MODULE 2. DECISION PROCESS

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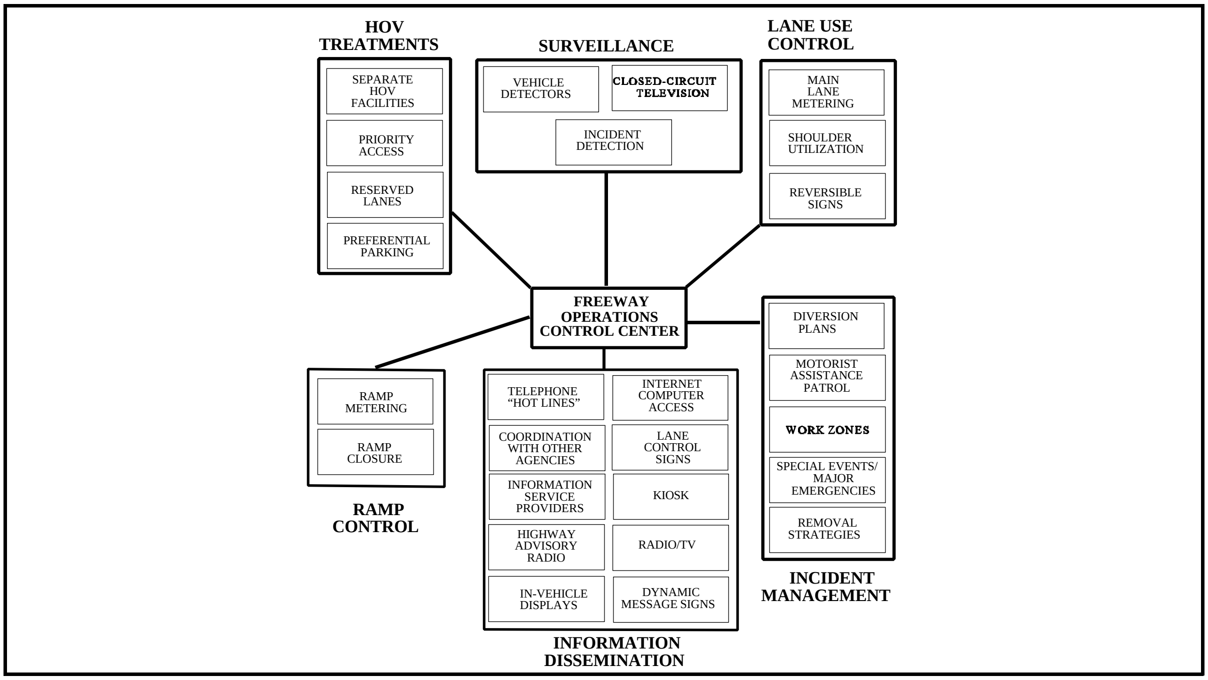


Figure 2-1. Elements of a Freeway Management System.

2.1 INTRODUCTION

Management of the freeway system has become increasingly popular as a tool for combating congestion problems in urban areas. A freeway management system is a collection of strategies, personnel, and technologies combined together to accomplish the following:

To promote the efficient and effective movement of people and goods, to improve the safety of the traveling public, and to improve the environment by reducing both the duration and extent of recurring and nonrecurring congestion on the freeway system.

A freeway management system includes one or more subsystems to accomplish the following tasks:

- Monitoring operations of the freeways and detecting sources of recurring and non-recurring congestion.
- Controlling use of existing lanes and shoulders to maximize the use of the existing pavement within the freeway right-of-way.
- Managing the amount of traffic that enters and exits the freeways via the ramps.
- Providing priority treatment of high-occupancy vehicles within the freeway.
- Disseminating both pre-trip and en route information to travelers so that they can make informed mode, route, and departure time decisions.
- Restoring the freeway to full capacity as quickly as possible after an incident.

Regardless of the size of the freeway system or the level of sophistication and extent of the existing freeway management system, a systems engineering approach to planning and designing a freeway management system should be followed. A systems engineering approach is an iterative process whereby operational problems are identified, system concepts and objectives are established, potential solutions are developed and evaluated, new solutions are identified, and system objectives are redefined. The approach is applied throughout the entire life cycle of the system (planning, design, operations, and maintenance), with the level of detail being progressively refined. The same systems engineering process can be used in each of the following applications:

- Planning and implementing a new system where no current freeway management system exists.
- Modifying an existing system to add new freeway management functions.
- Upgrading the technology in an existing freeway management system to current standards.

MODULE OBJECTIVES

The objectives of this module are as follows:

- Describe the systems engineering approach to planning and designing a freeway management system.
- Present techniques for quantifying operational problems and measuring performance of a freeway management system.
- Highlight some of the special issues that need to be considered in planning, designing, operating, and maintaining a freeway management system.

MODULE SCOPE

This module describes a systems engineering process for planning and designing a freeway management system. It highlights some of the major issues and decisions that planners and designers must address when developing a freeway management system. It also illustrates how decisions made during the planning and design phase affect the operations and maintenance of the system and how operational and maintenance issues can be addressed during the planning and design phases.

2.2 DESIGN PROCESS

A systems engineering approach examines how various tasks, components, and operational strategies can be combined to form a working and coherent unit to address specific goals, objectives, and user needs.(1) With the systems engineering approach, the components of the system are viewed as an entity rather than as an assembly of individual parts.

Figure 2-2 illustrates the steps involved in a typical systems engineering analysis. These same steps can be used to complete a systems engineering analysis, whatever the size of the system being designed and evaluated. The same process can be used to design an entire freeway management system, individual components of the system, or individual elements within each component: what varies is how much detail is used in the analysis and the data required to complete the analysis.

Also note that the process is iterative. After defining the problem, those internal and external organizations and agencies that must be brought on board if the system is to be effective can be identified. In cooperation with these organizations and agencies,

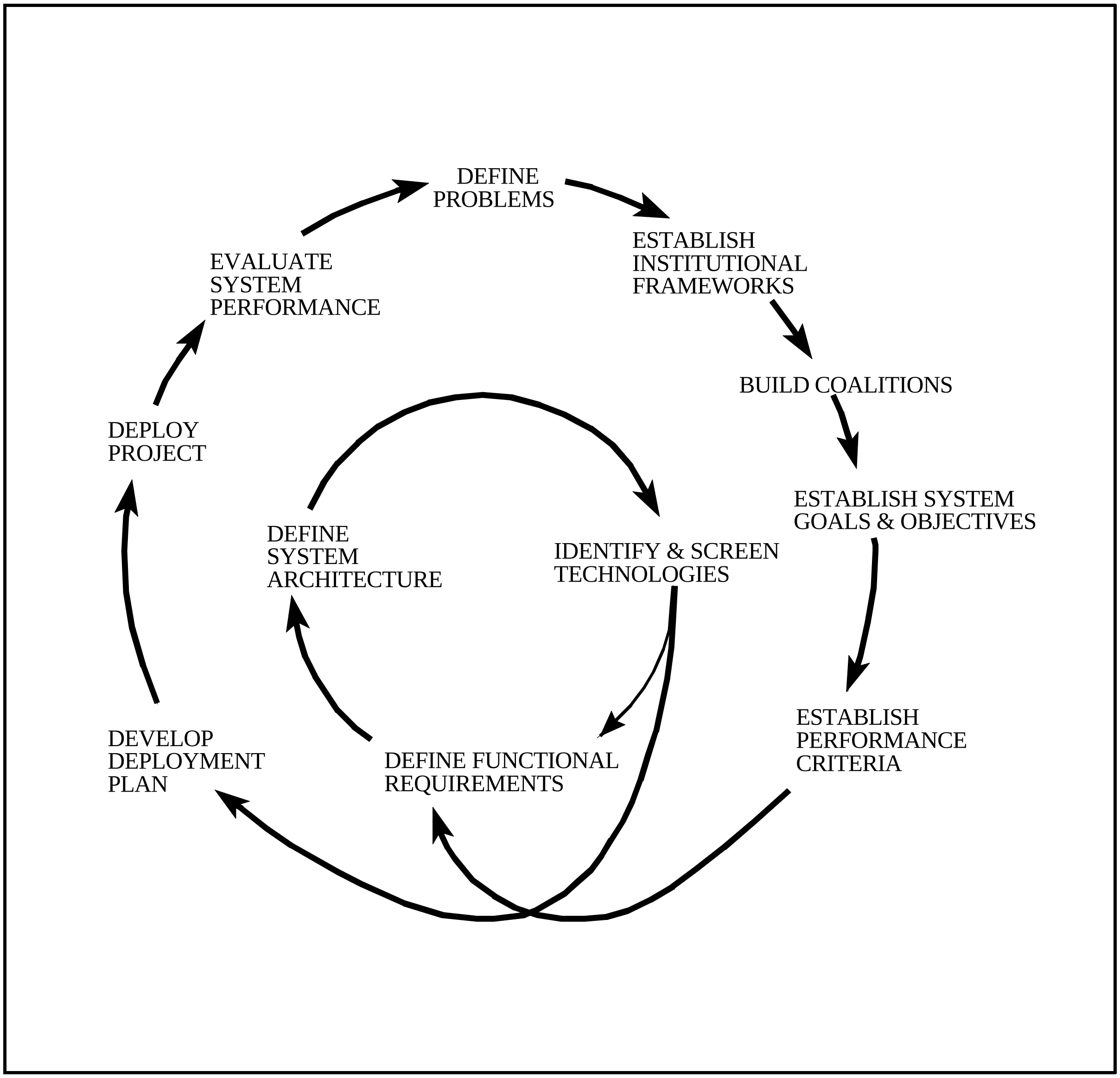


Figure 2-2. Steps Performed in a Typical Systems Engineering Analysis.

system goals and objectives can be identified and performance criteria established. Functional requirements can then be defined to meet the specified goals and objectives. Once the functional requirements have been identified, the system architecture can be defined, and technologies can be identified and screened. The process of defining functional requirements, defining system architecture, and identifying and screening technologies is reiterated at increased levels of detail until system plans and specifications can be prepared. Once the final design of the system is complete, the process of deploying the system can be planned. Using this plan, individual projects can be identified that will lead to the full deployment of the system. Once individual projects have been installed, the performance of the system can then be evaluated. This evaluation may lead to new operational problems being identified, whereby the systems analysis process can be used to identify new improvements to the system. Each step in a typical systems engineering analysis is discussed in the sections below.

A similar process was used to develop the National Intelligent Transportation System (ITS) Architecture. That process is shown in figure 2-3.(2) It is beyond the scope of this handbook to provide a detailed treatment of the National ITS Architecture development. The Architecture was being developed during the same time this handbook was prepared and, as of this date, has not been finalized. The reader is referred to numerous National ITS Architecture documents developed under a Department of Transportation contract with Loral Federal Systems and Rockwell International. In particular, the National ITS Architecture Implementation Strategy is of benefit because it summarizes many of the previous efforts and provides broad guidance in implementing not only freeway systems, but also other related systems.(2)

The National ITS Architecture approach began in 1993 with a concept of "user services" rather than specific hardware items or techniques to support the development of the architecture. The National Architecture work enhanced the user services concept by defining "market packages" that provide groupings of technologies and techniques to satisfy those user services. Reference is made to table 2.2-2 (page 2-29) in the Implementation Strategy document for a relationship of market packages to various services. Succeeding discussions in this module will refer the reader to the appropriate sections of the Implementation Strategy where appropriate.(2)

DEFINE PROBLEMS

The first step in the systems engineering approach is to adequately and properly define and quantify the problems to be addressed by the freeway management system. Properly defining the problems to be addressed by a freeway management system directly leads to the identification of the subsystems that can address those problems.

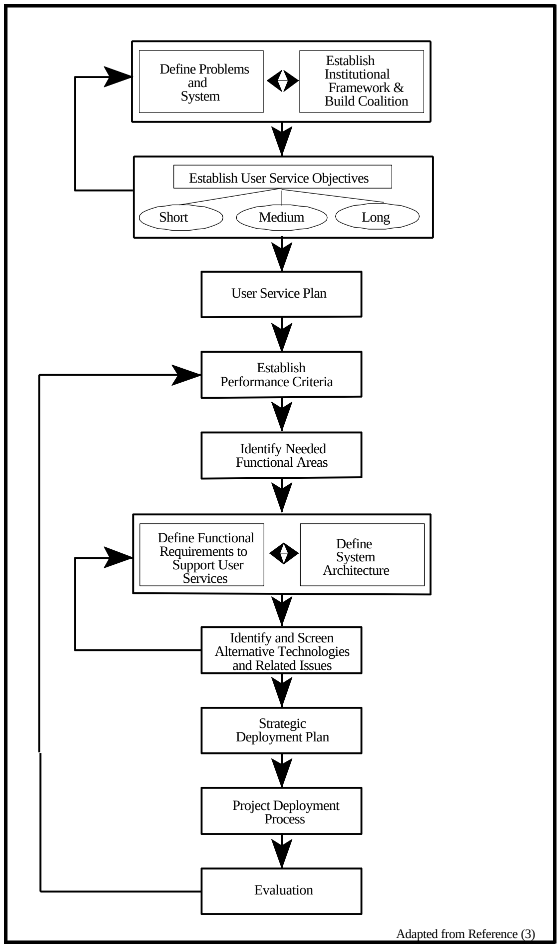


Figure 2-3. Systems Engineering Process Used to Develop National ITS Architecture. (2)

Several methods are available for quantifying the magnitude of the operational problems that can be potentially addressed by a freeway management system. Traditional analytical techniques that can be used to quantify operational problems in a freeway network include the following:

- Capacity and level of service analysis.
- Bottleneck analysis.

- Queuing analysis.
- Travel time and delay studies.
- Computer simulation modeling.
- Crash history analyses.
- Origin/destination studies.

The major tools available for conducting operational analyses of the freeways are discussed in Section 2.3 below.

The importance of coordinating with other transportation-related agencies to identify problems to be addressed should not be overlooked. For example, long-range transit plans can provide an indication of when high-occupancy vehicle facilities may be needed in the freeway system. Input from commercial industries can also be valuable in identifying specific areas of concerns or needs. Finally, and perhaps most importantly, input from local elected officials can also provide insight into the public's perception of problems with the roadway system.

Most of the techniques above help identify existing operational problems; however, in planning a freeway management system, it is important to consider the location and type of operational problems that might occur in the future. Potential sources of information that could be used to identify future operational problems include the following:

- Regional transportation and land use planning studies.
- Site impact analyses.
- Air quality assessments.

In addition to quantifying existing and future operational problems, another critical element in defining the problems that exist is to obtain an accurate and complete inventory of the entire existing transportation system. This inventory should include both physical and organizational components. Examples of physical components that should be identified in the inventory include the following:

- Roadway network.
- Existing surveillance and control systems.
- Existing information dissemination systems.

In addition to the existing physical elements in a system, how the system is envisioned to operate can also influence the design of the system. Examples of the operational components that might influence the design of a traffic management system and, thus, must be identified in an inventory include the following:

- Operating agencies.
- Funding sources.
- Political and agency jurisdictions.

ESTABLISH INSTITUTIONAL FRAMEWORKS AND BUILD COALITIONS

The most critical step in implementing a successful freeway management system is to build critical coalitions and institutional frameworks. Institutional frameworks and coalitions need to be established at the beginning of the planning and design process. These coalitions and institutional frameworks need to be established at three levels: between agencies (inter-agency), within agencies (intra-agency), and with other stakeholders (including the private sector) affected by traffic operations.

Traffic congestion is not restricted by jurisdictional boundaries. When one part of the transportation system (e.g., the freeway network) is not functioning properly, it affects the operations of other parts of the system (e.g., the surface streets, the high-occupancy vehicles lanes, etc.). Therefore, there is a strong need to develop good working relationships and build coalitions among agencies responsible for managing traffic in an area. Examples of the types of agencies with which strong coalitions would help in implementing a freeway management system include the following:

- Metropolitan planning organizations (MPOs).
- Federal, State, and local traffic and transportation engineering agencies.
- Federal, State, and local transit agencies.
- State and local law enforcement agencies.
- Emergency services (fire, ambulance).
- Turnpike / toll road authorities.
- Port authorities.
- State and local emergency management authorities.

In addition, private sector needs should be considered in developing a freeway management system, and should be included in the consensus building process. Examples of these private sectors entities that agencies may want to include in the consensus building process include the following:

- Private transportation information providers and services.
- Private transportation companies.
- Commercial delivery services.
- Interstate and intrastate commercial trucking companies.

Cooperation and coalitions within an agency are also essential in establishing an effective freeway management system. Often, this type of cooperation is the hardest to obtain. Some sections within an agency may view a traffic management system as usurping some of their responsibilities and power. It is essential that all elements within an agency (e.g., planning, administrative, construction, design, operations, and maintenance) are committed to constructing, operating, and maintaining the system.

Finally, there may be others in the community that may be important allies when implementing freeway management systems. Perhaps the most important of these is the general public. Without the support of the general public, it will be extremely difficult to implement a traffic management system. Extensive public relations and media campaigns may be required to show the public how a traffic management system will directly benefit them. Strong public support makes it easier to secure funding and political support. Without public support, it will be extremely difficult to generate elected officials' and agency interest and support for freeway management.

Other stakeholders that may be useful in implementing traffic management systems include the following:

- Major traffic generators.

- Utility companies.
- Elected officials.
- Media.
- Private transportation providers.

Establishing institutional frameworks and coalitions can be difficult at times. The first step in building effective coalitions is to identify "champions" in those agencies responsible for transportation in a community (e.g., State highway agencies, MPOs, transit authorities, etc.). These individuals are likely to be top administrative officials in these organizations. Since traffic management systems often compete with other "traditional" agency activities and expenditures (e.g., pot-hole patching, construction, etc.), the support of top management is essential if agency resources are to be allocated to the operation and maintenance of the system. If congestion is widely recognized as a major issue in a community, upper management support may already exist within many organizations and propagate through the agencies in a "top-down" fashion; however, if it is not, support must be generated from the bottom up.

In addition to identifying "champions" for the system, it is also important to identify those individuals who will be critical to the success of the systems (e.g., the public, elected officials, major employers, etc.). The support of one or more local elected officials can be highly effective in securing funding for the system. Often this support is automatic if traffic conditions have already deteriorated or if the potential for major traffic problems looms on the near horizon.

Another effective way of building strong coalitions between and within agencies is to take advantage of institutional frameworks that already exist. Many locales have institutional frameworks to address freeway management concerns. For example, many locations use Traffic Management Teams and Incident Management Teams to address problems on freeways. Often these teams are a coalition between State and local transportation agencies, and law enforcement personnel. These coalitions can be expanded to encompass additional functions of a traffic management system.

Finally, in building effective coalitions, it is important to identify, within organizations, key individuals who have the appropriate level of knowledge and experience. These individuals must have the level of authority that is appropriate to the type and level of responsibilities that will be performed by the agency. In addition, it is also important to identify individuals who are likely to be present throughout the entire planning and design process for a traffic management system. A common thread among past successful transportation management systems is that key personnel committed to the system have remained with the agencies throughout the planning, implementation, and ongoing operation of the system.

ESTABLISH SYSTEM GOALS AND OBJECTIVES

Once coalitions have been formed, agencies should work together to define the goals and objectives of the system. The system goals and objectives should describe what it is the system is supposed to accomplish. The goals and objectives should be directly related to the specific problems to be addressed by the system. Typical system goals include the following:

- Optimize the utilization of capacity on the freeway.
- Maintain an acceptable level of service of the freeway.

- Provide a balance between demand and capacity in a freeway corridor.

- Provide for the rapid detection, response to, and clearance of freeway incidents.

- Reduce the number of vehicle crashes on the system.

- Improve vehicle operating costs, fuel consumption, and air quality by reducing the amount of travel delay on the freeway system.

Generally, system goals are used to define the long-range vision of the system. System goals also tend to be broad in scope. System objectives, on the other hand, define the level of performance that is expected to be obtained in the future. As such, system objectives are measurable. Often, more than one system objective is required to fulfill a system goal. Likewise, more than one system goal may be required to address an identified problem in a system.

Figure 2-4 provides an example of a system goal and objectives developed to address the problems of incidents in a system. Note that while the defined problems and system goals are broad in nature, the objectives of the system are specific and measurable. Also note that more than one objective is required to fulfill the goal of the system.

It is also important to note that system objectives are defined in terms of what services and functions a system is to provide — not in terms of technology. Notice in the example that no mention is made of the type of technology that will be employed to achieve a 2-minute detection time. Focusing on what the system is to achieve, instead of on how it is to achieve it, gives the designers flexibility in the way that they can combine components to build a system to achieve a desired outcome.

The National ITS Architecture Implementation Strategy provides a good overview of the connection between problems, solutions, and the National Architecture.[2] The approach identifies traditional problems (e.g., traffic congestion) and a solution in terms of both a conventional approach (e.g., roadway construction) and an advanced systems approach (e.g., computer traffic control), and links them to ITS marketing packages. The reader is referred to that document for problems and solutions in the context of the National ITS Architecture.

ESTABLISH PERFORMANCE CRITERIA

After establishing the system goals, the next step in the systems engineering approach is to establish the criteria for judging the performance of the system or subsystem. The performance criteria are used to determine whether the objectives of the system are being achieved. The criteria include both qualitative and quantitative measures of performance for the system. They also form the basis for evaluating the design and operations of the system. The criteria used to measure the performance of the system should correspond directly to the objectives of the system. Examples of the type of criteria that are commonly used to evaluate the effectiveness of freeway management systems include the following:[3]

- Changes in congestion levels and travel patterns.

- Changes in system operation costs, both to the user and to the system operator.

- Changes in other measures that effect the overall community (e.g., reduction in crash frequencies, vehicle emissions, and increased transit usage).

Identified Problem

- Incidents are the primary source of congestion on freeway

System Goal

- Reduce the impacts of incidents

System Objectives

- Detect all major incidents within 2 minutes of occurrence
- Reduce the time to clear an incident from the freeway by 5 minutes

Figure 2-4. Example of System Goal and Objectives to Address an Identified Problem.

- Improved accessibility as evidenced by decreased delays, increased economic activity, and reduced travel time for commuters benefiting from HOV improvements.

- Changes in vehicular demands on congested facilities.

In selecting criteria for evaluating the system performance, the measures of effectiveness must reflect the goals and desires of the community, and must be important and understandable to local elected officials, administrators, citizens, and other affected groups.[3] Table 2-1 lists some of the criteria that should be used in developing and selecting measures to evaluate the performance of a freeway management system. Common measures used to evaluate the effectiveness of freeway management systems include the following:

- Reduction in total travel time.

- Reduction in individual and overall delays.

- Reduction in crash frequencies and rates.

- Reduction in the duration of periods of congestion.

- Reduction in the number of congested freeway segments or length of congestion on a freeway section.

- Improvements in throughput in a corridor.

- Reduction in vehicular demands in a corridor.

- Improvements in network speed.

- Improvements in the consistency of travel times on individual trips.

- Reduction in the number of single-occupant vehicles in the freeway system.

- Improvements in the response and clearance times of freeway incidents.

- Improvements in air quality.

The National ITS Architecture Implementation Strategy considers benefits in the context of market packages, where the benefits are likely to occur, and where

Table 2-1. Criteria for Developing Measures of Effectiveness (MOEs). [4]

• **Relevancy to Objectives** Each MOE should have a clear and specific relationship to transportation objectives to assure the ability to explain changes in the condition of the transportation system • **Simple and Understandable** Within the constraints of required precision and accuracy, each MOE should prove simple in application and interpretation • **Quantitative** Specify MOEs in numerical terms whenever possible • **Measurable** Each MOE should be suitable for application in pre-implementation simulation and evaluation (i.e., have well-defined mathematical properties and be easily modeled) and in post-implementation monitoring (i.e., require simple direct field measurement attainable within reasonable time, cost, and staffing budgets)	• **Broadly Applicable** Use MOEs applicable to many different types of strategies whenever possible • **Responsive** Specify each MOE to reflect impacts on various groups, taking into account, as appropriate, geographic area and time period of application and influence • **Sensitive** Each MOE should discriminate between relatively small changes in the nature or implementation of a control strategy • **Not Redundant** Each MOE should avoid measuring an impact sufficiently measured by other MOEs • **Appropriately Detailed** MOEs should be formulated at the proper level of detail for the analysis

the benefits may accrue.[2] The reader is referred to that document for a more detailed treatment of the approach as related to freeway systems, in particular tables 4.2.3, 4.2.4, and 4.2.5 (pp 4-17 and 4-18.)

DEFINE FUNCTIONAL REQUIREMENTS

The next step in the systems engineering approach in designing a system is to define all of the features or activities (commonly called functions) of the system that are necessary to achieve the identified objectives. The system functions need to be described, at least initially, independent of the technology or architecture to be employed in the system. In other words, this step focuses on describing *what* it is the system will be designed to do, not *how* the system will be doing it.

The functional requirements needed to achieve a system objective can often be outlined in hierarchial order. For example, the functional requirements of an incident management program might be described as shown in table 2-2. Note that each of the functional requirements defines an action or activity that is to be performed by the system and that is independent of technology.

DEFINE FUNCTIONAL RELATIONSHIPS, DATA REQUIREMENTS, AND INFORMATION FLOWS

After defining *what* the system is supposed to accomplish, the next step in the systems approach is to define the functional relationships, data requirments, and information flows of the system. This provides a framework within which the system carries out the functions required to support the desired objectives. It describes the system elements and their relationship to one another.

The functional relationships, data requirements, and information flows of many freeway management systems in operation today have evolved as new functions were added to the system. However, there are real benefits to be achieved in planning how systems relate to one another in advance, even if the system will not be fully implemented immediately. Planning these relationships minimizes the number of redundant functions and efforts performed by the system. It also promotes the efficient use of equipment, staff, and resources. A well-planned system permits easy expansion and modernization of the system in the future. How the functions relate to one another also facilitates the sharing of information between jurisdictions, and leads to cost savings throughout the design, implementation, and operation of the system.

The design or architecture of a system consists of three elements: the functional requirements, the logical design, and the physical design. As discussed above, the functional requirements define what the system is supposed to do. The logical design identifies what information flows between the functions. The physical design identifies where functions occur and who is responsible for performing each function. The physical design permits like functions to be grouped into subsystems.

It is extremely important when defining the design of the system that it remain as open as possible. An "open" design is a system that has been designed with standard data interfaces so that equipment from multiple vendors can be used throughout the system. In addition, an open design helps to keep the system from becoming obsolete, because new functions and technologies can be easily added as they became available. Furthermore, an open design will make systems being developed today compatible with the National ITS Architecture as it emerges.

IDENTIFY AND SCREEN TECHNOLOGIES

Once the system functional relatioships, data requirements, and information flows have been defined, the next step in the systems engineering process is to identify alternative technologies whose performance and reliability meet the defined functional requirements. Methods for estimating the benefits derived by implementing a particular technology or system component include the following:

- Capacity and level of service analyses.
- Bottleneck and queuing analyses.
- Computer simulation.
- Field measurements.

In addition, evaluation studies from other systems, promotional documents from vendors, and demonstrations from

Table 2-2. Example of Functional Requirements of an Incident Management System.

- ♦ Detect incidents
  - Identify location of incident
  - Identify impacts of incident
  - Identify characteristics of incident
- ♦ Formulate response actions
  - Identify necessary emergency vehicle response
  - Select incident information for dissemination to travelers
  - Identify traffic control strategies
- ♦ Initiate and monitor response
  - Provide response procedures to agencies
    - Implement emergency vehicle response
    - Provide incident information to travelers
    - Implement traffic control strategies
  - Monitor response
    - Arrival emergency vehicles
    - Implementation of traffic control
    - Clearance of incidents
    - Clearance of congestion

manufacturers are excellent sources of information on the state-of-the-art of specific technologies. Site visits to existing systems that use specific types of technologies can also be an excellent tool for evaluating various technologies.

The interaction between alternative technologies and other elements within the system should be considered when evaluating different technologies. How the systems work together and what functions they perform can greatly influence how different technologies perform in a system. The impacts of different technologies on the physical configuration of the system and on the performance of other technologies and components in the system should also be considered. The expandability and flexibility of the technologies should also be considered.

Cost is another factor that should be considered when identifying and screening different technologies. The designers should consider the life-cycle costs (see Module 11) of each alternative technology. When examining the life-cycle costs of each technology, the engineer should consider the following costs:

- The costs associated with procuring, installing, and constructing each alternative technology.
- The costs associated with operating and maintaining each alternative technology within the overall system.
- The costs associated with replacing each technology at the end of its life.
- The costs associated with expanding the system, given that each alternative technology has been implemented.

Operation and maintenance are also important factors that must be considered when evaluating different technologies for use in a management system. Often, each technology requires unique operating and maintenance activities. The resource requirements, in terms of the number and qualifications of the personnel, the equipment and facility needs, and the operating and maintenance costs, should be factored into the evaluation. In evaluating system alternatives, the following operations and maintenance requirements should be considered:[(5)]

- An assessment of the existing operation and maintenance capabilities in terms of personnel, skills, and equipment.
- A determination of the necessary skills and work load impact of each system alternative.
- A comparison of the existing conditions with what is required for the successful operation and maintenance of the various alternatives.
- An analysis of the operational and maintenance deficiencies that exist with each system alternative.
- An assessment of the feasibility of providing additional operational and maintenance capabilities to address the identified deficiencies.

The process of identifying and screening different technologies for inclusion in a system is often iterative. There are multiple ways that different technologies can be combined to achieve an objective. Because how different technologies interact with one another can affect system performance, each combination must be evaluated in an iterative fashion.

DEVELOP IMPLEMENTATION PLAN

After the technologies that will be used in the system have been selected, the next step in the process is to develop a plan for implementing the system. The implementation plan documents the results of the previous steps and identifies how the system will be implemented in the field. At a minimum, an implementation plan should include the following elements:

- A description of the transportation system problems and opportunities to be addressed by the system.
- The institutional arrangements (i.e., who, what, when, where, why, and how) needed to make the system work.
- The goals and objectives of the system (i.e., what the system will be expected to do).
- The functional requirements and architecture of the entire system.
- The technology options to be used in the system.

The implementation plan should also assess the phasing, procurement, and funding options available for implementing the system.

The purpose of an implementation plan is "to ensure that the system is designed, built, operated, and maintained so that it accomplishes its purpose in the most efficient manner possible, considering performance, cost, and schedule." An implementation plan is required when either a new traffic control system or an expansion of an existing system uses Federal funds. Because it completely describes how the system is going to be designed, operated, and maintained, it is highly recommended that an implementation plan be developed as well for those systems that do not use Federal funds. Figure 2-5 lists the elements of a typical implementation plan.[(6)]

The National ITS Architecture Implementation Strategy provides guidance for major traffic management design options in the context of its market packages.(2) The reader is referred to Section 4.5 of that document in particular tables 4.5.2 and 4.5.3 (pp. 4-59 to 4-63) for the National ITS Architecture approach to implementation.

DEPLOY PROJECTS

There are a number of approaches that are commonly used by agencies to deploy individual projects or systems. The more common types of procurement approaches include the following:(6)

- Sole-source.
- Engineer/contractor.
- Two-step approach.
- System management.
- Design-build.

With a sole-source project, a contract is awarded to a named supplier without any competition for the project. This type of procurement approach typically involves a standard off-the-shelf product that can be made only by one manufacturer. Such an approach should be used only if it can be justified to be more cost-effective than a competitive low-bid process.

With an engineer/contractor approach, a single contract is awarded to the lowest responsive bidder to a specific request by the highway agency. The contractor is then responsible for providing a complete and fully operational system. In designing and deploying the system, the contractor may elect to subcontract much of the work that is outside the area of expertise of the contractor. The highway agency should be careful to specify the appropriate level of qualifications for the prime contractor to avoid getting a contractor who is unable to complete the job.

A two-step procurement process helps to eliminate some of the problems associated with the standard engineer/contractor approach. With a two-step procurement approach, a formal technical prequalification process is added to the engineer/contractor approach. This helps ensure that the contract team has the appropriate skills and expertise for implementing the desired type of system.

A systems management approach is commonly used by many highway agencies to implement freeway management systems. With this approach, a system manager is hired to perform the system design, software development, and system integration activities. Separate contracts are then prepared and awarded for implementing the various subsystems as dictated by the design.

A design-build type of procurement approach is another common way that highway agencies deploy freeway management projects. In a design-build approach, a single entity is responsible for all of the work associated with deploying a system. This includes the system design, the contracts for and the construction of the system components, and the integration of the system elements. Upon completion of the project, the designer-builder turns over the system to the agency for operations and maintenance. This process is often used to fast-track projects, since it can significantly reduce the process time. Agency supervision is required, however, to ensure that a satisfactory quality of product is provided by the contractor.

The reader is referred to the *Traffic Control Systems Handbook* and Part 655-Traffic

- Needed Legislation
- System Design
  - System Designer
  - System Design Life
  - System Coverage
  - System Design and Operations/Maintenance Philosophies
  - System Architecture
  - Integration of Other Functions
  - System Components and Functions
  - Communication Subsystem Design Approach
  - Traffic Operations Center Design Features
  - Project Phasing/Scheduling
  - Design Review
- Procurement Methods
- Construction Management Procedures
  - Division of Responsibilities
  - Scheduling and Establishing Mileposts
  - Conflict Mitigation
  - Coordination with Other Projects
- System Start-up Plan
  - Software and System Acceptance Tests
  - Partial Acceptance
  - Documentation
  - Transition from Old to New Control
  - Operational Support and Warranty Period
  - Training
  - Coordination with Media
- Operations and Maintenance Plan
  - Evaluation
    - System evaluator
    - Method of evaluation
    - Cost of evaluation
  - Maintenance Plan
    - Maintenance policies for preventative maintenance, system malfunctions, etc.
    - Formal maintenance management programs
    - Initial inventory of spare parts and all necessary test equipment
    - Training in providing limited maintenance to software and equipment
- Institutional Arrangements
  - Contact Person/project Liaison Within Each Organization
  - Delineation of Organizational Responsibilities
  - Provisions for Periodic Project Updates
  - Utility Arrangements
  - Written Cooperative Agreements for Personnel-sharing, Cost-sharing, Metering, Traffic Diversion, Etc.
- Personnel and Budget Resources
  - Staffing Plan (including the number of persons and their functions per shift)
  - Contract Operations Staff Agreements (if used)
  - Provisions for Training New Staff
  - Sources of Budgetary Resources
  - Estimates of Annual Expenses by Category
  - Signatures of the Head of the Operating Agency, Head of State Highway Agency, and the FHWA Division Administrator (or their designates)

Figure 2-5. Elements of a Typical Implementation Plan.

Operations, Subchapter G-Engineering and Traffic Operations in the *Federal-Aid Policy Guide* (which has been regenerated in Appendix A at the end of this module) for more information on alternative procurement strategies.[3,6]

Staffing plays a critical role in the timing of the implementation of the system. Sufficient lead time must be allocated to allow system operators to establish new positions (if needed); develop position descriptions and salary classifications; recruit, hire, and train needed personnel. The agency's system supervisor should be employed (i.e., designated/hired) no later than the start of the implementation phase of the project. Other operations and maintenance personnel need to be employed during system construction so that they may receive training providing by the contractor/system manager, review system documentation, and participate in system testing. If these persons are to assist with construction inspection, they need to be hired even earlier.[5]

In addition, good preventative maintenance begins with and depends upon proper installation. Proper installation requires thorough inspection and testing of contractors' work. The system operators and maintainers should participate in the inspection process and during the acceptance testing. Such involvement is an excellent method of informal training and fosters the acceptance of the new system by these personnel. [5]

It is essential that all specified documentation and training be obtained during the installation phase of the system. Submitted materials (e.g., manuals, training course outlines, etc.) should be closely examined to ensure that they are complete and clear to the agency's personnel. Furthermore, the documentation must be kept up-to-date throughout the entire implementation phase to reflect any hardware or software modifications.[5]

EVALUATION

Evaluation is an ongoing process that occurs at all stages of system development and continues for the entire life of the system. Through the evaluation process, the system designers and operators are able to determine how well individual projects meet the previously established system objectives. The evaluation process also allows system managers to identify possible enhancements to the system. These enhancements can be to correct operational or design problems, expand the system either functionally or geographically, or incorporate additional systems into a regional architecture.

The most common method of evaluating the effectiveness of a freeway management system is *Before-and-After* studies. With Before-and-After studies, the performance of the freeway management system is measured before the system (or subsystem) being evaluated is implemented. The same performance measures are then taken again after the system has been implemented. The effectiveness of the system is then determined by comparing the performance of the freeway before the system (or subsystem) was implemented to the performance of the freeway after the system (or subsystem) was implemented.

Potential limitations of the *Before-and-After* approach for evaluating system performance include the following:[7]

- The effects of individual improvements are difficult to distinguish when more than one improvement is made at a time.
- Usually there is a long time lag between the "before" condition and the "after"

condition, which causes this approach to be susceptible to errors caused by time-related factors (such as changes in travel patterns, population growths, economic fluctuations, etc.).

- Usually, it takes some time for the drivers to adjust their travel behavior after the system has been implemented; therefore, depending upon when the "after" data are collected, true system performance may not be measured.

- Some performance measures (like the number of crashes, or demand) can fluctuate considerably over time. There is a tendency for these performance measures to return to more typical values after an extraordinary value has been observed. This tendency is called *regression to the mean*. It is possible that either the "before" condition or the "after" condition could fall at one of these extreme values, thereby, hiding the true performance of the system.

Before-and-After studies with a Control Condition is one way of mitigating the negative aspects of Before-and-After studies.(7) The concept of this evaluation methodology is illustrated in figure 2-6.

With this approach, the before-and-after system performance measures are compared to the same performance measures taken from a segment of freeway with similar characteristics as the first freeway, but not affected by the operation of the system. While this approach reduces history, maturation, and regression to the mean problems, it may be difficult to find a segment of freeway not impacted by the performance of the freeway management system.

In evaluating the effectiveness of the components of a freeway management system with field measured data, it is important to remember the following considerations:(3)

- The impacts of many alternative strategies are frequently small both in absolute and in percentage terms.

- The impacts of specific strategies may be confined to isolated or small geographic areas.

- It may not be possible to accurately estimate the specific impacts using commonly available data and estimation procedures.

In some limited situations, it may be appropriate to use simulation models to estimate the effectiveness of different elements of a freeway management system. Oftentimes, systemwide benefits of different freeway management elements are difficult to measure directly. In these cases, simulation could be used as a tool to estimate the impacts of isolated control elements on the entire system. Furthermore, the results of a simulation study should only be considered as estimates of the performance of the system, since the performance measures are often directly influenced by the assumptions inherent in the simulation model. Whenever simulation is used as an evaluation tool, limited field data should be collected to support the results of the simulation model. As a general rule, simulation should never be used when the same performance indicators can be measured directly in the field.

Another way to illustrate the benefits of a freeway management system is to use anecdotal information collected from travelers who have benefited from the system. For example, many locations keep records on the number of positive letters

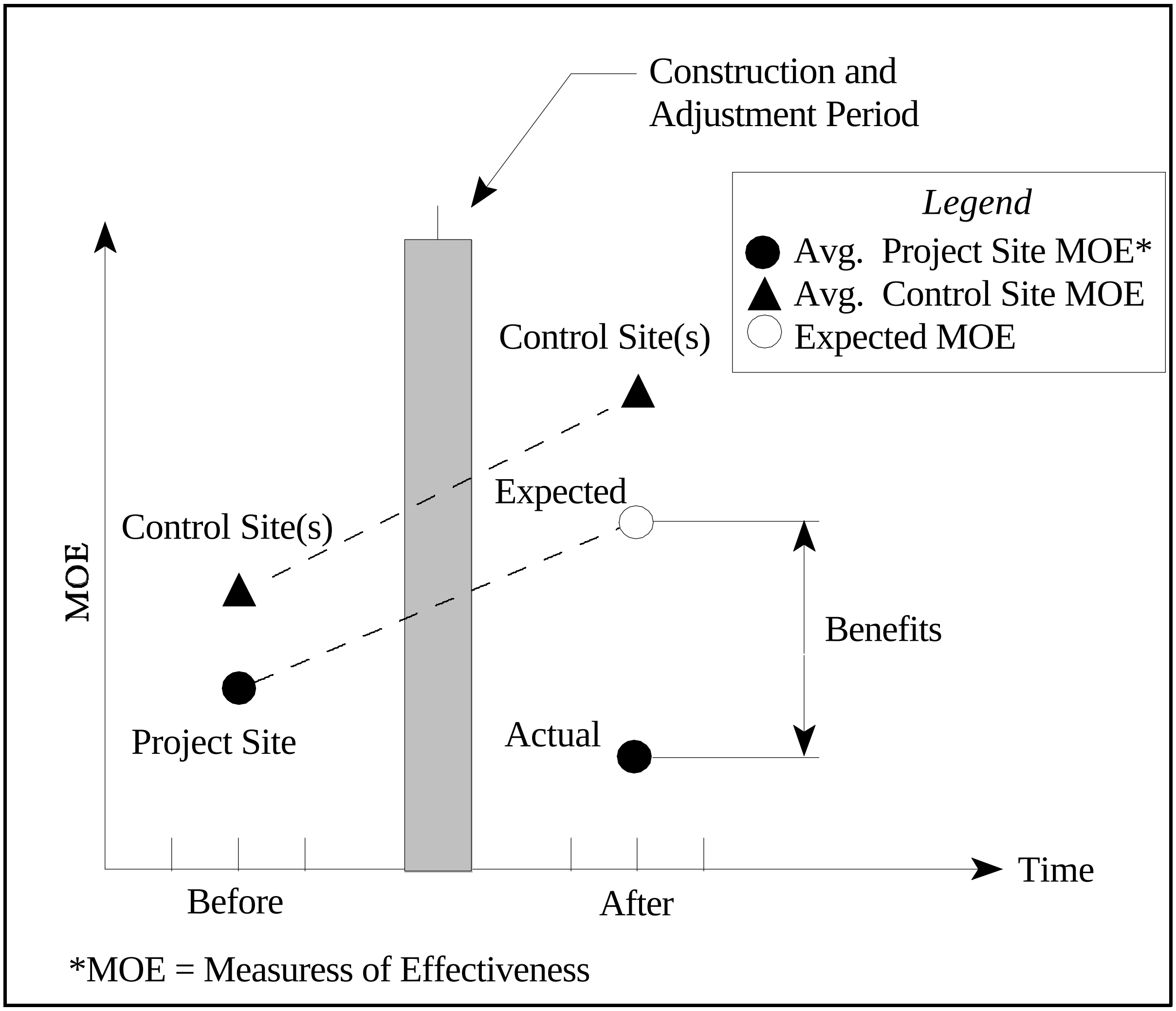


Figure 2-6. Conceptual Illustration of Before-and-After Evaluation with Control Conditions. (7)

they receive concerning their freeway service patrols.

Also, one of the most critical parts of the evaluation process is to document the lessons learned during the development and operations of the system. These lessons provide critical information to others who may be considering implementing a similar type of system. The lessons learned should not focus solely on the problems that were encountered during the development or operations of the system, but also describe the positive elements of a particular system architecture or technology.

2.3 TECHNIQUES AND TECHNOLOGIES

This section describes some of the measures of performance, techniques, and technologies used to identify and quantify operational problems on freeways.

PERFORMANCE MEASURES

Congestion occurs when the amount of traffic desiring to use a facility (demand) exceeds the traffic-carrying capabilities of the facility (capacity). There are two types of congestion: recurring and nonrecurring. Recurring congestion occurs when normal, everyday demand exceeds the physical capacity of the freeway. Nonrecurring congestion is caused either by a temporary reduction in capacity (e.g., a crash or stalled vehicle blocking a lane) or by a temporary excess of demand (caused by a special event or other similar activity).

In planning and designing a freeway management system, it is important to quantify the magnitude of the congestion problem and the amount of improvement that can be made by implementing elements of a freeway management system. The following section provides some of the more common measures of performance used to quantify congestion levels both from a systemwide perspective and at isolated locations such as bottlenecks and incident sites.

Systemwide

There are a number of measures that have traditionally been used to quantify the performance of the freeway system, both with and without a freeway management system in place. These measures include the following:[8]

- Total Travel Time.
- Total Travel.
- Vehicle Delay.
- Total Minute-Miles of Congestion.

Each of the traditional measures of system performance is discussed below. Most of these measures can be computed using data routinely collected by freeway surveillance systems.

Total Travel Time

Total Travel Time is one measure used to quantify operational deficiency and measure the performance of the freeway system. Expressed in units of vehicle-hours, it is the product of the total number of vehicles using the roadway during a given time multiplied by the average travel time of the vehicles. The equation that can be used to compute the Total Travel Time is as follows:

$$TTT_j = N_j \overline{tt}_j = \frac{N_j X_J}{\overline{V}_j}$$

where,

TTT_j = Total Travel Time over freeway section j, in vehicle-hours.

N_j = Number of vehicles traveling over freeway section j, during time period T.

$\overline{tt}_j$ = Average travel time of vehicles over freeway section j, in hours.

X_j = Length of roadway section j, in kilometers.

$\overline{V}_j$ = Average speed of vehicle over freeway section, in kilometers per hour.

The Total Travel Time, TTT, in vehicle-hours, for all sections of a freeway can be computed using the following equation:

$$TTT = \sum_{j=1}^{K} TTT_j$$

where,

TTT = Total Travel Time for all sections of the freeway, in vehicle-kilometers.

TTT_j = Total Travel Time for section j, in vehicle-kilometers.

K = Total number of freeway sections.

Total Travel

Total travel is another measure commonly used to quantify operational problems and measure the performance of the freeway system. Total travel is the product of the total number of vehicles using the freeway during a given time interval multiplied by the average trip length of the vehicles. It can be determined using the following equation:

$$TT_j = X_j N_j$$

where,

TT_j = Total Travel over freeway section j, in vehicle-kilometers.

X_j = Length of freeway section j during time period T, in kilometers.

N_j = Number of vehicles traveling over section during time period T.

Total Travel (TT) for all sections of freeway can be computed using the following equation:

$$TT = \sum_{i=1}^{K} TT_j$$

where,

TT = Total Travel for all sections of the freeway, in vehicle-kilometers.

TT_j = Total travel for section j, in vehicle-kilometers.

K = Total number of freeway sections.

Vehicle Delay

Vehicle delay is another common measure used to quantify the level of performance of the freeway system. For freeways, vehicle delay is defined as the increase in travel time on a route over the free-flow travel time. Vehicle delay can be computed by subtracting the total free-flow travel time from the total travel time. Total free-flow travel time is the product of the total number of vehicles using the roadway during a given time interval multiplied by the average free-flow travel time.

Total Minute-Miles of Congestion

Originally developed to measure the effectiveness of the Chicago Area Freeway Surveillance Project, the total minute-miles of congestion method was used to indicate the extent of freeway congestion in both time and space.[9] (Minute-Miles was the measure of performance at the time of the study. Minute-kilometer is also appropriate.) To compute the total minute-miles of congestion, each mainline detector is assigned a section of freeway that covers half the distance between the adjacent mainline detectors on either side. The minute-miles of congestion at each detector is equal to the product of the minutes of congestion at the detector, multiplied by the distance, in miles, assigned to the detector. The sum of the minute-miles of congestion of all detectors then would represent the total minute-miles of congestion.

Isolated Locations

Congestion caused by incidents and bottlenecks tends to be located at isolated locations. Engineers evaluating these locations are primarily concerned with the following issues:

- What is the cause of the congestion?
- How quickly can the congestion clear?
- What are the effects of the congestion on drivers through the congested area?
- How large is the effected area?

The types of measures that are commonly used to quantify the impacts of congestion at isolated locations include the following:

- Time until normal flow.
- Total vehicles delayed.
- Average delay per vehicle.
- Maximum time of queue.
- Maximum queue length.
- Fuel consumption.
- Air pollution.

Most of these measures can be computed by conducting a bottleneck/queuing analysis, which is discussed below.

METHODS TO QUANTIFY OPERATIONAL PROBLEMS ON FREEWAYS

The types of analytical methods used to quantify the freeway operational problems include the following:

- Capacity and Level of Service Analysis.
- Bottleneck and Queuing Analysis.
- Computer Simulation.
- Field Measurements.

How these methods are used to quantify operational problems on freeways is discussed in more detail below.

Freeway Capacity Analysis and LOS

One of the most basic types of analysis required for a section of freeway is a determination of the amount of traffic-carrying capacity that the section can provide. Capacity is defined as the maximum number of vehicles that can reasonably be expected to use the facility in a given time period under prevailing roadway, traffic, and control conditions.(10) Related to this definition is the concept of the operational quality or level of service (LOS) provided to users of a facility.

Definition of Freeway Subareas for Capacity Analysis

Freeways are composed of three types of component subsections. These are defined as follows:

- *Basic Freeway Segments* -- These are freeway sections that are unaffected by either merging or diverging traffic movements at nearby ramps or by weaving movements.

- *Weaving Segments* -- These are freeway sections where two or more vehicle flows must cross each other's path. Weaving areas exist where merge areas are closely followed by diverge areas, and where a freeway on-ramp is followed closely by an off-ramp and an auxiliary lane is used to connect the two.

- *Ramp Junctions* -- These are freeway sections where on- and off-ramps join the freeway.

Figure 2-7 illustrates the various types of freeway components. Capacity analyses treat each one of these components with a separate computational procedure. After the components have been evaluated in isolation, the results are laid out together to assess how the freeway operates as a system. A system analysis perspective is particularly important in the evaluation of closely-spaced ramp effects upon the capacity and operating characteristics of the freeway.

Basic Freeway Segments

Definition of Ideal Freeway Capacity. According to the 1994 edition of the Highway Capacity Manual, the capacity of basic freeway segments under ideal roadway, traffic, and environmental conditions is assumed to be 2,200 passenger cars per hour per lane (pcphpl) on four-lane freeway sections and 2,300 pcphpl on six-or-more lane freeway sections.(10) These capacity values represent the maximum number of vehicles that can reasonably be expected to use the facility (an average over all lanes) in a given time period under prevailing roadway, traffic, and control conditions. Flow rates in excess of these values can sometimes occur in individual lanes, particularly in inside or median lanes where there is no influence of upstream or downstream ramps.

Conditions that are "ideal" from a freeway capacity perspective include the following:

- 3.6 m (12 ft) minimum lane widths.

- 1.8 m (6 ft) minimum lateral clearance between the edge of the travel lane and the nearest roadside or median obstacle influencing traffic behavior.

- All passenger cars in the vehicle stream (no trucks, buses, or recreational vehicles).

- Motorists who are regular and familiar users of the freeway.

Factors Affecting Capacity. Obviously, conditions more restrictive than those listed above reduce the traffic-carrying capacity of the freeway. For example, lane widths narrower than 3.6 m (12 ft) cause drivers to travel closer to one another laterally, and so they adjust by increasing the distance between themselves and the vehicle in front of them. Roadside obstructions closer than 1.8 m (6 ft) to the roadway cause drivers to shy away from the edge of the roadway, and they again respond by increasing the gap between their vehicles and the vehicles they are following. Trucks, buses, and recreational vehicles are larger than passenger cars and have more sluggish operating characteristics, which create larger gaps between them and passenger vehicles. Finally, the characteristics of the driving population have been shown in several studies to affect the capacity of a freeway segment. Nonfamiliar users of a facility are generally more cautious and therefore leave more room between themselves and vehicles they are following.

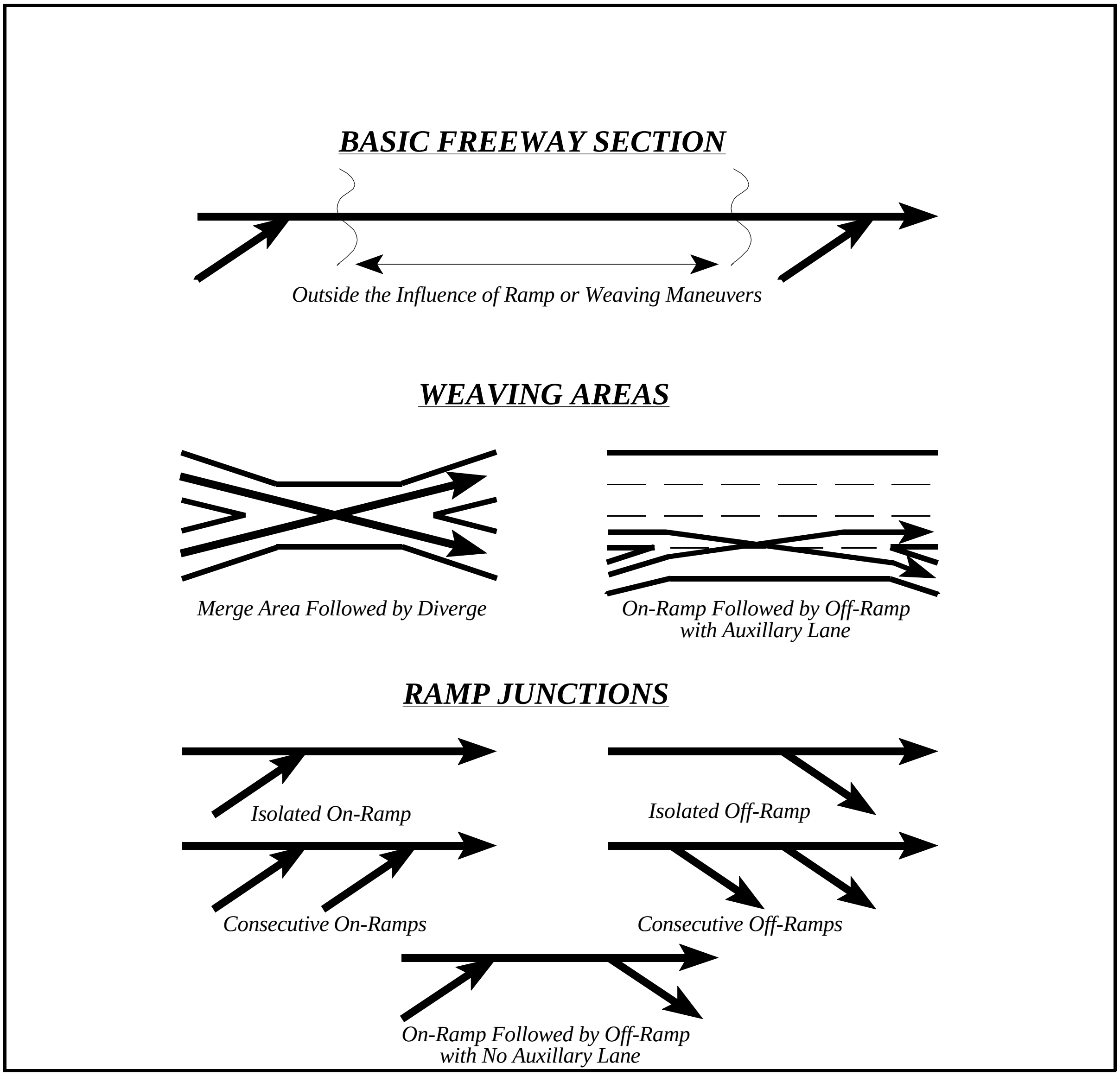


Figure 2-7. Illustration of Freeway Components for Capacity Analysis. [11]

Traffic operations and the capacity of basic freeway segments are also affected by horizontal and vertical alignment. Specifically, sharper horizontal curves and longer, steeper grades reduce the traffic-carrying capacity of the freeway segment.

Level of Service. As indicated previously, the concept of LOS was introduced into operational analysis as a means of quantifying the quality of operation attainable under a given roadway and traffic configuration. Although the traffic-carrying capacity of a basic freeway segment is defined in terms of vehicular flow, density (number of vehicles per lane per kilometer (mile)) is the parameter used to define LOS for basic freeway segments. LOS is defined by the letters A through E, with LOS F used to define breakdown, stop-and-go conditions. Table 2-3 gives a qualitative description of each level of service, and the density value that has been associated with each level.

Weaving Areas

Definition of Weaving Area Capacity. Weaving is defined as the crossing of two or more traffic streams traveling in the same general direction along a significant length of freeway. Weaving areas represent a region of intense lane-changing behavior and increased traffic flow turbulence as drivers attempt to access lanes to reach their desired exit points from the weaving area. Many different roadway and traffic factors can influence operations within these areas. Because of this complexity, the capacity of weaving areas as estimated by procedures in the *Highway Capacity Manual* is not defined in terms of maximum flow rates or vehicle densities, but in terms of estimated operating speeds.[10] Specifically, calculations are made to estimate the speeds expected of weaving and of nonweaving vehicles. These are then compared to tabular values to determine the LOS being provided by that weaving section.

Types of Weaving Areas. Because lane-changing is the critical operational feature of weaving areas, weaving sections are categorized according to the minimum number of lane changes that must be made by weaving vehicles.

Weaving areas are referred to as Type A, Type B, or Type C sections. Figure 2-8 illustrates each type of weaving area.

Type A weaving areas require that each weaving vehicle make one lane change in order to execute the desired movement. These areas may be ramp-weave areas created by adjacent entrance and exit ramps connected by an auxiliary lane, or major weaving areas characterized by three or more entry and exit roadways having multiple lanes.

Type B weaving areas may also be referred to as major weaving sections if they involve multilane entry and/or exit lanes. However, these areas differ from Type A areas in that one weaving movement can be accomplished without changing lanes, whereas the other weaving maneuver requires no more than one lane change.

Type C weaving areas are similar to Type B areas in that one weaving movement can be made without changing lanes. The major difference between these two types of areas is that Type C areas require the other weaving maneuver to make two or more lane changes. This can be an effective design if the second weaving flow is fairly small. However, it can have very adverse effects on operations if the second flow is large, the number of lane changes being made is large, and the length of the weaving area is fairly short.

Operational Characteristics of Weaving Areas. Traffic operations within weaving areas are affected by the following geometric features:

- Weaving length.
- Weaving area configuration.
- Number of lanes (weaving width).

Shorter weaving lengths create greater traffic flow turbulence as drivers are forced to make necessary lane changes over a limited distance. The configuration of a weaving area influences the number of lane changes that must be made and also the proportion of vehicles that must make a weaving maneuver. The number of lanes available within the weaving area defines the amount of space available to weaving vehicles to make the various types of lane changes.

Table 2-3. Level of Service (LOS) Descriptions. [11]

Level of Service	Status	Density Threshold, pc/km/ln (pc/mi/ln)	Description
A	Free Flow	6.25 (10)	Individual motorists are unaffected by the presence of others in the traffic stream. Freedom to select desired speeds and to maneuver within the traffic stream is high.
B	Stable Flow	10 (16)	Freedom to select desired speeds is relatively unaffected, but there is a slight decline in the freedom to maneuver within the traffic stream. The presence of others in the traffic stream begins to affect individual behavior.
C	Stable Flow	15 (24)	The behavior of individual motorists is significantly affected by interactions with others in the traffic stream. Selection of speed is affected by other vehicles and maneuvering within the traffic stream requires vigilance by the motorist.
D	High-Density Stable Flow	20 (32)	Speed and freedom to maneuver are severely restricted, and the driver experiences a generally poor level of comfort and convenience. Small increases in traffic flow will generally cause operational problems.
E	Unstable Capacity Flow	23-30 (36.7-47.9)[a]	Operations are at or near capacity. Speeds are lower, but relatively uniform among vehicles. Freedom to maneuver is extremely limited. Operations are unstable.
F	Forced or Breakdown Flow	>23-30 > (36.7-47.9)[a]	Amount of traffic approaching a point exceeds the amount which can traverse the point. Queues form and operations are characterized by unstable stop-and-go waves.

[a] Capacity occurs at different densities depending on the design speed of the freeway

If the weaving length, configuration, and width in combination with the traffic demand pattern permit the weaving and nonweaving vehicles to spread out evenly across the available lanes in the weaving section, the operation of the weaving area is more effective and is classified as **unconstrained**. Conversely, if the configuration and traffic demand limit the ability of weaving vehicles to occupy their proportion of available lanes to maintain balanced operations, the operation is less effective and is classified as **constrained**. Imbalanced or constrained operations within weaving sections will result in weaving vehicles traveling at a lower average speed than nonweaving vehicles. Not only will the LOS being provided by the weaving section be lower because of this condition, but also the general safety of the section will be lower because of a mixing of lower and higher speed traffic flows.

Capacity and Level of Service for Weaving Areas. In weaving sections, operations are estimated to be at capacity when estimated weaving and nonweaving speeds are between 48 and 56 km/h (30 and 35 mph). Table 2-4 summarizes the weaving and nonweaving speed thresholds that have been defined for the other levels of service. Those average speeds are based on regression equations.

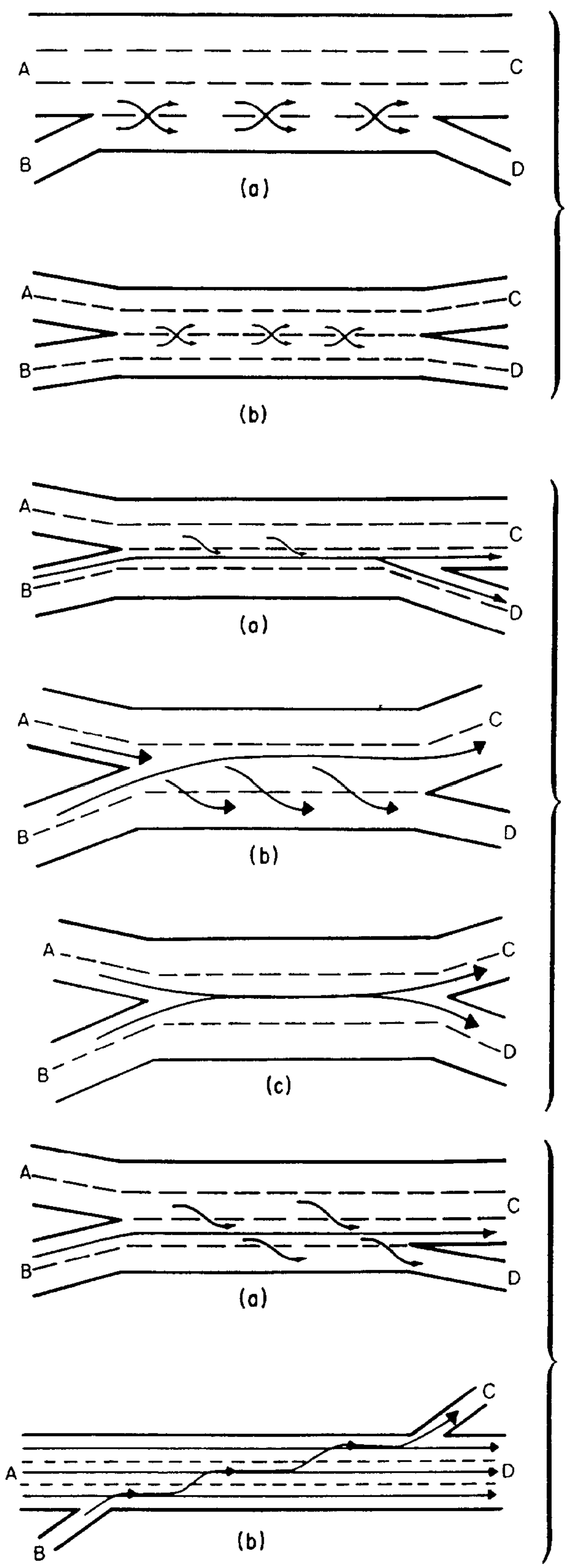
The regression constants vary according to the weaving configuration of the section and whether or not the weaving section operation is unconstrained or constrained. Both the weaving and nonweaving speeds must satisfy the criteria specified in table 2-4 for a given LOS. For example, the average weaving speed must exceed 80 km/h (50 mph) and the average nonweaving speed must exceed 90 km/h (54 mph) in order for the weaving section to be considered as operating at LOS B.

It is important to note that the above LOS criteria have been established in conjunction with the regression equations, and only provide a mathematical procedure for assessing the general operations at weaving areas. Considerable variation may exist between the estimates obtained via the mathematical procedures and the actual operations observed at a given weaving area. Research continues to improve the estimates of weaving area operations. The formulas and thresholds presented in this chapter should be supplemented with sound engineering judgement and actual field data as necessary until a better understanding and mathematical formulation are available.

Ramp Junctions

Definition of Ramp Junction Capacity. The points at which vehicles enter a freeway mainlane from an on-ramp or the point at which mainlane traffic diverges to an off-ramp are termed freeway-ramp junctions. A freeway-ramp junction is an area of competing traffic demand for space. Analyses of freeway-ramp junctions focus on the merging and diverging behaviors required in the outer two freeway lanes and the acceleration or deceleration lane in the vicinity of on- and off-ramps, respectively, as depicted in figure 2-9. Elements such as the length and type (e.g., taper, parallel) of acceleration and deceleration lanes, free-flow speed of the ramp in the immediate vicinity of the junction, and sight distances all influence traffic operations within these regions.

For freeway-ramp junctions, two capacity values are important. The first refers to the requirement that the capacity of the freeway lanes (plus the off-ramp lane in the case of diverging freeway-ramp junctions) where vehicles *exit* the region of ramp influence must not exceed the capacity of those lanes as defined for basic freeway segments. This value is 2,200 pcphpl for four-lane facilities or 2,300 pcphpl for freeway facilities with six or more lanes. The second capacity value of interest is the freeway traffic flow *entering* the ramp influence area. This cannot exceed 4,400 pcph on four-lane



Type A weaving areas: (a) ramp-weave/one-sided weave, and (b) major weave with crown line.

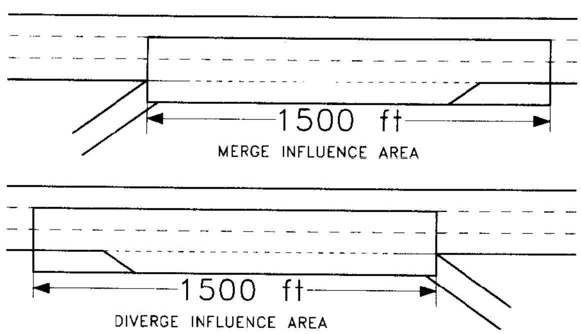
Type B weaving areas: (a) major weave with lane balance at exit gore, (b) major weave with merging at entrance gore, and (c) major weave with merging at entrance gore and lane balance at exit gore.

Type C weaving areas: (a) major weave without lane balance or merging, and (b) two-sided weave.

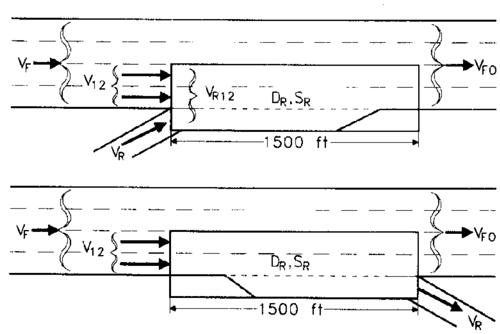
Figure 2-8. Categories of Weaving Areas. [13]

Table 2-4. Level-of-Service Criteria for Weaving Sections. [11]

Level Of Service	Minimum Average Weaving Speed, S_w km/h (mph)	Minimum Average Nonweaving Speed, S_{nw} km/h (mph)
A	90 (55)	100 (60)
B	80 (50)	90 (54)
C	70 (45)	77 (48)
D	60 (40)	67 (42)
E	50/60 (35/30)	50/60 (35/30)
F	<60/50 (<35/30)	<60/30(<35/30)



On- and Off-Ramp Influence Areas



Critical Ramp Junction Values

Figure 2-9. Influence Areas and Critical Flow Values for Freeway-Ramp Junctions. [11]

facilities or 4,600 pcph on six- or more lane facilities.

Operational Characteristics of Ramp Influence Areas. In the merge area at an on-ramp, individual merging vehicles from the ramp attempting to enter the outer freeway lane (lane 1) create turbulence in the traffic stream in the vicinity of the ramp. Approaching freeway vehicles therefore tend to move towards the left to avoid this turbulence. As ramp volumes increase, more and more freeway vehicles will move to the left as long as there is available capacity to do so. However, the interaction between freeway and ramp vehicles in the influence area is quite dynamic. Although the intensity of the ramp demand flows most generally affects what percentage of approaching freeway vehicles move to the left, any congestion that develops on the freeway itself affects the ability of ramp vehicles to enter the freeway and can cause diversion of some of the ramp traffic to other routes or ramps in the vicinity, or excessive ramp queuing.

In the diverge area of an off-ramp, the basic maneuver being performed is the separation of a single traffic stream into the through and exiting movements. Since exiting vehicles must occupy lane 1 in order to utilize the off-ramp, they begin moving towards that lane in the influence area. This in turn also causes through freeway vehicles to begin moving towards the left in order to avoid the turbulence of the diverge area.

These operational characteristics serve as the basis of current freeway-ramp junction analytical procedures included in the 1994 *Highway Capacity Manual*.[10] Regression equations are presented in that manual to estimate the percentage of freeway traffic that remains in the two lanes closest to the ramp in the influence area. The choice of the appropriate regression equation depends on the following factors:

- The number of freeway lanes in the influence area.

- The presence of nearby on- or off-ramps.

Level of Service of Freeway-Ramp Junctions. Although the capacity analysis procedures for freeway-ramp junctions focus on the flow rates entering and exiting the influence area, traffic flow is not the primary measure used to evaluate the LOS that exists within a ramp influence area. Rather, as is done for basic freeway segments, vehicle density is the primary measure used to define levels of service. Table 2-5 provides the density thresholds corresponding to each level of service in ramp influence areas. Regression equations presented in the Highway Capacity Manual are used to estimate volumes, densities, and speeds in the ramp influence area.

As shown in table 2-5, the density threshold values for each LOS are somewhat higher than for basic freeway segments. This is because drivers naturally expect some increased turbulence and closer proximity of other vehicles in a merge or diverge area, and because drivers are typically traveling at a slightly slower speed in any given lane in the influence area than they would on a similar section of open freeway.

Freeway Systems

The freeway is a complex facility made up of many component segments, each having a potential impact on operations in upstream and downstream segments. Capacity and LOS analyses discussed to this point have addressed each of the major types of freeway components. After the component analysis has been completed, the final step in such an analysis is to put the various components

Table 2-5. Level of Service (LOS) Descriptions for Freeway-Ramp Junction Influence Areas. [11]

Level of Service	Status	Density Threshold, pc/km/ln (pc/mi/ln)	Description
A	Unrestricted Operations	6.25 (10)	Merging and diverging maneuvers occur without disrupting freeway flow. No noticeable turbulence exists. Freeway speeds are nearly as high as in basic freeway sections.
B	Stable Operations	12.5 (20)	Merging and diverging maneuvers become noticeable to motorists, but only minimal levels of turbulence exist. Merging vehicles must adjust their speeds in order to move into available gaps in the freeway traffic stream.
C	Stable Operations	17.5 (28)	Average speeds in the ramp influence area begin to decline. Driving conditions are still relatively comfortable at this level.
D	High-Density Stable Operations	21.9 (35)	Turbulence levels become intrusive. All vehicles in influence area slow to accommodate those making merging and diverging maneuvers. Freeway operations tend to remain stable.
E	Capacity Operations	> 21.9 (> 35)	Operations are at or near capacity. Speeds are lower. Freedom to maneuver is extremely limited and intrusive to all drivers. Operations are unstable.
F	Breakdown Operations	[a]	Traffic attempting to use influence area exceeds the amount which can traverse the area.

[a] Density criteria is not valid or relevant under breakdown conditions

together to get an overall systemwide picture of anticipated freeway operations.

Generally speaking, capacity and LOS analyses can be oriented towards design (determining necessary number of lanes, locations of ramps, weaving area lengths, etc.) or operations. In this section, the basic steps for an operational analysis of a freeway system are outlined.

As the first step, the analysis of individual freeway components occurs as per the techniques described earlier.

1. Basic freeway segments are evaluated using the procedures discussed in chapter 3 of the *Highway Capacity Manual*.(10)

2. Ramp junctions are evaluated using the procedures in chapter 4 of the *Manual*, considering each ramp as follows:(10)

- As an isolated ramp.

- In conjunction with the adjacent downstream ramp.

- In conjunction with the adjacent upstream ramp.

  Ramps that are clearly operating as part of a weaving section would not be evaluated with these procedures.

3. Weaving sections are evaluated using the procedures documented in chapter 5 of the *Manual*.(10)

When a given component falls under more than one of these categories, the analysis category that results in the lowest LOS is used as the controlling factor defining operations within that component.

Once the analysis results of the various freeway components have been computed, a graphical procedure can then be used to obtain an overall perspective of the operating conditions of the freeway system as a whole. The general freeway alignment is plotted along with an indication of the level of service that has been predicted for each particular freeway component or segment. Figure 2-10 illustrates this pictorial layout of level of service for a hypothetical freeway section.

As the illustration shows, the weaving area in section 4 of this hypothetical situation is a candidate bottleneck situation that will likely be the segment that controls the operation of the overall system. Whereas the weaving section is anticipated to operate near level of service E, the upstream segments **could** operate at levels of service B or C as long as the weaving section does not break down and create queues and congestion that propagates upstream into these segments. However, if flows are slightly higher than anticipated, it is likely that the weaving segment would break down very quickly and lead to operational problems within those upstream segments as well.

Highway Capacity Software (HCS)

Capacity and LOS analyses for each type of freeway segment can be performed manually using the procedures, nomographs, tables, and worksheets that are provided in the *Highway Capacity Manual*. However, these computations can be quite repetitive and time-consuming for the analysis of many design or operational alternatives. Fortunately, these procedures have been automated, and can be performed quite easily on a personal computer using the *Highway Capacity Software (HCS)*, developed under FHWA sponsorship and maintained by the McTRANS Center at the University of Florida.

The HCS is a macroscopic, primarily empirical, deterministic simulation program used to quickly and easily evaluate traffic flow conditions at specific freeway features. The program contains separate modules for analyzing basic freeway segments, freeway-ramp junctions, weaving areas, and freeway systems. Modules for analyzing signalized and unsignalized intersections are also included (these may be needed when

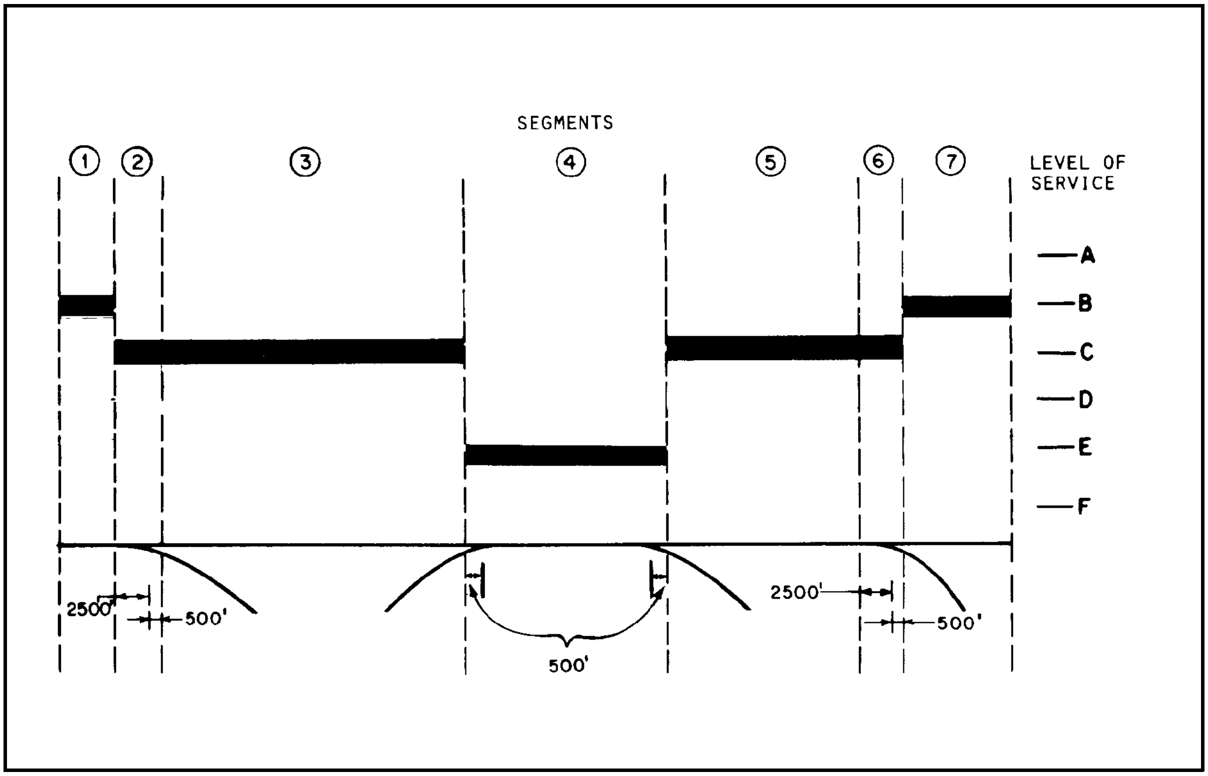


Figure 2-10. Graphic Representation of Level of Service for Freeway Systems. [11]

evaluating ramp-arterial street terminals at the ends of exit ramps).

The HCS (and the HCM procedures in general) are most appropriate for quick analyses of individual freeway components or for specific locations. If a more accurate and detailed evaluation of freeway operations as a system is required or desired, it is necessary to revert to the more sophisticated traffic simulation and optimization models in order to fully examine traffic operating conditions. These simulation and optimization models are addressed below.

BOTTLENECK/QUEUING ANALYSES

The state of the freeway (as determined by its flow-speed-density relationship) changes over space and time. When these changes of state occur, a boundary is established that denotes the time-space domain of one flow state as distinguishable from another. These boundaries are referred to as shock waves. As shown in figure 2-11, when a change in state occurs on a high-volume freeway, the queue and its resulting congestion begin to back upstream from the scene of the bottleneck. The boundary that denotes this change in state is a shock wave.

As shown in figure 2-12, there are four common types of shock waves. A *frontal stationary* shock wave always forms at a bottleneck location and occurs when demand exceeds capacity. It can be caused by either recurrent or nonrecurrent congestion situations. The term *frontal* implies that the shock wave is at the front (or downstream edge) of the congested region. It is called *stationary* because the shock wave is fixed by the location and does not change its location over time.

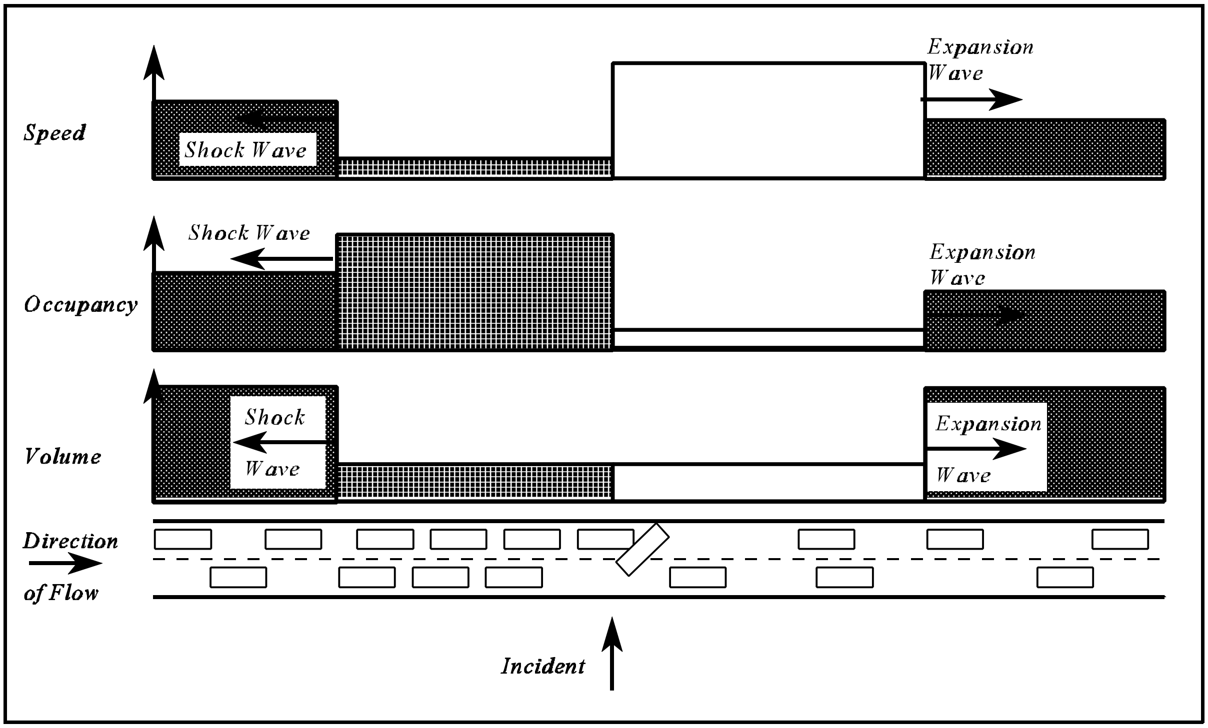


Figure 2-11. Fundamentals of Shock Wave Analysis. (15)

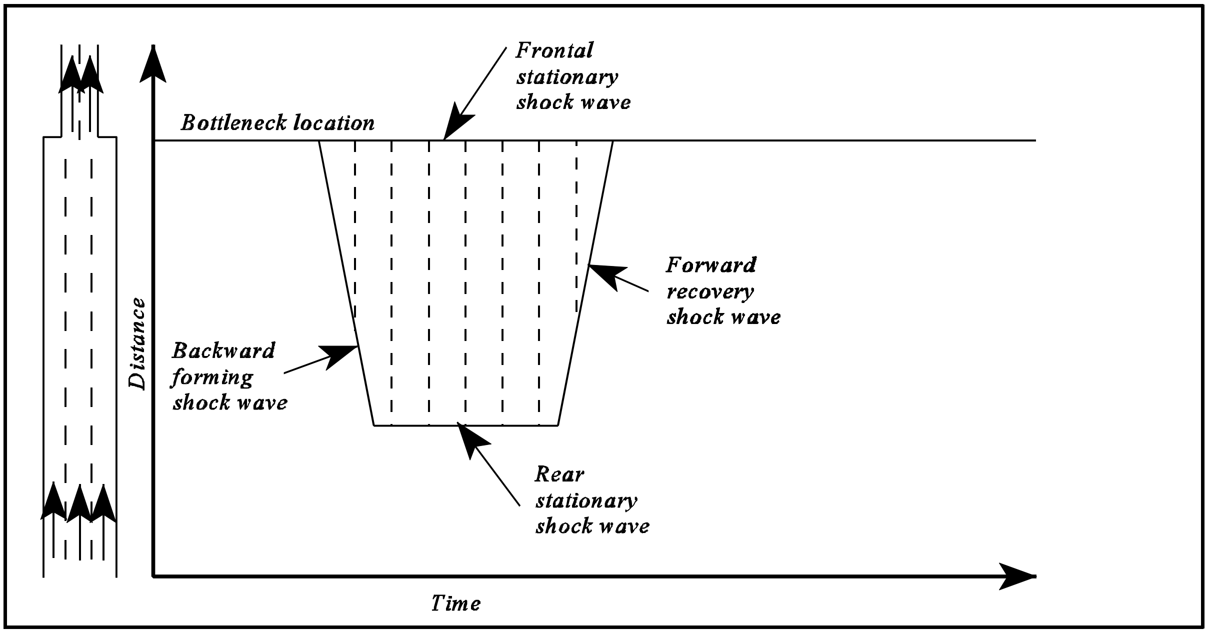


Figure 2-12. Shock Wave Phenomena at a Freeway Bottleneck During a Peak Period. (14)

A *backward forming* shock wave is also always present when congestion occurs. It is formed by the area where excess demands are being stored (i.e., the queue). It is termed *backward* because, over time, the shock wave moves backwards or upstream in the opposite direction of traffic. The term *forming* implies that, over time, the congestion gradually extends farther upstream. The slope of the wave represents how fast the shock wave is traveling upstream (e.g., a flatter slope implies that the shock wave is moving slowly upstream, while a steeper slope implies that the shock wave is moving rapidly upstream). A backward forming shock wave is the most commonly occurring type.

A *forward recovery* wave is the next most commonly encountered type of shock wave. It occurs when there has been congestion but demand decrease is below the bottleneck capacity. It forms as the length of congestion reduces. It is a *forward* wave because it moves downstream in the same direction as the flow of traffic. The term *recovery* implies that free-flow conditions are gradually occurring as the wave moves forward.

A *rear stationary* shock wave occurs when the arriving traffic demand is equal to flow in the congested region for some period (i.e., the queue is neither growing or dissipating). It is a *rear* wave because it occurs at the rear (or upstream edge) of the congested region with higher densities downstream and lower densities upstream. It is *stationary* because the shock wave does not change its location over time.

Another type of shock wave encountered on freeways is the *backward recovery* shock wave. This wave commonly occurs after the source of congestion (e.g., an incident) has been removed from the freeway. After the capacity has been restored, the discharge rate through the congested area exceeds the flow rate in the congested region. This causes the shock wave to move upstream (or *backwards*) in the opposite direction from traffic. It is a *recovery* wave because over time, free-flow conditions are extending further and futher upstream from the previous bottleneck location.

A final type of shock wave that may be encountered is the *forward forming* shock wave. This type of shock wave moves in the same direction of traffic. It is a *forming* wave because, over time, congestion is gradually extending further and further downstream. This type of wave is not commonly observed with freeway operations.

Queues form when demand on a freeway facility exceeds the capacity for an interval of time. To conduct a queuing analysis the following inputs are required: [14]

- The mean (or average) arrival flow rate (vph).
- The distribution of arriving vehicles.
- The mean (or average) service flow rate (vph).
- The distribution of vehicles being serviced.
- The queue discipline.

"First In First Out (FIFO)" is the commonly used queuing discipline used in transportation engineering. With FIFO, vehicles are serviced in the order in which they arrive. Another queuing discipline that can be used is "first in last out (FILO)." This type of queuing discipline would be used to model how queues might dissipate from behind a slow-moving vehicle on a multilane freeway.

Queuing analyses can be conducted at two levels of detail. With the first, queues are analyzed at a macroscopic level where arrival patterns and service patterns are considered to be continuous. The other level of detail is microscopic, and is conducted where arrival and service patterns are considered to be discrete.

One situation where queuing analysis is commonly used in freeways is in analyzing the impacts of temporary blockages (caused by incidents or work zone activities) on traffic flow. Figure 2-13 provides an illustration of this situation. Figure 2-13a provides all the input requirements needed to analyze this situation. The arrival rate (λ) is specified in vehicles per hour and is constant for the analysis period. The normal service rate (without the blockage) is indicated in the diagram as μ, and since it exceeds the arrival rate, no queuing would normally exist. However, an incident occurs that reduces the service rate to μ_R, which is below the arrival rate, and this lower service rate is maintained for t_R hours. As is the case in most freeway situations, a FIFO queue discipline is assumed.

In figure 2-13b, a cumulative vehicles versus time diagram is constructed. The arrivals are shown as a straight line passing through the origin with a slope up and to the right equivalent to the arrival rate (λ). For the first period, the service line follows the arrival line, until the blockage occurs. At that point, the service rate becomes equivalent to μ_R and maintains a flatter slope until the blockage is removed. When the service rate increases to μ, the service line asumes a steeper slope. This continues until the arrival line and service line intercept, at which time the service line once again overlays the arrival line. A triangle is formed with the cumulative arrival link forming the top side of the triangle and the cumulative service line forming the other two sides of the triangle. The triangle represents the congestion that is caused by the bottleneck. Table 2-6 summarizes the equations used to analyze this queuing situation.

FREEWAY SIMULATION/ OPTIMIZATION MODELS

Capacity and LOS analysis is a very useful tool for gauging the expected operating conditions at certain freeway locations, and for determining the magnitude-of-scale changes that would result in those operations if a major freeway improvement were made. However, the characteristics of the freeway system and/or the traffic demands on the freeway create conditions that cannot be easily or accurately evaluated with the capacity analysis techniques. The changes to the freeway may be too subtle in nature to be addressed by the capacity and LOS analysis. In addition, the capacity analysis procedures only indicate where traffic operations are expected to break down or the LOS being provided by a particular roadway and traffic configuration. Information on total and individual vehicle delays, stops, fuel consumption, vehicle emissions, and other measures are not provided by capacity analysis techniques. Consequently, it is often necessary to turn to more complicated but powerful traffic simulation or optimization analyses.

The following sections provide an overview of the major traffic simulation and optimization computer models available for freeway operations analysis. The models are discussed according to the analysis approach used to represent traffic flow in each. First, the macroscopic models are described. Then, models that provide a microscopic analysis of freeway operations are reviewed.

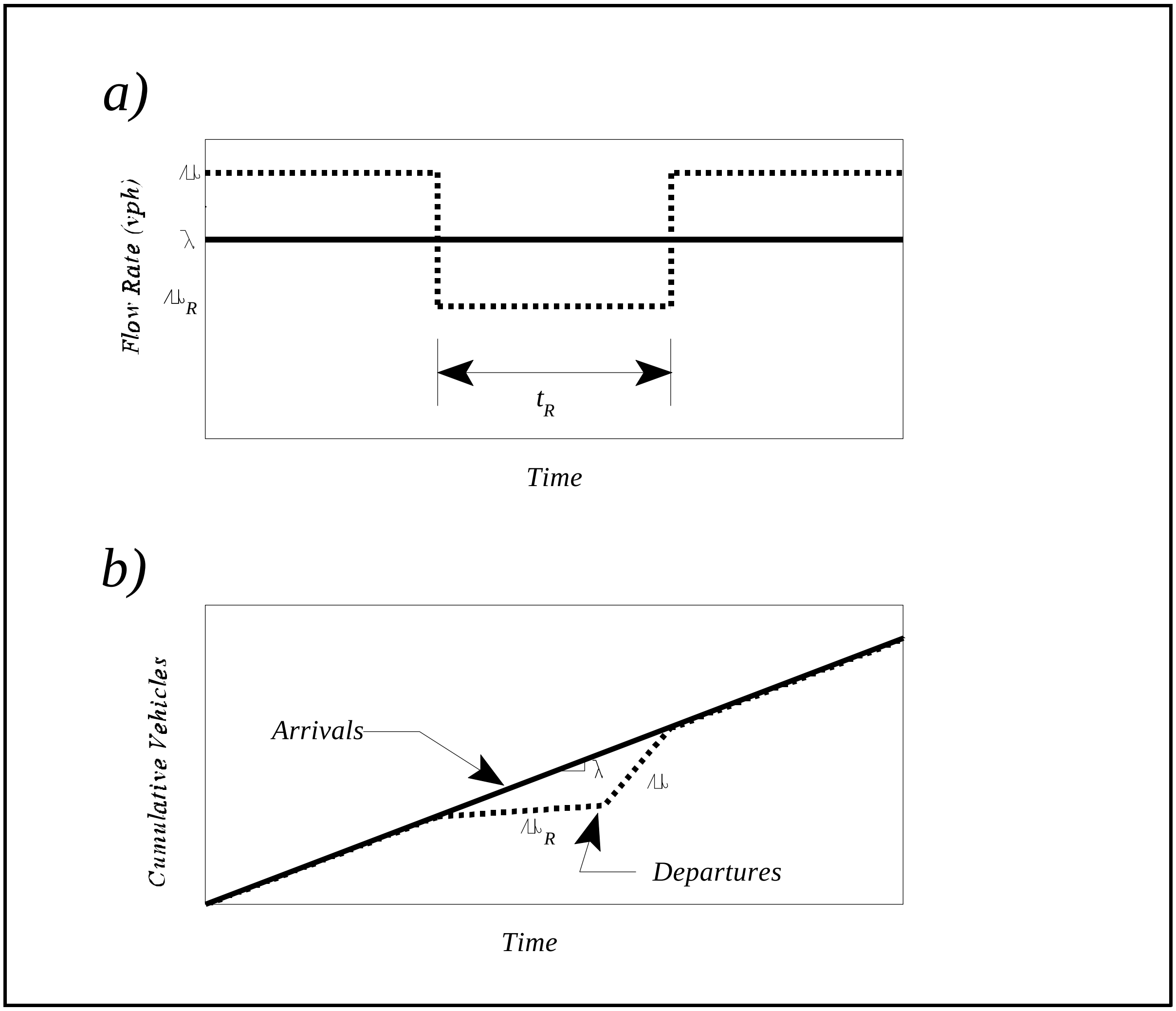


Figure 2-13. Use of Queuing Analysis to Analyze Temporary Blockage. [14]

Macroscopic Freeway Simulation/Optimization Models

One of the principal advantages of most freeway simulation/optimization models is their incorporation of the time element into the analysis. Typically, this is accomplished by dividing the duration of analysis into incremental units, or "slices," of time over which traffic demands and freeway characteristics are approximately constant. The time slices are then analyzed sequentially to allow the traffic impacts of previous slices to be considered in the evaluation of the current time slice. In a similar manner, the spatial relationships between various components on the freeway are specified by defining homogenous segments of freeway in the program and linking those segments together to form the freeway section of interest. These segments have uniform characteristics in terms of traffic demand, number of lanes, basic geometry, etc.

A number of simulation and optimization models have been developed over the years to assist in the analysis of macroscopic traffic flow behavior on freeways. Characteristics of the three such programs that are most widely used are discussed below:

Table 2-6. Queuing Performance Equations for Freeway Lane Blockage. [14]

Performance Measure	Equation
Time duration in queue, t_Q (hr)	$\frac{t_R(\mu - \mu_R)}{\mu - \lambda}$
Number of vehicles queued, N_Q (vehicles)	λt_Q
Maximum queue length, Q_M (vehicles)	$t_R(\lambda - \mu_R)$
Average queue length while queue present, $\overline{Q}_A$ (vehicles)	$\frac{t_R(\lambda - \mu_R)}{2}$
Maximum individual delay, d_M (minutes)	$\frac{60t_R(\lambda - \mu_R)}{\lambda}$
Average individual delay while queue present, d_A (minutes)	$\frac{30t_R(\lambda - \mu_R)}{\lambda}$
Total delay TD (vehicle-hours)	$\frac{t_R t_Q(\lambda - \mu_R)}{2}$

λ = the mean arrival flow rate (vph)
μ_R = Capacity flow rate during incident (vph)
μ = Capacity flow rate (vph)
t_R = duration of incident (hrs)

- FREQ.
- CORFLO.
- QUEWZ-92.

FREQ

FREQ is a macroscopic, analytic, deterministic, simulation and optimization program designed to evaluate freeway operations in a single direction of travel.

The program has been tested and validated extensively, and is widely used to evaluate the impacts of temporary freeway lane blockages, various freeway lane and ramp configurations, and high-occupancy vehicle treatments (dedicated lanes, priority treatments at entrance ramps).[15,16] FREQ can also develop optimized timing plans for ramp metering, based on one of several optimization objectives (e.g., maximize vehicle throughput, vehicle-kilometers of travel, passenger throughput, or passenger-kilometers of travel). However, the program is not capable of evaluating freeway-to-freeway interchange operations.

Input data requirements for FREQ include the following characteristics for each freeway segment within the study section:

- Segment length.
- Number of travel lanes.
- Grade.
- Capacity.
- Design speed.
- Ramp configuration.
- Ramp capacity.

Traffic demand data required by FREQ are as follows:

- Mainline volume entering the upstream end of the first freeway segment in section.
- Mainline volume exiting the downstream end of the last freeway segment in section.
- All entrance and exit volumes within the section being analyzed.

The major types of output of the FREQ analysis are listed below:

- Freeway travel time (vehicle- and passenger-hours).
- Ramp and freeway delays (vehicle- and passenger-hours).
- Total travel time (vehicle- and passenger-hours).
- Total travel distance (vehicle- and passenger-kilometers (miles)).
- Speed and density contour maps.
- Average speeds.
- Fuel consumption.
- Vehicle emissions by pollutant type.
- Optimized ramp metering rates.

CORFLO

CORFLO is an FHWA-sponsored package of macroscopic, analytical, deterministic simulation models that allows the analyst to evaluate traffic operations on a freeway, a freeway corridor, or an entire roadway network. CORFLO consists of a freeway simulation model, FREFLO, an arterial street analysis tool, NETFLO, and a user-equilibrium traffic assignment program, TRAFFIC. These programs have a common coding format that allows a unified, interactive analysis of combined freeway-arterial street operations.

The freeway component, FREFLO, is capable of evaluating freeway-to-freeway interchanges, or even an entire freeway network. The program is capable of simulating ramp metering impacts on operations, but is not capable of optimizing the metering rates. Temporary lane blockages and HOV treatments can also be evaluated using the FREFLO program.[15,17]

Data input requirements for FREFLO are similar to those for FREQ. These requirements are listed below:

- Segment length.
- Number of travel lanes for regular use and HOV operations.
- Capacity.
- Free-flow speed.
- Ramp configuration.
- Volumes entering at the upstream segment and at on-ramps.
- Traffic volume exiting percentages at off-ramps.
- Percentage of volumes which are trucks or carpools.

The measures-of-effectiveness attainable from FREFLO are as follows:

- Travel distance measures (vehicle and person trips, vehicle- and person-kilometers [miles] traveled).
- Travel time measures (vehicle- and person-minutes).
- Average speed measures (vehicle- and person-kilometers per hour [miles per hour]).
- Space mean speeds by vehicle type and lane type.
- Lane density by vehicle type and lane type.

QUEWZ-92

QUEWZ-92 (Queue and User Cost Evaluation of Work Zones) is a simple macroscopic, analytical, deterministic simulation program designed to evaluate the traffic impacts and additional road user costs of freeway work zone lane closures. The program can also determine acceptable times of the day when lane closures can be allowed without causing freeway queues to become too extensive.[15,18]

QUEWZ-92 relies on simplistic assumptions about the freeway segment being analyzed, treating the approach as a basic freeway segment. The data requirements of the program are listed below:

- Configuration of the work zone (how many lanes are open, how many lanes are normally available, how long is the work zone section).
- The schedule of the lane closure activities.
- Hourly freeway traffic volumes approaching the lane closure.

The output obtained from QUEWZ-92 consists of hourly and cumulative estimates of the measures listed below:

- Average speed through the work zone.
- Average queue length if one exists.
- Traffic volumes diverted because of excessive queuing.
- Additional road user costs.

Microscopic Freeway Simulation Models

In cases where macroscopic models do not provide the measures needed to properly analyze a freeway situation, or the assumptions about traffic behavior inherent in the macroscopic models do not represent the condition being evaluated, it may be necessary to utilize a microscopic freeway simulation model for the analysis. Generally speaking, such models are extremely data intensive and time-consuming to set up, debug, and use in an analysis. However, they are very powerful tools for assessing the impacts of more subtle changes in freeway geometrics and for evaluating complicated freeway sections such as at weaving areas with unusual geometrics.

There are two main microscopic freeway simulation models available at the present time. These include FRESIM, an FHWA-sponsored model that is designed to fit within the TRAF system of computer models that FHWA has developed, and INTEGRATION, a proprietary model developed in Canada that links the freeway and arterial street systems together in a single modeling structure. A third model, INTRAS, was also developed under FHWA sponsorship and has been used in past microscopic analyses of freeway operations. However, the more recent FRESIM model is intended to replace INTRAS. Consequently, that model is not discussed in detail.

FRESIM

FRESIM is a microscopic, analytical, stochastic freeway simulation model. FRESIM is capable of simulating freeway mainlanes, ramps, freeway-to-freeway connectors, variations in grade, horizontal curvature and superelevation, lane additions and drops, temporary lane blockages, acceleration or deceleration lanes, and auxiliary lanes. The model can also simulate freeway surveillance via loop detectors, one of three incident detection algorithms based on the loop detector data, and ramp metering operations.(19) However, the model is not capable of optimizing these metering rates. Furthermore, the user has the ability to control very detailed driver characteristics such as the parameters of the lane-changing algorithm or the aggressiveness of the driving population (which affects the acceleration and deceleration rates and gap lengths that will be acceptable to drivers).

FRESIM requires extensive input data in order to fully analyze a given freeway section. Fortunately, default values are provided for many of the input requirements. However, the analyst should understand what these default values represent and be able to adjust them to local conditions if warranted. The following is a list of the data that can be entered into FRESIM on a segment-by-segment basis:

- Segment length and type (mainlane or ramp).
- Number of through and auxiliary lanes.
- Length of auxiliary lanes.
- Grades and superelevation.
- Pavement condition (dry, wet, asphalt, concrete).
- Free-flow speed.
- Average queue discharge headway.
- Lanes that are restricted to trucks.
- Turning/exiting percentages.
- Loop detector locations and characteristics.
- Incident characteristics (effect of lane blockage on capacity, effect of rubbernecking on capacity, duration of incidents).

- Location of lane additions or drops.

- Ramp metering settings and operating type (fixed, demand/capacity, speed control, gap acceptance).

- Traffic volumes entering and exiting the section.

- Car-following sensitivity factors.

- Pavement friction coefficients.

- Lane-changing characteristics (rates of compliance to warning signs, acceptable gap sizes, speed of lane change, acceptable acceleration rates).

- Operating characteristics by vehicle type.

Categories of output statistics computed by FRESIM for each segment and for the entire section include the following:

- Vehicles discharged from each segment.

- Vehicles making turning/exiting maneuvers.

- Average delay (actual travel time minus free-flow travel time) per vehicle.

- Average time spent moving.

- Average speed.

- Number of lane changes.

- Total travel distance (vehicle-kilometers [vehicle-miles]).

- Volume.

- Density.

- Speed.

- Vehicle emissions.

INTEGRATION

INTEGRATION is also a microscopic, analytical, stochastic traffic simulation model. The major difference between INTEGRATION and FRESIM is that the former includes dynamic routing capabilities that can change the intended trip path of vehicles as they progress through the network, depending on current estimates of travel time on the available paths. The program developers see this model as a way of evaluating the effect of advanced technologies (particularly advanced traffic management systems and advanced traveler information systems) upon traffic operations in urban areas. The program has been tested on networks in both the United States and Canada, with favorable results.[20,21]

Because the program models both freeway and arterial street segments within the analysis area, data requirements are fairly large. However, specific geometric details such as grades, superelevation, and pavement conditions are not modeled explicitly. Specific data items needed are listed below:

- Segment length.

- Number of “effective” through lanes.

- Saturation flow rate per lane.

- Free-flow speed.

- Traffic signal characteristics for ramp meters and signalized intersections.

- Loop detector locations and characteristics.

- Incident characteristics (effect of lane blockage on capacity, effect of rubbernecking on capacity, duration of incidents).

- Zonal traffic origin-destination tables for each time period (work is underway to build these synthetically from freeway and ramp volumes).

The output of the INTEGRATION model includes the following categories of statistics:

- Trip times for each origin-destination pair (total and per vehicle).
- Total trips entering the network.
- Speeds on each segment.
- Volume-to-capacity ratio for each segment.
- Trip times on each segment (total and per vehicle).
- Number of stops.
- Queue sizes.
- Fuel consumption.
- Vehicle emissions.

Strengths and Weaknesses of the Available Models

Table 2-7 summarizes the strengths and weaknesses of each of the freeway simulation/optimization models discussed in this chapter. Generally speaking, the microscopic models offer more detailed analyses, but at the cost of more extensive data requirements. The inability to model freeway-to-freeway connectors is the major limitation of FREQ, whereas the FREFLO portion of the CORFLO computer package does not collect environmental statistics on the freeway segments that are evaluated.

QUEWZ-92 is a special-use tool appropriate only for the evaluation of alternative work zone lane closure alternatives. FRESIM does not offer the ability to model HOV lanes, nor can the influence of reduced lane widths be modeled. Finally, despite the microscopic analysis approach utilized by INTEGRATION, the model is not designed to offer detailed operational analyses of freeway geometrics. Rather, the model focuses attention on how operational control and driver information influence freeway and arterial street traffic conditions.

FIELD MEASUREMENTS

One way to quantify the magnitude of operational problems on freeways is through field studies. The following two types of field studies can be used to provide useful insight in identifying problem locations on a freeway and to identify methods for improving operations on the freeway.

Travel Time and Delay Studies

Travel time and delay studies can be used quantitatively for the following purposes, which can help identify and equate operational problems and solutions in a freeway management system:[22]

- Determining the efficiency of a route with respect to its ability to carry traffic, and relative to other routes, through the use of sufficiency ratings or congestion indices.
- Providing input to capacity analysis of roadway segments.
- Identifying problem locations as indicated by delay.

Table 2-7. Strengths and Weaknesses of Freeway Traffic Simulation/Optimization Models. [12]

	Macroscopic Models			Microscopic Models	
	FREQ	**CORFLO**	**QUEWZ-92**	**FRESIM**	**INTEGRATION**
Strengths	Widespread validation Easy to use Can optimize ramp metering rates	Can explicitly model freeway-arterial street interface Can simulate freeway-to-freeway connectors	Simple to use Tailored to work zone lane closure analysis Computes road user costs directly	Detailed analysis of geometrics are possible Can configure parameters to local driver and vehicle characteristics Can simulate freeway-to-freeway connectors	Explicitly models freeway-arterial street interface Can dynamically route vehicles to simulate real-time motorist information Can simulate freeway-to-freeway connectors
Weaknesses	Analysis limited to one direction of a single freeway Does not model freeway-to-freeway connectors	FREFLO does not provide fuel consumption or vehicle emission statistics	Does not evaluate restricted lane widths only Applications limited to work zone analyses	Does not model HOV lanes Does not evaluate impact of reduced lane widths Extensive geometric data requirements (curvature, superelevation rates, grade)	Detailed vehicle interactions and lane-changing behavior not explicitly modeled Extensive data requirements (i.e., zonal origin-destination data)

Source: Adapted from Reference 11.

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- Providing input to transportation planning models, trip assignment models, and route diversion models.
- Providing input to economic analyses of alternatives.
- Generating travel time contour maps.
- Providing input to studies that evaluate trends in efficiency and level of service over time.

There are several techniques available that can be used to conduct travel time and delay studies, including the following:

- Test-car runs.
- License-plate observations.
- Toll-road electronic payment/automatic vehicle identification cards.
- Observation of vehicles from vantage points.

The reader is referred to ITE's *Manual of Traffic Engineering Studies* for specific details on how to perform travel time and delay studies.[22]

Origin/Destination Volume Studies

In a number of situations, simply knowing the number of vehicles at various locations is not sufficient to assess travel demands and patterns on the freeway system. Knowing where vehicles are coming from and where they are going is essential in many freeway applications. For example, simply counting the number of vehicles entering and exiting a certain ramp on the freeway does not provide the type of information that allows alternative routes and diversion strategies to be adequately planned and analyzed. For these applications, it is important to know how many vehicles entering the freeway at a specific ramp exit at another ramp downstream. This type of information can be collected using origin/destination studies. Situations where origin/ destination information would be useful include the following:

- Freeway interchanges.
- Weaving areas.
- Traffic at major activity centers.
- Regional planning studies.

There are a number of techniques that can be used to collect origin/destination information from travelers, including the following:

- Light-on studies.
- License-plate studies.
- Post-card studies.
- Interview studies.

The reader is referred to ITE's *Manual of Traffic Engineering Studies* for specific details on how to use these techniques to collect origin/destination information.[23]

2.4 LESSONS LEARNED

SYSTEM MAINTENANCE

System maintenance should be considered at all levels of the planning, design, and implementation process of the freeway management system. Without proper maintenance, the effectiveness of the system is significantly reduced. Equipment failures can lead to vehicle crashes that not only affect the overall level of congestion on the freeway system, but also expose the agency to liability concerns if the malfunction is not corrected in a timely manner. Inadequate maintenance also affects the ability of the control system to perform at an optimal level. Furthermore, inadequate maintenance can also reduce the service life of system components, leading to higher overall life-cycle costs in the system.

To be effective, a maintenance program must have the following elements:[(5)]

- Adequate staff of well-trained personnel.
- Up-to-date documentation on all system components.
- Adequate budget for spare parts and expendables.
- A long-term commitment on the part of the agency to utilize the system to its full potential including keeping the system "up-to-date" on a continual basis.

Ways in which maintenance can be supported during the design of the system include the following:[(5)]

- Specify modular components so that components can be swapped in the field and repairs handled in the shop, where they will not interfere with field operations.
- Specify environmentally-hardened components that meet recognized standards.
- Use standardized equipment makes and models to reduce the number of spare parts and different maintenance techniques.
- Specify self-diagnostic capabilities.
- Specify transient protection (e.g., power surges and lightning) and equipment grounding.
- Locate components to minimize vulnerability to damage (e.g., knockdowns of field equipment).
- Provide for safe and convenient access to the hardware for maintenance personnel (e.g., will traffic lanes need to be closed when variable message signs are being repaired or relamped, etc.).

Types of Maintenance Requirements

The maintenance of hardware elements in a system traditionally falls under the maintenance heading. In fact, there are three major types of maintenance activities that are performed in a freeway management system:[(3)]

- Functional.
- Hardware.
- Software.

Functional

Traffic conditions, travel patterns, land-use patterns, and the political environment in many communities are continuously changing. Therefore, the control strategies and functions performed by a freeway management system need to be continuously reviewed, revised, and updated to keep pace with the change in operating environments. The types of activities included in this maintenance category include the following:

- Relocating or repositioning system detectors and surveillance equipment.
- Reconfiguring subsystems.

- Expanding the system to cover a greater geographic area.
- Expanding the system to provide additional functionality.
- Changing detection and/or control technologies to keep pace with technological changes.
- Updating or improving control strategies.
- Updating, revising, and improving incident response plans.

Hardware

Hardware maintenance can be divided into three categories, each of which must be planned for in designing the system and accounted for in the preparation of annual operating budgets:(3)

- Remedial.
- Preventative.
- Modification.

Remedial maintenance refers to the type of maintenance activities performed to correct or replace malfunctioning or failed equipment. Because this type of maintenance activity includes maintenance performed on an emergency basis, it usually commands the highest priority.

Preventative maintenance refers to those activities that are performed to keep equipment failures from occurring. Examples of the types of activities performed in this category include the following:

- Relamping and cleaning of variable message signs, ramp meters, etc.
- Inspection of poles, foundations, and wiring.
- Re-tuning of detectors.

Good preventative maintenance begins with and depends upon proper installation, and proper installation requires thorough inspection and testing throughout the design and installation process.(5) System operators and maintainers should participate in the inspection process and acceptance testing. Such involvement is an excellent source of informal training and fosters a sense of ownership of the new system, essential ingredients to developing an effective maintenance program.

System modification or reconstruction is often included as a maintenance item because, in many cases, maintenance personnel are used to implement the changes. Generally, system modification or reconstruction becomes necessary when the following situations occur:

- A manufacturing or design flaw is identified.
- Changes are needed to improve the performance characteristics of the equipment.

Good maintenance practices require that hardware functions and specifications be well documented. Table 2-8 lists some of the items that should be included in the documentation of the hardware to support hardware maintenance activities.

Software

The maintenance of software is often overlooked in freeway management systems. Most computer software undergoes (or should undergo) complete and extensive testing and debugging before it is accepted by the operating agency; however, because of the multitude of different possible computational combinations and operational circumstances, it is impossible to discover every flaw or bug during the testing and acceptance period. Additionally, as operators gain experience with the system, they often discover additional procedures or features that could improve operations. Agencies need to have a mechanism for making corrections and modifications to software after the initial warranty period has expired.

Operating agencies must be committed to providing adequate funding and staffing resources to effectively maintain software. Traditionally, two mechanisms exist for maintaining system software:

- In-house.
- Maintenance contract.

If an agency elects to maintain the software system in-house, it must provide a sufficient number of qualified staff to perform these functions. If software maintenance is to be performed in-house, most agencies devote one or more full-time positions solely to developing and maintaining system software. Many agencies use engineering staff that also happen to have the requisite software skills to maintain their system software.[22] Because highly qualified programmers and software engineers are in great demand, agencies may find it difficult to attract and retain qualified programmers. In these situations, an agency can contract its software maintenance. Under this type of agreement, the contractor can correct any latent bugs and make minor enhancements based on the experience of the operations personnel.[5] Oftentimes, software maintenance can be accomplished over a phone link and modem.

One way software maintenance can be facilitated at the design and implementation phase of the system is through the adoption of coding standards.[24] Coding standards should be adopted prior to beginning work on the system. The purpose of the coding standards is to ensure that programmers use the same style and format when developing their software. The coding standards are to be used by every programmer working on the system. Coding standards are important because many routines written by one programmer may be used by other programmers in developing their routines. Furthermore, since all the programmers use the same style, the overall package has a consistent “look and feel” about it. Coding standards also lead to better documentation and enforce good programming practices. All of these aspects of coding standards can save considerable time in the initial programming of the system, plus making it easier for unfamiliar programmers to make modifications and enhancements after the original programmers are no longer working on the system.

Another way software maintenance can be fostered in the initial design and implementation phase is through good documentation.[24] Documentation is one of the most valuable and yet variable deliverables associated with any software development effort. It can be very difficult to obtain the necessary level of detail when project funds run short and the programmers are disinterested in the documentation effort. Documentation standards should be established as a guide for both in-house and contract programmers. Table 2-9 lists some of the elements that should be submitted as part of the software documentation.

Table 2-8. Items to be Included in Hardware Documentation. [5]

- General description — General description of the component.
- Theory of operation — Detailed description of the operation of the component.
- Normal operating procedure — Description of the procedure for the routine operations of the component, including normal operating characteristics, voltage levels, and waveforms measured at test points.
- Parts list — Listing and identification of various parts of the component.
- Schematic drawings — Complete and accurate electronic schematics that specify component interconnections, component values, voltage levels, and component locations.
- Drawings of cabinet layouts, wiring diagrams, and lightning protection. Wiring and cabling lists describing interconnection of all plugs, chassis, and other components. In addition, they must identify wire type, size, and color code. They should also identify connector type, pin numbers or terminal strip numbers, and test points.
- Mechanical details — Equipment layouts, physical dimensions, access points, and test point locations.
- Power supply cabling — A description of the power supply, the power distribution system, and the characteristics of the power supply. The power source and all protective devices in the power system must also be described.
- Environmental controls — Power, heating, cooling, and humidifying.
- Descriptions of all preventative maintenance activities for all system components (e.g., computer, communications units, controllers, etc.). This information must include both the procedures and the frequency with which these activities are to be performed.
- Description of emergency maintenance trouble-shooting and diagnostic procedures. This documentation begins with a list of symptoms and proceeds through a series of analyses until the most common cause of the symptom is identified.
- A recommended set of spares and test equipment to be purchased by the local agency or supplied under the contract.
- Instructions on the use of computer diagnostic software furnished by the computer manufacturers for evaluation of the computer and peripheral equipment operation.

MARKETING SYSTEMS

The importance of marketing freeway management systems should not be overlooked. Public acceptance and cooperation are essential to achieving the goals and objectives of a freeway management system. Without public acceptance and support, an agency will find it difficult, if not impossible, to maintain a secure and stable political support and funding base for operating and maintaining a freeway management system. Marketing the system — highlighting what it does and how it will directly benefit the traveling public — is crucial to building public support and acceptance.

Target Audiences

Transportation agencies should develop a plan for marketing their freeway management system. The market plan should address how the system will be marketed to the following four target audiences:[26]

- The operating agency itself.
- Other agencies that are affected by the system.
- Important public and elected officials.
- The general public and users of the system.

Operating Agency

A freeway management system will not be successful or effective without strong support from those individuals who will be funding, operating, and maintaining the system. Decision-makers within the agency need to be aware of the costs and benefits of the system and where the freeway management system fits into the overall future of the organization as a whole.[25] Often, these decision-makers can be converted to being champions for the system. Marketing strategies need to be employed internally within an organization so that champions can be identified, and pride and ownership in the system can be developed.

Affected Agencies

The marketing plan should also include those agencies that are not directly responsible for but directly affected by a freeway management system. Examples of affected agencies that should be addressed in a marketing campaign include the following:

- Law enforcement agencies.
- Emergency service providers.
- Local and regional transportation agencies.
- Transit providers.

These agencies are concerned primarily with how the system will affect their operations. Law enforcement agencies will want to know whether the system will require additional enforcement emphasis, reduce their enforcement burden, or have no effect on their service. Emergency service providers will want to know whether the system will enhance or hinder their response time and access to facilities. Local transportation agencies and transit providers will want to know whether the system will increase or decrease the demands on their systems.[25] A marketing strategy should be developed that addresses these concerns.

Table 2-9. Elements of Software Documentation. [5]

- Source listings of the programs. These listings must be well-annotated to describe input/output, variables, purpose of subroutines, other lower level subroutines called.
- Flowcharts or HIPO's indicating the processing steps taken by every functional grouping of instructions. The flowcharts should be keyed to the software listings using instruction addresses and subroutine names. Each flowchart must be preceded by a functional description of the subroutine's purpose, storage requirements, and execution time.
- Descriptive discussion of each routine and subroutine in the application program and the database update program.
- Lists that define every variable used in the software. These definitions must include variable name, its purpose, structure, and a list of the routines in which it is used.
- Maps showing the layouts of data and programs within the computers and storage facilities.
- A summary of system timing, including average execution times of all routines and average execution times of each priority level.
- All computer inputs and outputs, including addresses, command structures, data transfer rates, source/destination equipment, and printer and CRT formats.
- Backup and disk-resident copies of the source programs, along with hard-copy listings.

Elected Officials

Elected officials are primarily interested in cost-effective systems that support the goals of their jurisdiction or district. They are interested in secondary effects of technologically advanced systems, such as the effects on the environment, privacy, and land use. They are also interested in the views of constituents, and whether the systems will be perceived as having a positive or negative impact on their constituency. To enable the system to be effectively marketed to elected officials, the information about the system should be concise and easy to understand.[25]

General Public

The ultimate success of any advanced transportation system depends on the perceptions of the users of the system. If the general public does not see benefits that outweigh any perceived costs or disadvantages, the system will not be successful, even if there are positive benefits being achieved by the system. It is critical that public agencies remember that the ultimate customers of the system are the people who will be traveling on the freeway. The marketing campaign should illustrate how these travelers will directly benefit from the system.[25]

Marketing Strategies

There are numerous methods available for marketing freeway management systems. Determining which is the most appropriate and effective method depends on the target. Strategies commonly employed to market freeway management systems included the following:

- Logos.
- Brochures.
- Slide shows/videos.
- Meetings with agency boards, citizen advisory committees, and operating staffs.
- Meetings with community groups, professional organizations, high schools, college groups, employers, etc.
- Workshops and meetings with City Council members, public works departments, and transportation advisory committees.
- Press releases and media events.
- Displays and billboards.
- Newsletters and fact sheets.
- Internet home pages.
- Tours and site visits.

Table 2-10 lists some of the key items to be remembered and included in developing a marketing plan for freeway management systems.

Table 2-10. Guidelines for Developing a Marketing Plan for Freeway Management Systems. [27]

- While it is critical and necessary to involve members of operating and affected agencies early in the marketing of the system, be careful about involving the public too early. Very early involvement of the public can lead to high and unrealistic expectations.

- Identify the target audiences in the beginning stages of the program. Have a clear understanding of what it is the audience is supposed to get from the media campaign and how they are likely to respond to having knowledge of the system.

- A good marketing plan supports the strategic plan for project implementation. The marketing plan should support the goals and expectations of the project and clearly convey them to the target audiences.

- Do not overexaggerate the impact the system will have on the transportation system. Encouraging high expectations may lead to disappointment and the immediate loss of public trust. Moderate goals are most appropriate when implementing new technologies. Do not let the public believe that the system will solve all their transportation problems.

- Keep communications as open and honest as possible throughout the program implementation. If something goes wrong, let the public know what happened in terms they can understand. Chances are the public will appreciate the explanation and understand the circumstances, and will be more likely to give you the benefit of the doubt if other problems arise.

- If you do not have the qualified staff to develop a marketing plan, hire an outside firm that is familiar with transportation projects to assist you. Human behavior is an unpredictable phenomenon. It may be beneficial to consult with individuals who are experienced with dealing with the public in formulating your marketing plan.

- When promoting the system, whether verbally, visually, or in written form, use terms that are understandable and tangible to the general public. Highlight the positive aspects of the system. For example, indicate that the ramp metering system is intended to maintain speed above 40 mph on the freeway. Take car to mak the wording direct so that it cannot be misinterpreted easily.

- Have something to show. A tangible product is easier to relate to than a drawing or report. The public will be able to see how it works and the benefits that can be derived. They want to see it, not just hear about it.

- Throughout the implementation of the system, survey user needs to determine whether the needs of the public are being met. If not, adjust the program accordingly. Monitoring of user acceptance and attitudes should continue after the system has been implemented to ensure that it is working as planned.

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APPENDIX A: SUBCHAPTER G - ENGINEERING AND TRAFFIC OPERATIONS

PART 655 - TRAFFIC OPERATIONS

Subpart D - Traffic Surveillance and Control

Subpart E - [Reserved]

Authority: 23 U.S.C. 101(a), 104, 105, 109(d), 114(a), 135, 217, 307, 315, and 402(a); 23 CFR 1.32 and 1204.4; and 48 CFR 1.48(b).

Source: 49 FR 8436, Mar. 7, 1984, unless otherwise noted.

Sec. 655.401 Purpose.

The purpose of this regulation is to provide policies and procedures relating to Federal-aid requirements of traffic surveillance and control system projects.

Sec. 655.403 Traffic surveillance and control systems.

(a) A traffic surveillance and control system is an array of human, institutional, hardware and software components designed to monitor and control traffic, and to manage transportation on streets and highways and thereby improve transportation performance, safety, and fuel efficiency.

(b) Systems may have various degrees of sophistication. Examples include, but are not limited to, the following systems: traffic signal control, freeway surveillance and control, and highway advisory radio, reversible lane control, tunnel and bridge control, adverse weather advisory, remote control of movable bridges, and priority lane control.

(c) Systems start-up is the process necessary to assure the surveillance and control project operates effectively. The start-up process is accomplished in a limited time period immediately after the system is functioning and consists of activities to achieve optimal performance. These activities include evaluation of the hardware, software and system performance on traffic; completion and updating of basic data needed to operate the system; and any modifications or corrections needed to improve system performance.

Sec. 655.405 Policy.

Implementation and efficient utilization of traffic surveillance and control systems are essential to optimize transportation systems efficiency, fuel conservation, safety, and environmental quality.

Sec. 655.407 Eligibility.

Traffic surveillance and control system projects are an integral part of Federal-aid highway construction and all phases of these projects are eligible for funding with appropriate Federal-aid highway funds. The degree of sophistication of any system must be in scale with needs and with the availability of personnel and budget resources to operate and maintain the system.

Sec.655.409 Traffic engineering analysis.

Traffic surveillance and control system projects shall be based on a traffic engineering analysis. The analysis should be on a scale commensurate with the project scope. The basic elements of the analysis are:

(a) Preliminary analysis. The Preliminary Traffic Engineering Analysis should determine: The area to be controlled; transportation characteristics; objectives of the system; existing systems resources (including communications); existing personnel and budget resources for the maintenance and operations of the system.

(b) Alternative systems analysis. Alternative systems should be analyzed as applicable. For the alternatives considered, the analysis should encompass incremental initial costs; required maintenance and operating budget and personnel resources; and expected benefits. Improved use of existing resources, as applicable, should be considered also.

(c) Procurement and system start-up analysis. Procurement and system start-up methods should be considered in the analysis. Federal-aid laws, regulations, policies, and procedures provide considerable flexibility to accommodate the special needs of systems procurement.

(d) Special features analysis. Unique or special features including special components and functions (such as emergency vehicle priority control, redundant hardware, closed circuit television, etc.) should be specifically evaluated in relation to the objectives of the system and incremental initial costs, operating costs, and resource requirements.

(e) Analysis of laws and ordinances. Existing traffic laws, ordinances, and regulations relevant to the effective operation of the proposed system shall be reviewed to ensure compatibility.

(f) Operations plan. The final element in the traffic engineering analysis shall be an operations plan. It shall include needed legislation, systems design, procurement methods, construction management procedures including acceptance testing, system start-up plan, operation and maintenance plan. It shall include necessary institutional arrangements and the dedication of needed personnel and budget resources required for the proposed system.

(Approved by the Office of Management and Budget under control number 2125-0512)

Sec. 655.411 Project administration.

(a) Prior to authorization of Federal-aid highway funds for construction, there should be a commitment to the operations plan (see Sec.655.409 (f)).

(b) The plans, specifications, and estimates submittal shall include a total system acceptance plan.

(c) Project approval actions are delegated to the Division Administrator. Approval actions for traffic surveillance and control system projects costing over $1,000,000 are subject to review by the Regional Administrator prior to approval of plans, specifications, and estimates.

(d) System start-up is an integral part of a surveillance and control project.

(1) Costs for system start-up, over and above those attributable to routine maintenance and operation, are eligible for Federal-aid funding.

(2) Final project acceptance should not occur until after completion of the start-up phase.

1. ELIGIBILITY OF POLICE ENFORCEMENT AND SURVEILLANCE ACTIVITIES IN TRAFFIC MANAGEMENT DURING MAJOR HIGHWAY RECONSTRUCTION (23 CFR 655.403)

a. In December 1986, the Washington Headquarters office provided guidance on traffic management actions that may be eligible for Federal-aid (FA) funding during major highway reconstruction. See NS 23 CFR 655A, paragraph 1, for activities discussed involving police surveillance and enforcement necessary to mitigate congestion and/or improve the safety of motorists and workers within the highway corridor. General guidance for these particular activities are contained in 23 CFR 655A, Traffic Operations Improvement Programs (TOPICS), and 23 CFR 655D, Traffic Surveillance and Control.

b. Police surveillance and enforcement activities are often essential to safety and efficient traffic operations during major highway reconstruction. To avoid any possible misunderstanding, this supplement is intended to further define FHWA's policy regarding the eligibility of FA funding. The following criteria are provided.

(1) Police enforcement and surveillance activities that normally would be expected in and around highway problem areas requiring management of traffic are not eligible for Federal-aid funding.

(2) On projects where normal police enforcement and surveillance practices within construction zones may not be adequate, the traffic management plan should address the appropriate extra police activities required.

(3) The primary purpose of extra police enforcement and surveillance activities must be to control traffic in order to maintain safe travel and efficient operations throughout the highway corridor.

(4) The State and FHWA division office must agree that extra police activities would be an effective and appropriate means to maintain safe and efficient travel and adequately protect workers. The traffic management plan should set forth the justification and details of the proposed activities. The costs of extra police enforcement and surveillance activities documented in the approved traffic management plan are eligible for Federal-aid reimbursement.

(5) Extra police activities should not be limited to passive monitoring and could also include appropriate positive guidance of traffic and enforcement of regulations.

2. <u>IMPLEMENTATION PLAN GUIDANCE (23 CFR 655.409)</u>

a. An Operations Plan is the final element of a traffic engineering analysis according to 23 Code of Federal Regulations (CFR) 655.409(f). Since an operations plan covers such a wide range of activities both prior to and after construction such as system design, procurement, personnel, operations and maintenance, the name **"Operations Plan"** is being changed to **"Implementation Plan"** to more accurately reflect its contents. The name change is being made in the CFR and will be used throughout the remainder of this guidance. The following is issued to provide State and other agencies, which are utilizing Federal funds, guidance traffic control systems, ensure adequate planning by the sponsoring agency, and commit the sponsoring agency to use Federal funds efficiently.

b. Implementation plans are **required** both for new traffic control systems, as well as expansions of existing systems, which use Federal funds and are encouraged for those systems which do not use Federal funds. Traffic control systems are defined as systems which contain elements to monitor, guide, control, and/or process forms of traffic along the surface streets and/or freeways. Implementation plans can be for individual projects (i.e. stand-alone), or as a part of a larger system. For expansion projects, if an implementation plan had not previously been prepared, one **must be prepared** and include the expansion as well. The plan should be completed prior to authorization of construction. This will ensure that the system is designed, built, operated, and maintained so that it accomplishes its purpose in the most efficient manner possible, considering performance, cost, and schedule. Too often in the past, plans were developed after the system was operational and did not include the design approach and other information which should have previously been addressed and documented.

c. An implementation plan need not be a legal document; however, if it is to be effective, it must carry the weight of a memorandum of agreement (understanding) and should be signed by the head of the operating agency, State highway official, and Federal Highway Division Administrator, or their designates.

d. Before the guidance is explained, a few words need to be mentioned in regards to conformity and the planning process. Transportation Improvement Programs (TIPs) and Statewide Improvement Plans (STIPs) are area wide programs, while implementation plans are project specific. Hence, projects for which implementation plans are being developed have already been approved in the related TIPs and STIPs and the related conformity and management systems issues have been addressed. In non-attainment areas, the traffic control system being proposed for implementation must be consistent with what was proposed in a conforming transportation plan. If the traffic control system deviates from that design concept and scope, it may trigger a new conformity determination.

e. The following sections correspond to the implementation plan **requirements** listed in 23 CFR 655.409 (f) and provide discussion for each. The level of detail of the implementation plan will depend on the type and size of the system. Since some of the items required in an implementation plan will have been covered in other contract documents and other elements of the traffic engineering analysis (23 CFR 655.409), these items may be summarized and referenced in the plan.

(1) Legislation. This section includes the legal considerations, if any, for the project. **Existing** laws, regulations, and policies affecting the project need to be reviewed and assessed. In addition, State or local legislative changes such as authority for metering and HOV facilities, enforcement authority, and roadway clearance policies should be addressed if applicable to the project. Also, the operating procedures for the system may need to be defined to be sure that there are no potential legal problems.

(2) System design. A system contains elements which may monitor, guide, control, and/or process forms of traffic along the surface streets and/or freeways. System design consists of taking the recommendations from the planning phase, converting those needs into hardware/software requirements, and formulating the equipment needs into contract documents. The system design may be based on off-the-shelf, customized, or experimental technologies. Actual systems vary greatly in practice. For example, a system may contain several like devices such as

an expansion of a traffic signal system, or it may consist of a traffic management center and its associated hardware/software. For the purpose of this guidance, system operation and maintenance must be the responsibility of a public agency. The conduct of the system operation and maintenance may be carried out either by (1) the public agency (2) contract, or (3) franchise operation. An implementation plan should include the following elements for the system design portion:

(a) System Designer: Depending upon the complexity of the system and in-house expertise, consultant services are usually needed to design a system. The designer needs to be identified in order to resolve any conflicts.

(b) System Design Life: The functional operating life of the system should be identified. The design life and the costs can be used to perform an economic analysis to identify the return on their investment. The system design life will be helpful for a Life-Cycle Cost Analysis (LCCA).

(c) System Coverage: This should address the area that the system covers. The coverage related to the future expansibility of the system should also be addressed. Ideally, the expansibility should be commensurate with the system's design life.

(d) System Design and Operations/Maintenance Philosophies: System operations philosophies have a significant impact on the system design. For example, system operations centers that are staffed only during rush hours do not require kitchen and/or shower facilities. However, operations centers that are staffed during the majority of the day, especially during special events and inclement weather, do require extra amenities. Ideally, system operations and maintenance functions, as well as facilities, should be close to each other to facilitate coordination.

(e) System Architecture: A discussion of the overall system architecture (i.e. central, distributed, or hybrid) should be addressed.

(f) Integration with Other Functions: Ideally, consideration should be given to integrating a traffic control system with other systems to provide for data base exchange and other strategies so that the entire metropolitan area is covered and coordinated.

(g) System Components and Functions: Hardware components needed to perform system functions such as, surveillance, control, and coordination should be identified.

(h) Communication Subsystem Design Approach: Typically, the communication portion of the system, because of the necessary redundancy, represents a large portion of the system budget. Great care should be given to the subsystem design approach. An economic analysis of the design approach, should be a key consideration.

(i) Traffic Operations Center Design Features: The design of a control center is largely dependent upon the agency's operating philosophies (time of operation, special event operation, tour accessibility; media facilities etc.) The size of the system will also affect the design (As an example, agencies utilizing large numbers of closed circuit television (CCTV) will need more space for wall monitors.)

(j) Project Phasing/Scheduling: A formalized tracking system should be used to manage the project. Many common methods utilize critical path analysis. Depending upon the approach used, these management tools don't necessarily have to be developed during the design phase but should be in place prior to any construction scheduling.

(k) Design Review: The system design is reviewed and the problems and concerns are addressed and documented. (The system design should be checked for consistency with the statewide and metropolitan plans, if applicable.)

(3) <u>Procurement methods</u>. An important element of the implementation plan is the method used for procuring and implementing the system (23 CFR 172). Regardless of the method used, the implementation plan should include the following procurement related items: (1)Method, (2) Schedule, and (3)Funding. A brief description of common procurement methods follows:

(a) <u>Sole-Source</u> - a single manufacturer's specifications are openly used, or they serve as the basis for contract negotiations between the owner and the supplier. The contract is then awarded without competition. Sole-source contracts can be used in Federal-aid projects, but only if there has been a finding that it is more cost-effective than a competitive low-bid process. This method is most common for system expansions.

(b) <u>Engineer/Contractor (turn-key)</u> - an engineer prepares a single set of contract documents (i.e., plans, specifications, and estimates (PS&E) for the proposed system), the contract documents go through the procurement channels, and the contract is awarded to the lowest responsive bidder. The winning contractor is responsible for providing a complete and fully operational system, including furnishing and installing all hardware/software, system integration efforts, and training and documentation. This method is the traditional low-bid process. However, there may be some significant potential problems with this method as it relates to traffic control systems: No single contractor may process the necessary experience and qualifications to perform all of the work; administering multiple layers of subcontractors and suppliers is difficult; and the prime contractor may not have sufficient knowledge of some of the elements of a traffic control system to select appropriate or qualified subcontractors.

(c) Two-Step Engineer/Contractor - in the first step, the plans and functional specifications, along with a Request for Proposals (RFP), are submitted to contractors. The submitted proposals are evaluated and the qualified proposals go to the second step. In the second step, a formal request for bid is issued. From this point on, the standard bid/award process of the engineer/contractor approach is used.

(d) Systems Manager - instead of a single turn-key contract in which all of the work is outlined, several contracts for the various subsystems are prepared. The agency's normal procurement process is utilized to obtain the equipment, but the systems manager administers the contracts and is responsible for integrating the various subsystems into an operating system.

(e) Design/Build- this concept involves awarding a single contract to provide for both the design and construction of a project. For certain circumstances, design/build has the potential for improving the contracting process by allowing contractors the maximum flexibility in the selection of innovative designs, materials, and construction techniques. Under current statutes and regulations, the design/build concept is a viable option for Federal-aid highway projects, as long as the following **requirements** are met:

1 The contracts are awarded following competitive bidding procedures;

2 If a warranty requirement is included, the period of coverage should only be sufficient in length (i.e., 1 - 5 years) to allow defects in materials and workmanship to become evident. Ordinary wear and tear, damage caused by others, and routing service maintenance should remain the responsibility of the State; and

3 Federal-aid projects which provide for evaluation of either the design/build or warranty concepts must be approved, under Special Experimental Project No. 14 (SEP 14), by FHWA Headquarters Office of Engineering (HNG-22), prior to project approval.

(4) Construction management procedures. Procedures which will be used for the particular system should be specified in the implementation plan. Construction management procedures provide the necessary framework for coordinating construction and installation activities to ensure the system is built in accordance with the contract documents. Implementation plan construction management procedures that can be addressed include, but are not limited to:

(a) Division of Responsibilities (identifying who is involved and their associated responsibilities).

(b) Scheduling and establishing mileposts (developing a construction schedule to keep track of system installation). This will also ensure a mechanism for monitoring progress, cost, and quality assurance.

(c) Conflict Mitigation (developing a procedure or mechanism for resolving contract disputes).

(d) Coordination with other projects (defining project's relationship with other projects).

(5) System start-up plan. Integration is the "glue" that binds components together to form the system. Components are physically tied based on interfaces defined by the system architecture and tests are performed to verify and validate whether or not system requirements are met. Verification of a component or subsystem determines if the components or subsystems are interfaced as per design and are working properly. Validation consists of ensuring (through acceptance tests) that all interfaced components or subsystems meet system requirements. Software coding and database development are also important elements of this phase. The start-up process is typically performed in a limited time period immediately after system integration. A start-up plan is necessary to document the validation process (software and system evaluation). An implementation plan should include, but is not limited to, the following:

(a) Software acceptance tests (responsibilities of those involved, test procedures, equipment involved, test criteria, verification of specific software features, methods to correct errors, etc.);

(b) System acceptance tests (responsibilities of those involved, test procedures, equipment involved, test criteria, verification that system performs required functions, methods to correct errors, final acceptance, etc.);

(c) Partial acceptance (provisions for accepting a partially completed system);

(d) Documentation (detailed documentation pertaining to hardware and software should be discussed as well as references to operating manuals for the system);

(e) Transition from old to new control (procedures for transitioning from a previously functioning system to a system with new features and functions);

(f) Operational support and warranty period (provisions for initial or continuing operational support and a system warranty period). Federal regulations on guaranty and warranty clauses are defined in 23 CFR 635.413;

(g) Training (provided to system operators and maintenance technicians prior to system acceptance);

(h) Coordination with the media is very important and should be included in the system start-up plan. Public support is critical to the success and ongoing operations of the system.

(6) Operations and maintenance plan. Traffic control systems require active management to be effective, including periodic reassessment of the control strategies used. In order to have a system that is operated and maintained properly, there must be a staff and budget commitment by the operating agency. The resources required to effectively operate and maintain a traffic control system may represent a significant continuing investment, particularly if the agency responsible for the system is relatively small or is implementing a traffic control system for the first time. The process of defining system operations and maintenance activities during the preparation of the implementation plan can expose these issues and allow time for their resolution prior to system implementation. The operations and maintenance plan may include a section for evaluation and applicable maintenance policies:

(a) Evaluation. Federal-aid highway funds may be used for evaluation activities (23 CFR 655.403 (c) (Systems Start-Up); (23 U.S.C.307 (c) (1) (e) (State Planning and Research); 23 U.S.C. 133 (b)(6) (Surface Transportation Program); and 23 U.S.C. 103 (i) (8) (National Highway System). A comprehensive evaluation of a traffic control system determines if the system meets the goals and objectives established for it. A formal evaluation is recommended at appropriate stages. The evaluation should be completed as soon after the implementation of the system as possible, after traffic patterns have stabilized. Regular system re-evaluating should subsequently be planned every few years and should be executed by the operations and maintenance personnel. Key evaluation issues to be described in the implementation plan include:

1 The system evaluator (Preferably, this should be an independent third party, **not** the system installer.) The system evaluator should be selected prior to the implementation of the system in order to properly perform the evaluation.

2 The method of evaluation (This should also include time period for evaluation.)

3 The cost of evaluation.

(b) Maintenance Plans. Development of maintenance plans cannot be performed by designers alone. Maintenance persons must be consulted. In addition, a system may require a higher and more responsive degree of maintenance than an agency may be accustomed to. Some agencies may choose to use contract maintenance as opposed to in-house staff. Whatever method of maintenance is selected, the following implementation plan issues will help the operating agency to determine the necessary maintenance resources (budget and staff) :

1 Maintenance policies for preventative maintenance, system malfunctions (response times), etc. There should be a documentation of the policies, possibly as an attachment.

2 Formal maintenance management programs (software and hardware agreements with the developers). There should be a documentation of the programs, possibly as an attachment.

3 Initial inventory of spare parts and all necessary test equipment.

4 Training in providing limited maintenance to software and equipment.

(7) Institutional arrangements. Nearly all projects involve numerous organizations and multiple levels of government, all of which approach the project from various perspectives. However, the institutional aspects of a system are likely to be even more complex because of the additional governmental entities and organizations (e.g., FHWA, regional organizations, State and local governments, traffic engineering departments, MPOs, fire, police, transit, private sector groups, media utility companies, etc.) which are typically involved. The complex mix of governmental and private sector interests has the potential for difficulties: overlapping responsibilities, lack of understanding, and conflicting priorities and policies. To avoid these problems, it is important that close coordination be established during the early stages of planning. This will permit the various agencies to develop a better understanding of the system alternatives and the recommended system's features and functions; to identify overlapping responsibilities and determine which agency will take the lead in various areas; and to work harmoniously so that each agency can better fulfill its role. Developing a good, early working relationship with each involved organization and then maintaining this cooperation throughout the system process will help ensure that the system effectively meets the needs and expectations of each agency. An implementation plan should include, but is not limited to, the following institutional arrangement issues:

(a) A contact person/object liaison within each organization should be identified.

(b) Delineation of organizational responsibilities and the lead organization for the various elements of the system.

(c) Provisions for periodic project updates to be given to upper management to keep them informed.

(d) Utility arrangements.

(e) Written cooperative agreements for: personnel-sharing, cost-sharing, metering, traffic diversion, etc.

(f) Consideration should be given to the formation of an "Advisory Committee" which will meet to discuss and resolve system issues and to acquaint participants with the overall project goals, schedule, and work plan. All agencies involved in the project should be represented on this committee and should be involved throughout the entire project.

(8) Personnel and budget resources. Staffing for operations and maintenance of systems is a function of system complexity, hours of operation, and activities supported by the system. Ideally, staffing responsibility for

operating and maintaining the system should be integrated into the operating agency's existing organizational structure. It is understood that institutional agreements may need to be developed for personnel/cost-sharing purposes. The following personnel and budget items, as a minimum, should be addressed:

(a) Staffing plan (listing of the job functions supported by the system and the number of persons who fulfill those functions).

(b) If shifts are to be used, the number of persons and their functions per shift.

(c) Contract operations staff agreement (if used).

(d) Provisions for training new staff on the system.

(e) Sources of budgetary resources, including Federal, and their committed contributions.

(f) Estimates of annual expenses by category (operations, maintenance)

(g) The last page should have a section for the signatures of the head of the operating agency, head of the State highway agency, and FHWA Division Administrator or their designates. This concurrence ensures that the necessary agencies are committed to the implementation plan.