2	Option 3
Community/Traffic Impact	Noise and glare	4	4	3
	Business impact	1	2	3
	School impact	2	2	3
	Emergency services	2	2	3
	Off-site traffic impact	4	2	3
	OVERALL RATING	2.6	2.4	3
Safety	Traffic accidents	2	3	4
	Construction accidents	3	3	3
	Pedestrian accidents	3	3	3
	OVERALL RATING	2.7	3	3.3
Constructability	Construction quality	2	3	3
	Lighting	4	4	3
	Supervision	3	3	2
	Materials/equipment	3	3	3
	OVERALL RATING	3	3.25	2.75

The following worksheet is developed to compute the cost-effectiveness scores, using the same procedure as in Problems #1 and #2.

Table 6-6 - Cost-Effectiveness Analysis Worksheet

		Option 1		Option 2		Option 3	
		$10.0 M		$9.2 M		$8.7 M	
OBJECTIVE	**Weight**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Community/Traffic Impact	2	2.6	5.2	2.4	4.8	3	6
Safety	1	2.7	2.7	3	3	3.3	3.3
Constructability	1	3	3	3.25	3.25	2.75	2.75
Effectiveness Rating			10.9		11.05		12.05
Effectiveness / Cost			1.09		1.2		1.39

Select preferred alternative

For this project, Option #3, night work, is clearly the most cost-effective option. While total construction cost including traffic control is slightly higher than the construction costs of the other options ($8.7M vs. $8.0M and $8.2M), because of the added user costs in Options # 1 and 2, Option # 3 has the lowest total costs and the highest effectiveness rating. This option satisfies essentially all of the evaluation factors at a high level. Although it requires detouring traffic through residential streets, traffic volumes are very low at night, and there is almost no truck traffic. Furthermore, much of the night traffic are local residents who will use a variety of diversions, rather than stay on the marked detour. Local opposition to the detour is thus not expected.

Both of the day work options barely satisfy several of the congestion/community impact factors. While Option #1 offers the lowest construction cost ($8M), including traffic control, it has the highest total cost ($10M) when user costs are added. It is also marginal in terms of construction quality because of the limited work site access.

The night work option will require some special attention to providing adequate management oversight and supervision during the night shift. Otherwise, it easily satisfies all of the evaluation factors and is clearly the preferred alternative for this project.

Appendix A

Development of Alternative Traffic Control Strategies

Because there is seldom an obvious "do-it-all" solution to any real-life maintenance or construction problem, the development of alternative traffic control strategies requires experience, wisdom and creativity. Numerous strategies are available to accommodate traffic demands on a highway while construction or maintenance is underway, but combining the proper combination of methods or techniques into an optimum overall strategy depends on the skills of the designer responsible for developing these plans. The National Highway Institute (NHI) Course "Developing Traffic Control Strategies"**(6)**, along with other references **(4,5),** provides an oversight of strategies that may be considered.

Traffic control strategies may be categorized into two broad groups:

- Traffic control plans (TCPs) - These techniques focus on work zone traffic control, specific detour routes, and construction procedures. Traffic demand on the facility under construction is accommodated either within the roadway or (by establishing detours to carry traffic) around the work area. Traditional TCPs consist of sharing the roadway between traffic and construction, or rerouting traffic onto other facilities using conventional traffic control devices and setups. Non-traditional TCPs typically may add contractual requirements to accelerate the work, introduce techniques to reduce the work space and time needed to complete the work, or shift the work to periods with less traffic (i.e., nights or weekends).

- Traffic management plans (TMPs) - These techniques are broader than TCPs, and address project-related impacts throughout the project corridor or beyond. A TMP typically includes both transportation system management (TSM) to optimize the traffic carrying capability of all highways in the corridor, as well as transportation demand management (TDM) to reduce traffic demand through the project and corridor.

Techniques that are included under each of these categories include the following:

TRAFFIC CONTROL PLANS

TRADITIONAL TCPs	NONTRADITIONAL TCPs
Construction phasing	Nighttime construction
Lane shifts or closures	Incentive/disincentive
Temporary roadways	Lane rental
Temporary pavement	A + B bidding
Median crossovers	Special materials
Temporary bridges	Innovative techniques
Off-site detours	Prefab components
Work hour restrictions	Rapid curing materials

TRAFFIC MANAGEMENT PLANS

TRANSPORTATION SYSTEM MANAGEMENT	TRANSPORTATION DEMAND MANAGEMENT
Signal improvements	Improved transit
Intersection improvements	Park and ride lots
Parking restrictions	Ride-sharing programs
Ramp metering	Bike/pedestrian facilities
Ramp closures	High occupancy vehicle lanes
Turn prohibitions	Parking supply/pricing
Incident management	Tolls/congestion pricing
Bus turnouts	Alternative work hours
Police traffic control	Telecommuting

The traffic control strategy for a construction or maintenance project typically consists of a combination of several of the individual techniques listed above. When it is considered, nighttime construction will always be combined with a number of other techniques to provide an overall strategy that adequately addresses all of the traffic control objectives. The essential conditions for night work to offer an advantage is that traffic volumes are lower during the night work hours, and that the roadway can be reconfigured to accommodate the full traffic volume during daytime hours.

Sections 6G and 6H of the Manual on Uniform Traffic Control Devices (MUTCD) provide an expanded discussion of traditional TCP techniques that are commonly used to carry traffic through work sites or to detour traffic. The previously mentioned NHI course provides additional discussion of TCP strategies.

Appendix B
Estimating the Capacity of Alternative TCPs for Highway Maintenance and Construction

(This Appendix was written by Joseph Hummer North Carolina State University)

The decision as to whether or not to consider night operations as a traffic control strategy is based largely on the anticipated effects of the alternative daytime strategies on traffic delays and the consequent inconvenience and cost to the public. Although any work zone activity may reduce capacity and increase delay (often as the result of "rubber necking"), the greatest effect is observed when traffic control results in the closure of one or more lanes. Any project for which the lane closure strategies for daytime work do not adequately accommodate the traffic demand is a candidate for night work alternatives. As such, an early step in the project planning as discussed in Section 4 of this procedure is an analysis of the capacity of the various TCP options being considered.

The most popular method for calculating the amount of delay caused by queuing is called the demand and discharge method. The method is given in Chapter 6 of the 1997 edition of the Highway Capacity Manual **(**HCM) **(7)** and is based on tables or graphs of demand and discharge. The popular software QUEWZ-92 also uses this method (Krammes et al., 1992) **(9)**.

The demand and discharge method of computing queue delay described above is popular, is easy to understand and explain, is easy to use, and probably is accurate enough for most applications. However, the demand and discharge method has serious theoretical weaknesses—assuming that vehicles do not join a queue until they reach the taper—and several researchers have questioned its accuracy, so researchers have developed other methods to estimate the amount of delay due to queuing.

A recent variation of the demand and discharge method appears in Chapter 22 of the 2000 HCM **(10)**. This variation allows analysts to compute delays and queue lengths in complex freeway systems, particularly where queues build up and block interchange ramps. The simple demand and discharge method from the 1997 HCM and QUEWZ-92 does not handle cases where queues block interchange ramps. There are several issues with the method in Chapter 22 of the 2000 HCM, however. The method in Chapter 22 of the 2000 HCM is computationally intense, requiring software for any realistic application, and has not yet been tested extensively in work zone applications. In addition, the method in Chapter 22 of the 2000 HCM assumes a uniform traffic density in all lanes leading up to the taper of the work zone, which is not how most queues operate heading into work zones that are not near interchange ramps.

Users examining work zones where queues may block interchanges or intersections should also consider microscopic simulation to estimate the delays. CORSIM **(11)** is the most popular microscopic simulation program on the market for such applications. FRESIM is the part of CORSIM that models freeways, and NETSIM is the part or CORSIM that models arterial streets. CORSIM is popular because it can be applied to a wide variety of conditions, has a long history of successful applications, has reasonable coding and running times, and is supported by FHWA. Some have criticized CORSIM because very detailed data are needed to calibrate it for work zone environments. Most users should therefore only consider CORSIM or other simulation packages to estimate delay in areas with complex roadway geometrics where very detailed data are available.

Considering the above options, analysts should probably use the simple demand and discharge method for estimating queue delay due to most freeway and arterial work zones. The method is simple to explain, the computations are not intense, the method has a long history of successful use, and (as shown below) analysts can adjust for cases where the traffic density approaching the taper is low. For work zones on freeways where the queues may block interchange ramps, or otherwise affect complex freeway geometry, the CORSIM simulation program or the method from Chapter 22 of the 2000 HCM would be good analysis choices.

Step One—Check Capacity

Section 3 mentioned that delay due to a work zone only becomes significant in typical cases when the traffic demand exceeds the remaining highway capacity for some length of time. Since traffic demands by 15-min periods are typically available, and this is a customary length of time to analyze in many types of highway capacity analysis, users should check the demand against the available capacity every 15 min. Table 3-1 provided average values of highway capacity for some work zone scenarios and values exceeded in 85 percent of work zones for users interested in conservative calculations. Before comparing demand with capacity, users should examine their demand estimates to make sure that they have accounted for traffic choosing to divert away from the work zone.

If the traffic demand is equal to or less than the available capacity in a time period, and there was no queue in the previous time period, the user may assume that delay costs are near zero in that work zone during that time period. Appendix C describes how to calculate the relatively small costs due to vehicle acceleration, deceleration, and reduced speed through the work zone for these cases. If the traffic demand is greater than the available capacity in a time period, the user should calculate delay costs due to a queue during that time period (and subsequent time periods until the queue clears) using Step Two below.

Step Two—Compute Delay

If Step One showed that delay due to queuing will be important, Step Two is necessary to estimate the amount of that delay. The simple demand and discharge method begins with construction of a table like Table B-1. The units in the table should be vehicles and hours. Each row of the table is a time period when queuing might be present. In the second column, the user writes the demand during that time period. In the third column, the user writes the "queue discharge" expected during that time period. The "queue discharge" is similar to the capacity; it is the volume of traffic actually getting through the key point in the work zone once a queue has formed. Research in the past 10 years has been consistent in that once a queue has formed, the queue discharge rate is 100 to 200 vehicles per hour per lane lower than the capacity.

The fourth column of Table B-1 is the demand minus the discharge. This is the amount by which the queue grows or shrinks during the time period. The fifth column is the size of the queue at the end of the time period, which is the size of the queue at the end of the previous time period (the previous entry in the fifth column) plus the entry in column four. The sixth column is the average queue size during the time period. This is computed as the queue size at the end of the previous period plus the queue size at the end of this period divided by two. Finally, the total queue delay during the time period is the average queue size from column six multiplied by 0.25 (the duration of the time period in hours).

The user keeps calculating the total queue delay for each time period until the queue dissipates. The average queue delay per vehicle, the most useful statistic for cost calculations, is the sum of the total queue delay values from each time period divided by the sum of the demand values from each time period.

Step Three—Compute Queue Length

Following the calculation of delay in Step Two, analysts should estimate queue lengths to see whether queues will extend back from the work zone to block upstream interchanges or intersections and for guidance on decisions like sign placement. If a spillback condition is expected, this could have serious negative consequences that are very difficult to estimate precisely, and, as noted above, analysts should turn to the more detailed procedures in simulation models like CORSIM or in the 2000 HCM.

The 1997 edition of the HCM contained the simplest and most popular method of estimating queue length from the beginning of the work zone taper, L, in meters. The equation was

$$L = Q * \text{length} / N$$

Where Q is the number of vehicles in the queue, 'length' is the average vehicle length in meters, and N is the number of lanes open upstream of the site. A good estimate for average vehicle length in a work zone queue is 20 meters, assuming space between vehicles and for trucks.

The problem with the 1997 HCM method is that it does not consider that many drivers, seeing signs and queues prior to a work zone, will abandon the lane to be closed well before the taper. Typical queues thus occupy longer distances than the 1997 HCM equation predicts. Based on fieldwork in North Carolina, Dixon and Hummer **(12)** suggest that a better estimate of queue length for the case of a work zone closing one of the two lanes on a highway is

$$L = Q * \text{length, if } L < S$$

Or,

$$L = 0.5\, S + (Q * \text{length} / 2)\text{, if } L > S$$

Where S is the distance from the beginning of the work zone taper to the point where the flashing arrow panel or changeable message sign is legible to drivers.

THE CONCEPT OF CAPACITY

In general, the capacity of a facility is defined as the maximum hourly rate at which vehicles can reasonably traverse a uniform section of a lane or roadway during a given time period under the prevailing roadway, traffic, and control conditions. As defined in the HCM, the factors used to describe each of these three prevailing conditions are as follows (note: from this point onward, "HCM" refers to both the 1997 HCM and the 2000 HCM):

(1) Roadway conditions refer to the geometric characteristics, including type of facility and its development environment, the number of lanes (by direction), land and shoulder widths, lateral clearances, design speed, and horizontal and vertical alignments.

(2) Traffic conditions refer to the characteristics of the traffic stream, as defined by distribution of vehicle types, the amount and distribution of vehicle types in the available lanes, and directional distribution of traffic.

(3) Control conditions refer to the types and specific design of control devices and traffic regulations present. The location, type and timing of signals are critical control conditions affecting capacity. Other important controls include STOP and YIELD signs, lane use restric-

Table B-1. Example of Demand and Discharge Method

1 Time period	2 Demand, vehicles	3 Queue discharge, vehicles	4 Queue change, vehicles	5 Ending size of queue, vehicles	6 Average size of queue, vehicles	7 Total queue delay, vph
1115 to 1130	320	280	40	40	20	5
1130 to 1145	320	280	40	80	60	15
1145 to 1200	340	280	60	140	110	28
1200 to 1215	360	280	80	220	180	45
1215 to 1230	360	280	80	300	260	65
1230 to 1245	340	280	60	360	330	83
1245 to 1300	300	280	20	380	370	93
1300 to 1315	250	280	-30	350	365	91
1315 to 1330	220	280	-60	290	320	80
1330 to 1345	200	280	-80	210	250	63
1345 to 1400	200	280	-80	130	170	43
1400 to 1415	220	280	-60	70	100	25
1415 to 1430	220	280	-60	10	40	10
1430 to 1435	80	90	-10	0	5	0
Totals	3730					646
Average delay per vehicle = 646/3730 = 0.17 hours						

tions, turn restrictions, and similar measures.

The capacity analysis procedures and tools in the HCM allow consideration of all of these factors in determining the capacity of a roadway or street section. It is also important to note that capacity refers to a rate of flow during a specified period of interest, which is most often a 15-min period, the shortest interval during which stable flow exists.

THE CONCEPT OF LEVELS OF SERVICE

Levels of service are defined in the HCM as a qualitative measure that describes operational conditions within a traffic stream in terms such as speed and travel time, freedom to maneuver, traffic interruptions, comfort, convenience, and safety. Six levels of service are defined for each type of facility for which analytic procedures are available. The “levels” are given letter designations from A (best) to F (worst). The HCM provides definitions for each level.

The procedures in the HCM attempt to establish or predict the maximum rate of flow at which traffic can be accommodated by various facilities at each level of service, except for level-of-service F, for which flows are unstable. Thus, each facility has five service flow rates. Service flow rate is defined as the maximum hourly rate at which vehicles (or pedestrians) can reasonably be expected to traverse a uniform section of a lane or roadway during a given time period under the prevailing conditions, while maintaining a designated level of service.

For each type of facility, levels of service are defined based on one or more operational parameters that best describe operating quality for the subject facility type: the measures of effectiveness. Table 1-2 in the HCM identifies the measures of effectiveness for each type of facility.

OPERATIONAL MEASURES USED IN THE HCM

The operational state of a traffic stream is defined by three primary measures: speed, volume and/or rate of flow, and density.

Speed Measure - For the purposes of the HCM, the speed measure used is average travel speed, sometimes referred to as space mean speed. For capacity analysis, the HCM recommends that the speed measure be based upon travel times over a known length of highway. Further, for ease of observation on uninterrupted flow facilities operating in a range of stable flow, the length of highway measured may be as short as several hundred feet. However, for interrupted flow situations, the HCM states that segments measured should be long enough to include those points of fixed interruptions of interest. The HCM also shows how the speeds measured at a point (e.g., by radar), yielding a time mean speed, can be converted to a space mean speed. The formula for converting the travel time data to average travel speed is given in the HCM, as is the method for converting time mean speed to space mean speed (i.e., average travel speed).

Volume and Rate of Flow Measure - Volume and rate of flow are two measures that quantify the amount of traffic passing a point on a lane or roadway during a designated time interval. Volume is the total number of vehicles that pass over a given point or section of roadway during a given time interval. Volume may be expressed in terms of annual, daily, hourly, or subhourly periods. Rate of flow is the equivalent hourly rate at which vehicles pass over a given point or section of a lane or roadway during a given time interval of less than 1 hour, usually 15 min. Consideration of peak-flow rates is of critical importance in capacity analysis in that it provides information as to when breakdowns in capacity are likely to occur. Peak rates of flow are related to hourly volumes through the use of the peak-hour factor, which is the ratio of total hourly volume to the maximum 15-min rate of flow within the hour. The HCM provides formulas for calculating peak-hour factor, and it is noted that the procedures of the HCM most often focus on the analysis of either a peak 15-min period or another 15-min period of interest. The HCM also provides the formula for the conversion of peak-hour volume to a peak rate of flow. Many of the procedures use this conversion to focus on the peak-flow period within the peak hour.

Density Measure - Density is defined as the number of vehicles occupying a given length of a lane or roadway, averaged over time, usually expressed as vehicles per mile (vpm). While direct measurement of density is difficult because of the high vantage point required to observe significant lengths of highway, density can be computed from the average travel speed and rate of flow with the formula given in the HCM. Note that the formula applies only for uninterrupted flow. Density is a critical parameter describing traffic operations in that it describes the proximity of vehicles to one another, and therefore reflects the freedom to maneuver within the traffic stream. The HCM provides a discussion and graphics showing the relationship among speed, density, and rate of flow for uninterrupted flow facilities. Also provided is a discussion of interrupted flow, including a discussion of the concept of green time at signalized intersections, and a discussion of saturation flow rate at signalized intersections.

APPLICATIONS OF THE HCM

As pointed out in the HCM, many of the procedures provide simple tabular or graphic presentations for a set of specified standard conditions, often ideal conditions. Warnings are given that the conditions represented in the tables and graphs must frequently be adjusted to account for whatever prevailing conditions exist. That is, an adjustment must be made for the prevailing roadway, traffic, and control conditions that were described above. The HCM provides a description of the influences that some of these factors can have on capacity, service flow rate, and level of service. Most of the procedural chapters address three different computational applications: operational analysis, design, and planning.

Operational Analysis Application - Operational analysis is the most detailed and flexible application of capacity analysis techniques. In this application, known, or projected, traffic flow rates and characteristics are compared with known, or projected, highway descriptions to estimate the level of service that is expected to prevail. While operational analysis allows for an evaluation of level of service on an existing facility, this is not its most powerful use. The analysis can be used to evaluate the level of service that would result from alternative spot or section improvements to an existing facility. The operational impact of various improvement measures can be estimated and compared and a rational decision made using the results. Alternative designs for new facilities (i.e., temporary traffic control strategies) can be similarly evaluated and compared. Most of the procedures in the HCM allow not only determination of level of service, but an estimation of the value of critical performance parameters as well.

Design Application - The application to design has the objective of determining the number of lanes required on a particular facility to provide for a specified level of service. The design application of capacity analysis procedures treats this aspect of the overall “design process” and can also be used to assess the impact of such design variables as lane and shoulder width, lateral clearance, grades, lane use allocations, and other features. Design computations are generally limited in scope and often result in the generation of alternatives that are subsequently subjected to detailed operational analysis. As such, it is possible to evaluate a number of different night work zone configurations using the design computations and to select only those that appear most adequate for a full-scale operational analysis to compare against alternative day operations.

Planning Application - Planning computations have the same objective as design computations. The planning application, however, provides for rough estimates at the earliest stages of planning when the amount, detail, and accuracy of information are limited.

The selection of level of analysis depends on the intended use of the results and on the availability of data on which to base the computations. Generally speaking, the use of capacity analysis to determine whether to consider night operations will entail operational analysis and its increased accuracy.

SUMMARY

By way of an introduction to those not highly familiar with capacity analysis, the material presented in this appendix covered the concepts underlying capacity analysis, along with identification of many of the computational formulas that are included in Chapter 1 of the HCM. Chapter 2 of the HCM covers traffic characteristics. Because traffic engineers are the target audience of this document, it was assumed that a synopsis of the traffic characteristics material in the HCM would be unnecessary since most would be highly familiar with the material covered. These two chapters constitute Part I of the HCM, and Parts II through IV provide the material on the capacity analysis procedures.

Part II of the HCM is devoted to freeways and includes material on the analysis of basic freeway segments, weaving areas, ramps and ramp junctions, and freeway systems. Part III is devoted to rural highways and includes analysis procedures associated with multilane highways and two-lane highways. Part IV is devoted to urban streets and includes procedures associated with signalized intersections, unsignalized intersections, urban and suburban arterials, transit capacity, pedestrians, and bicycles.

NOTES ON HCM

Some recent research has indicated that the HCM may not provide the best computational procedures for all situations involving work zones. For example, it has been found that "....the 1994 HCM does not produce today's observed capacity at different work zones" **(13)**. Reliance on the conservative HCM approach can lead the decisionmaker to select more costly alternatives. Therefore, for critical projects, it may be wise for a user to check other sources in the recent literature for guidance as to computational procedures and methods that better fit the situation under evaluation. There are a number of computer simulation and analysis models that have been developed to aid in some of the tasks that are associated with capacity-related analysis. With regard to simulation, Elefteriadou et al. **(14)** provide an overview of simulation models in a context consistent with facilities and situations addressed by the HCM, covering both interrupted and uninterrupted flow.

On the analytic side, Minderhoud et al. **(15)** provide a review and assessment of empirical capacity estimations and identify advantages and disadvantages of each. These are just some of the more recent examples of work that is going on in the area of capacity analysis. Such work will continue to be done to supplement the methods and procedures in the HCM.

Appendix C

Estimating User Costs Associated with Work Zone Traffic Control

User costs are normally divided into traffic delay costs, vehicle operating costs, and accident costs. This appendix considers the first two components, while accident costs are treated in Appendix D. Several methods are available for calculating each of these two components of user costs. It is essential that whatever methods are chosen, the same methods must be used to estimate the costs associated with each traffic control option being considered.

Vehicle Delay Costs

The traffic delay costs associated with work zones result from a reduction in speed through the work zone, a delay from congestion, or an increased travel distance when traffic is rerouted. Several models exist for estimating traffic delay costs, and these range from very simple to highly complex.

The most simple model for estimating vehicle delay costs is presented in the National Highway Institute (NHI) course, *Developing Traffic Control Strategies* **(6)**. The equations presented simply look at delay as the difference between the time to travel the work zone route and the time to travel the normal route. This difference accounts for all three components of vehicle delay. The delay time is converted to cost using a table from the 1975 edition of Highway Statistics. This table gives the cost per vehicle in minutes of delay up to 60 min. The cost associated with 60 min is $6.06. More recent studies have suggested delay costs of $8.00 regardless of vehicle type **(16)** and as high as $11.12 (automobile) to $30.26 (five-axle truck) depending on vehicle type **(17)**.

While the relative merits of different traffic control plan (TCP) options with respect to delay can be evaluated using these data, it is imperative that current data be used when the cost of delay is added to construction costs, as must be done to implement the cost-effectiveness model discussed in Section 5.

Vehicle Operating Costs

As with vehicle delay costs, there are several methods for calculating vehicle operating costs, but most are quite old and even if updated might not reflect the impact of current automotive technology **(3, 13)**. Updated operating costs for trucks may be obtained from the American Trucking Association **(18)**.

The NHI course **(1)** presents a reasonably simple solution. First, for roadways with sufficient capacity, the following formula is given.

$$TOC = ADC * V * D$$

where:

TOC = Total operating cost
ADC = Average operating cost per unit distance
V = Total number of vehicles, and
D = Distance traveled

The ADC is taken from a graph that provides operating cost in dollars per 1000 vehicle-miles. The TOC for each option being considered is the difference between the TOC for normal conditions and the TOC given the TCP for the project. If the TCP results in reduced speed without congestion, the total operating costs may be reduced during the construction period.

If the TCP results in congestion, a second component of cost must be calculated. This requires the calculation of queue length (see Appendix B) multiplied by volume to find vehicle miles. The difference in operating costs between congested and normal conditions is multiplied by vehicle miles to obtain the operating costs for the congested period. The average operating costs provided in the NHI course are 20 years old and should be adjusted for inflation.

Comprehensive Models

The NHI course, *Developing Traffic Control Strategies*, also recommends the application of the QUEWZ computer model, which is well documented and can be used to document both delay time and vehicle operating costs associated with lane closures **(19)**. This model can be used to compute the following:

1 Vehicle capacity
2 Average speed through work zone by hour
3 Hourly user costs
4 Daily user costs
5 Average length or queue each hour

The Highway Economic Requirements System (HERS) is designed to estimate the benefits from highway improvements and considers the costs of travel time (delay), operating costs, and accidents **(17)**.

The Indiana DOT recently developed a model that combines costs associated with vehicle delay and vehicle operating costs **(20)**. The model, which calculates total hourly excess user cost, includes the following components:

1 Deceleration delay cost
2 Reduced speed delay cost
3 Acceleration delay cost
4 Vehicle queue delay cost
5 Excess cost of speed change cycles
6 Excess running cost of vehicles at reduced speed

The model utilizes cost data presented in AASHTO's *A Manual on User Benefit Analysis of Highway and Bus-Transit Improvements*, including values for unit time for vehicles, excess costs of speed change cycles, and running costs of cars and trucks at different speeds **(21)**. The procedure to adjust these values, whose base year is 1967, does not account for the technological changes that have impacted the operating costs of vehicles.

The model was tested at two freeway work zones with results that showed that each of these components contributed to total cost differently for long and short work zones. Since night work typically involves short work zones, an analysis of how these components interact with work zone length is enlightening. Deceleration delay cost was more significant in short work zones and reduced speed delay cost was more significant in long work zones. Vehicle queue delay cost contributes much more to total costs in the short work zone than in the long work zone.

Given the absence of accurate and current cost data, the needs of the user of this procedure are probably best met by implementing the relatively simple procedures outlined in the NHI course, *Developing Traffic Control Strategies*.

Appendix D

Evaluating the Costs of Accidents Related to Work Zone Activity

As discussed in Section 5, the cost of traffic accidents is not an out-of-pocket cost to an agency and therefore may be viewed as a measure of effectiveness and not as a cost of construction. Ellis et al., based upon data obtained in California, concluded that work zones, even without lane closures, have more accidents, and that night work (usually with lane closures) has a marked increase in accident rates **(22)**. However, given that traffic volumes are normally lower at night, accident costs may still be reduced in spite of the higher accident rate.

If accidents are to be considered a cost of construction, the first step is to predict the accident rate, the second step is to determine the costs for each accident, and the third step is to project the expected traffic volume. The cost of traffic accidents may then be calculated as the product of rate, volume, and cost per accident. Of the three components needed to estimate total accident cost, the accident rate associated with each traffic control strategy is the most difficult to predict. Unfortunately, information regarding work zone accidents by type of work zone or the area of a work zone is not available. An FHWA-sponsored research project is currently in progress to address this problem. It is also to address the lack of exposure data needed to change accident frequencies into accident rates. This same FHWA-sponsored project will attempt to obtain exposure information by type of work and traffic operation.

Research has shown that the accident rate in a construction work zone is directly related to the accident rate before construction and the average daily traffic (ADT) on the route **(1)**. Using this information, the NHI course, *Developing Traffic Control Strategies*, presents tables that may be used to predict accident rates in construction work zones for different types of roadways and different lane closure scenarios. These data should be available for most roadways. If accident rate data are not available, the NHI course provides a table to help estimate these rates, but estimates should only be used when actual accident data cannot be obtained.

Once the accident rate for each traffic control option is established, the accident costs for each option must be calculated using these accident rates, projected volume, and accident cost data. Some states have developed their own accident cost data, and if these are current, they should be used. Otherwise, average accident cost data are provided by the NHI course **(1)** and Miller et al. **(23)**. More recent data may be available from NHTSA or the National Safety Council.

Finally, it is imperative that when computing the anticipated cost of traffic accidents for alternative strategies, the same methods and accident cost data are used for each option being evaluated.

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Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation

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