

NCHRP

SYNTHESIS 307

**NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM**

Systems Engineering Processes for Developing Traffic Signal Systems

A Synthesis of Highway Practice

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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**Systems Engineering Processes for Developing
Traffic Signal Systems**

A Synthesis of Highway Practice

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Highway Operations, Capacity, and Traffic Control

Research Sponsored by the American Association of State Highway and Transportation Officials
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WASHINGTON, D.C.
2003
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Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communication and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

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

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

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FOREWORD

*By Staff
Transportation
Research Board*

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, “Synthesis of Information Related to Highway Problems,” searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice*.

The synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

This report of the Transportation Research Board will be of interest to local, regional, state, and federal officials, as well as to other transportation professionals who work with them in the area of traffic engineering. This report presents a general discussion of the techniques employed in systems engineering, as well as techniques available to traffic systems engineers. The report identifies systems engineering methodologies used by practitioners for traffic signal systems, and gives an indication of the extent to which they are used.

Information was derived by means of a survey of state transportation agencies in combination with a literature review.

A panel of experts in the subject area guided the work of organizing and evaluating the collected data and reviewed the final synthesis report. A consultant was engaged to collect and synthesize the information and to write this report. Both the consultant and the members of the oversight panel are acknowledged on the title page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

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This study was managed by Donna Vlasak, Senior Program Officer, who worked with the consultant, the Topic Panel, and the Project 20-5 Committee in the development and review of the report. Assistance in project scope development was provided by Stephen F. Maher and Jon Williams, Managers, Synthesis Studies. Don Tippman was responsible for editing and production. Cheryl Keith assisted in meeting logistics and distribution of the questionnaire and draft reports.

Crawford F. Jencks, Manager, National Cooperative Highway Research Program, assisted the NCHRP 20-5 Committee and the Synthesis staff.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance are appreciated.

SYSTEMS ENGINEERING PROCESSES FOR DEVELOPING TRAFFIC SIGNAL SYSTEMS

SUMMARY

This synthesis presents a general discussion of the techniques employed in systems engineering. Systems engineering is generally considered to encompass the project life cycle, starting with problem definition and continuing through design, construction, testing, operation, and maintenance. It is an interdisciplinary approach and means to enable the realization of successful systems. Systems engineering techniques available to traffic signal systems engineers are discussed.

Key processes have been identified in the following traffic signal systems engineering areas:

- Goals and problem definition,
- Identification of constraints,
- Planning structure for identification of requirements,
- Traffic signal systems design engineering
 - Need for traffic signals,
 - Signal timing,
 - Requirements for signal coordination,
 - Selection of type of traffic signal systems control,
 - Communication systems,
 - Intersection field equipment,
 - Local intersection control strategies,
 - Preemption,
 - Transit priority,
 - Alternatives evaluation,
 - Systems procurement,
 - Operations and logistics, and
 - Project evaluation.

Systems engineering methodologies used by practitioners for traffic signal systems and an indication of the extent to which they are used are also identified. System methodologies related to the selection of objectives, alternatives evaluation, system procurement, operations, logistics, and project evaluation are described.

Summaries of existing practices are provided. These are comprised of responses to a survey questionnaire distributed to state transportation agencies to identify the system processes used by practitioners. Responses indicate that available methodologies are not used by practitioners for a significant number of functions because:

- The methodologies are not known by the practitioners or are not available in a user-friendly format.
- Organization practices and/or standard specifications limit the options available to designers. Organization practices are often designed to optimize operations for an agency. Most methodologies optimize for a particular project.
- Issues such as legacy requirements and resource constraints on operations and maintenance often limit the alternatives available to system designers.

The synthesis finishes with conclusions. A number of shortcomings in currently available traffic systems engineering methodologies are identified. Suggestions to remedy these shortcomings, as well as to better document a number of existing methodologies are provided.

INTRODUCTION

PURPOSE

This synthesis summarizes the systems engineering processes and methodologies, including those that have been developed and used by transportation agencies. It reports on the traffic engineering community's experience with various systems engineering approaches. The major aspects of the synthesis study are as follows:

- Definition of systems engineering and identification of the general processes, steps, and methodologies commonly used in industry.
- Relation of these processes to traffic signal systems.
- Potential requirements for traffic signal systems processes.
- Existing traffic signal systems processes and deficiencies.

- Results of a survey of transportation agencies to identify the practices currently used, the extent to which they are used, and user satisfaction with the results.
- Additional information that the survey respondents feel is required.
- Relative importance of various issues in traffic signal systems engineering.
- Recommendations for the development of additional methodologies and documentation.

BACKGROUND

Transportation agencies are developing, redesigning, or upgrading traffic signal systems using a number of different processes with varying degrees of success. Figure 1 highlights the city and county of Denver, Colorado's



FIGURE 1 The city and county of Denver (Colorado) Public Works Department maintains a website describing traffic signal upgrades using advanced technologies. (Courtesy: City and County of Denver Public Works Department.)

program for upgrading its signal system. Systems engineering processes have been successfully applied to the design of similar complex systems in other industries. Systems engineering logically identifies requirements and ensures that the resulting systems satisfy those requirements throughout their life cycle. Such processes can aid transportation agencies in the planning, design, operations, and maintenance of their systems in a manner that supports interoperability and growth.

Chapter two presents systems engineering approaches, definitions, and key resources. Chapter three provides an overview of various systems engineering approaches based on a review of the relevant literature and current methodologies used by state and local organizations. Chapter four reviews the current state of the practice considering the

extent to which operational agencies use systems engineering. Chapter five summarizes the results of current, formal engineering practices in planning and evaluating traffic signal systems by the surveyed organizations. Chapter six presents a summary of the findings. Suggestions are offered to resolve current shortcomings and to prepare a user-friendly document for practitioners. Abbreviations used in the report are provided after the references. The appendixes provide a copy of the survey questionnaire (Appendix A) and a list of survey respondents (Appendix B), as well as examples of the Structured Analysis Process (Appendix C) and the Quality Functional Deployment Methodology (Appendix D), Interface Alternatives for Communicating with Controllers (Appendix E), and Methodology for Communication System Selection (Appendix F).

SYSTEMS ENGINEERING

PURPOSE

The purpose of this chapter is to present systems engineering approaches, definitions, and several key resources. Three examples of general process descriptions are provided.

The following four methodologies that are commonly used in diverse systems engineering applications are reviewed:

1. System development life cycle,
2. Structured analysis,
3. Quality functional deployment, and
4. Industry-specific methodologies.

DEFINITION

With the advent of large military and space systems in the 1960s engineers began to think of systems engineering in

terms of the amalgamation of a number of engineering disciplines together with economics, human factors, goal setting, and evaluation techniques. A great deal had been written on the subject by the 1980s. Systems engineering has been described in many ways. Two definitions are provided here.

- Systems engineering is “the intellectual, academic, and professional discipline, the principal concern of which is the responsibility to ensure that all requirements for a bioware/hardware/software system are satisfied throughout the life cycle of the system” (Wymore 1993).
- The International Council on Systems Engineering (INCOSE), whose website is shown in Figure 2, defines systems engineering as “an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle,

The screenshot shows the INCOSE website homepage. The browser window title is "International Council on Systems Engineering (INCOSE) - Microsoft Internet Explorer". The address bar shows "http://www.incose.org". The page layout includes a left-hand navigation menu with links such as "Table Of Contents", "Recent Changes", "Members' Area", "Introduction to INCOSE", "INCOSE Events", "Frequently Requested Items", "Membership Information", "Technical Community", "Organization", and "Documents and Resources". The main content area features the INCOSE logo and several text-based announcements, including the 2001 Annual Report, a server migration notice, a list of technical committees, and a free download of the book "Putting Systems to Work".

FIGURE 2 INCOSE website provides links to systems engineering resources. (Courtesy: International Council on Systems Engineering.)

documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem:

- Operations
- Performance
- Test
- Manufacturing
- Cost and schedule
- Training and support
- Disposal.

Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs” (INCOSE 1999).

RESOURCES

Many articles, papers, and books have been written on the subject. Some describe generalized approaches, whereas others address particular aspects.

Systems engineering is the specialty of the International Council on Systems Engineering, which publishes *The Journal of Systems Engineering*.

Chambers (1986) provides an annotated and classified bibliography of early systems engineering research and Dean (n.d.) a more current listing.

Although systems engineering embraces a wide range of disciplines, the following are often used by systems engineers for many different applications:

- Optimization theory;
- Probability, statistics, and queuing theory;
- Simulation and modeling;
- Experimental design;
- Engineering economics;
- Human factors engineering;
- Information theory, game theory, and decision theory; and
- Reliability and failure theory.

PROCESSES

Attempts to generalize the systems engineering approach have resulted in a large number of descriptions, including standards established by the U.S. Air Force (1969, 1974) and civilian agencies (ANSI n.d.).

Three examples of general process descriptions are provided here.

1. Sage (1981) defines the logic structure of systems engineering in a wide context of systems with societal implications. He describes the major functions of systems engineering as follows:

- Formulation of issues, or identification of problems or issues, objectives, or values associated with issue resolution, and alternative policies or controls that might resolve or mitigate issues;
- Analysis of impacts of alternative policies; and
- Interpretation or evaluation of the utility of alternatives and their impacts upon the affected stakeholder group and selection of a set of action alternatives for implementation.

2. Mosard (1982) describes the following steps in systems engineering:

- Defining problems,
- Setting objectives and developing evaluation criteria,
- Developing alternatives,
- Modeling alternatives,
- Evaluating alternatives,
- Selecting an alternative, and
- Planning for implementation.

3. Lacy (1992) identifies the following “logic dimensions” of systems engineering:

- Problem definition,
- Value system design,
- Function analysis,
- Systems synthesis,
- Systems analysis,
- Decomposition (providing more detail concerning the requirements), and
- Description (documentation of the systems engineering effort).

In addition, Leslie (1986) describes the following issues in undertaking a systems analysis:

- Inclusion–Exclusion—Setting boundaries between what is outside and what is inside the system.
- Leveling—Defining the hierarchical (vertical levels) for expressing requirements.
- Partitioning—Defining the sequential (horizontal) operations for each vertical level.
- Relating process flow to information flow.

COMMONLY USED METHODOLOGIES

The following sections describe four methodologies that are used for a significant number of diverse systems engineering applications.

System Development Life Cycle

Life-cycle process management is an important consideration in systems engineering. Sage (1992) illustrates the key elements of this process in Figure 3.

Structured Analysis

Structured analysis is a methodology that defines processes and data flows in a hierarchical sense. It is a commonly used alternative to flow chart methodology. Figure 4 illustrates the data flow diagrams for two analysis levels. The

circles identify the processes (through process specifications) and the lines identify the data flows. Appendix C provides an example of the use of structured analysis for an application other than traffic control.

The logical architecture element of the National Intelligent Transportation System (ITS) Architecture uses the structured analysis methodology. Figure 5 shows a particular function that includes traffic control elements. Figure 6 shows how one element of traffic signal control are segmented into subordinate levels. Table 1 provides representative process specifications.

Quality Functional Deployment

Another general methodology that may be useful for traffic signal systems engineering is the Quality Functional Deployment approach used by some manufacturing companies. Quality Functional Deployment uses a series of charts

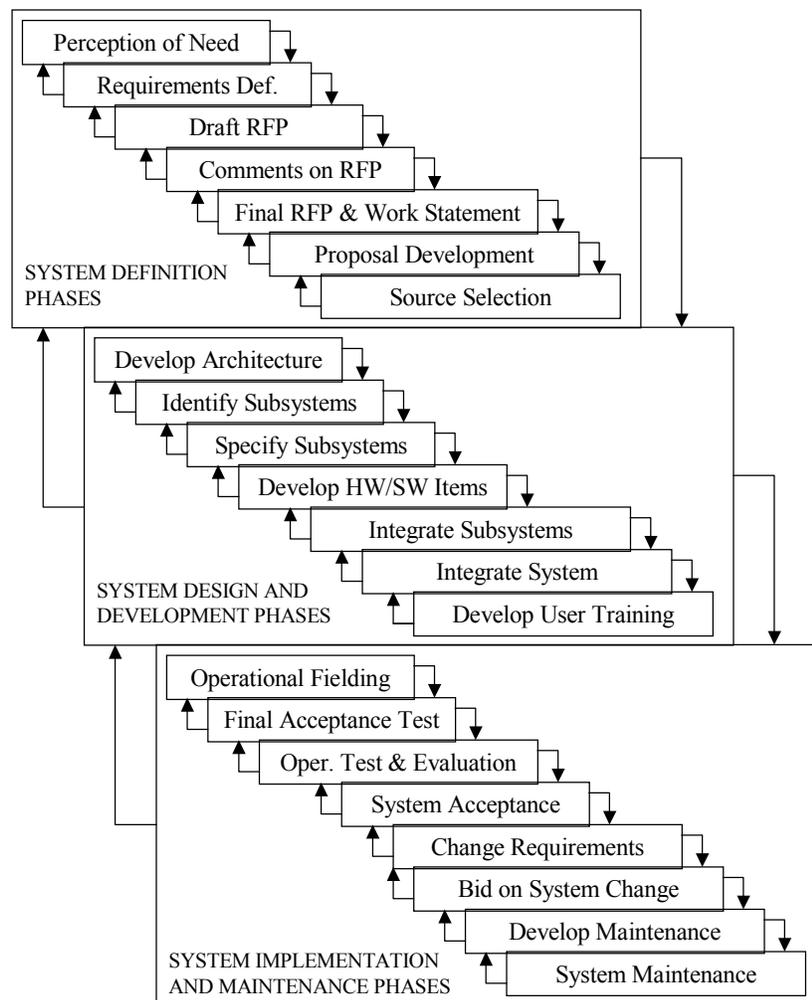


FIGURE 3 A 22-phase systems engineering life cycle (Sage 1992). (Reprinted by permission of John Wiley & Sons, Inc.)

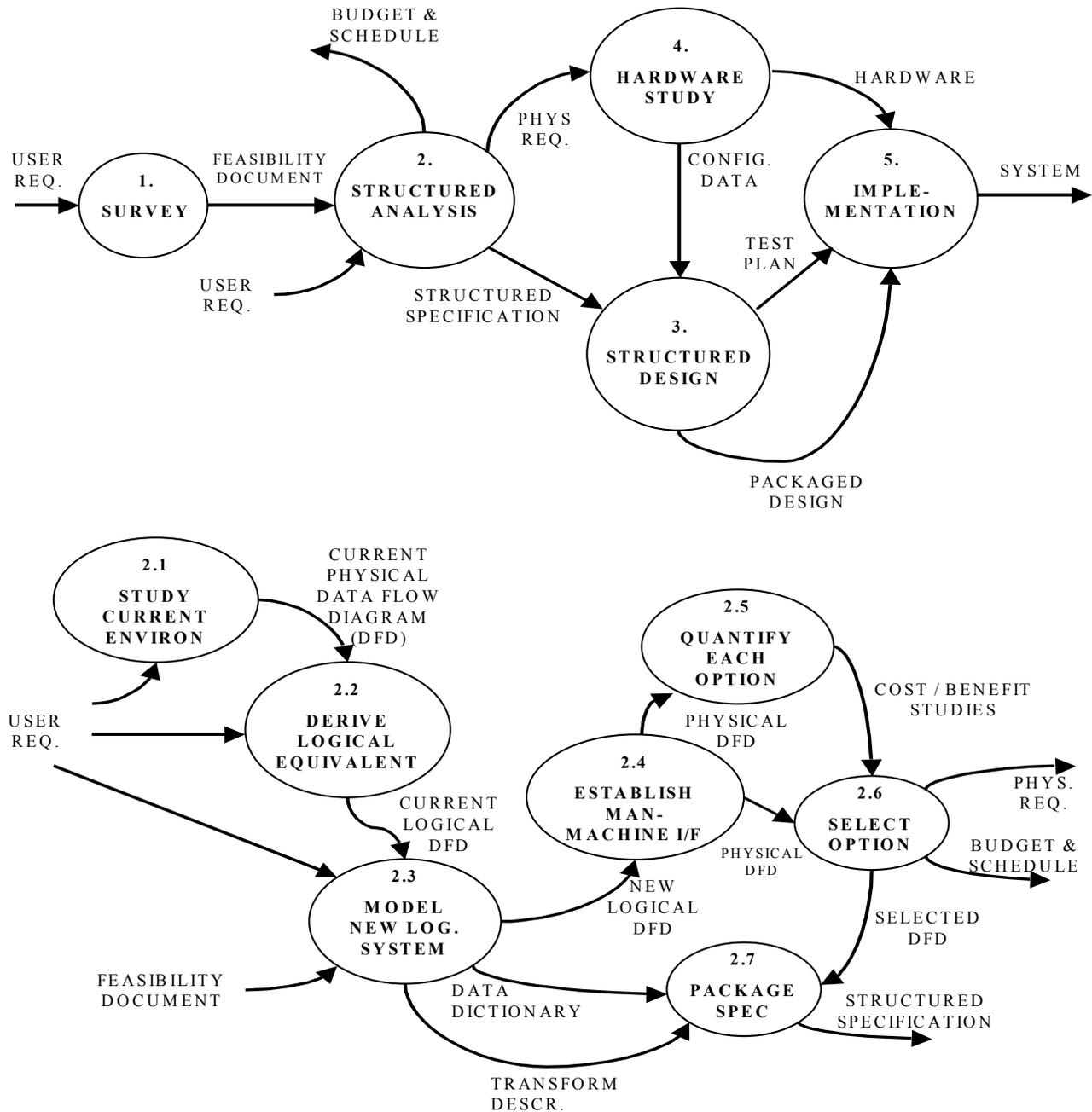


FIGURE 4 Presentation of two levels of structured analysis (DeMarco 1979). (Reprinted with permission of Pearson Education, Inc., Upper Saddle River, N.J.).

to establish interrelationships, performance measures, and characteristics. Appendix D discusses this methodology further.

Industry-Specific Methodologies

Industries and sectors within industries (e.g., suppliers versus users) have developed specific methodologies to satisfy the systems engineering functions unique to the indus-

try. Although these methodologies apply to the disciplines identified previously as well as to others, they are usually quite specific to the industry and are not often easily shared with other industries not closely related.

RELATIONSHIP TO TRAFFIC SIGNAL SYSTEMS

Previous sections discuss systems engineering definitions and approaches as they generally apply to issues across

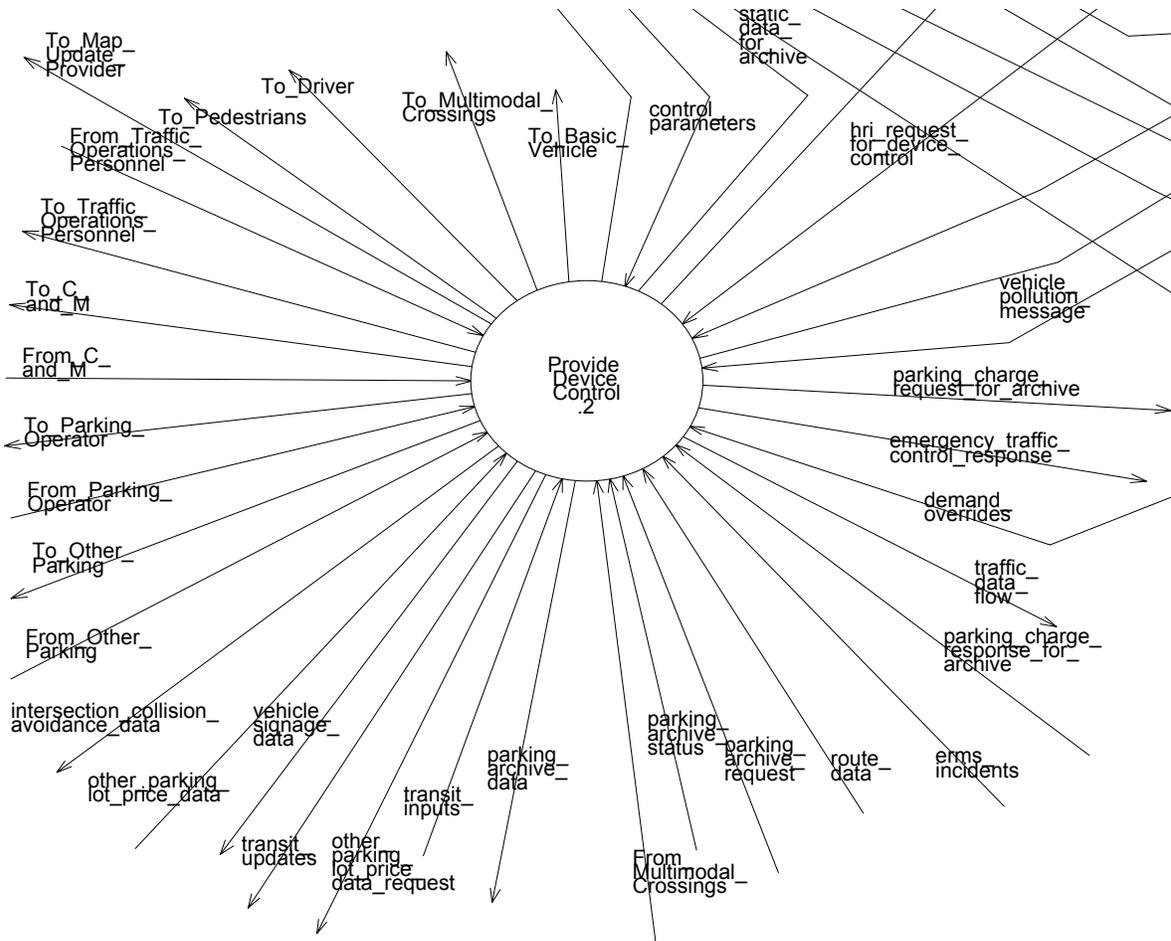


FIGURE 5 Portion of National ITS Architecture data flow diagram (*The National ITS Architecture* 1999).

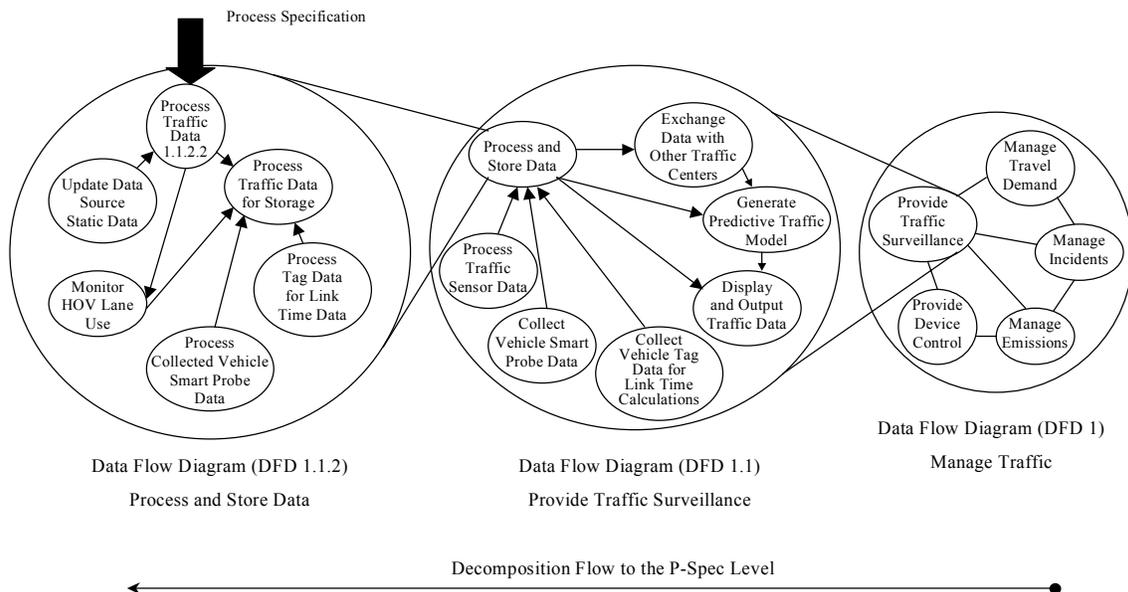


FIGURE 6 Example of logical architecture functional segmentation (*Developing Traffic Signal Control Systems . . .* 1998).

TABLE 1
EXAMPLE PROCESS SPECIFICATIONS (Overview Descriptions)

Task	Overview
Process traffic data (P-Spec 1.1.2.2)	This process shall be responsible for collecting all of the processed data supplied from traffic sensors and from sensors at highway research institutes. The process shall distribute it to processes in the Provide Device Control facility responsible for freeway, highway rail intersections, parking lot, ramp, and road management. It shall also send the data to another process in the Provide Traffic Surveillance facility for loading into the stores of current and long-term data.
Select strategy (P-Spec 1.2.1)	This process shall be responsible for selecting the appropriate traffic control strategy to be implemented over the road and freeway network served by the Manage Traffic function. The strategy shall be selected by the process from a number that are available; e.g., adaptive control, fixed-time control, local operations, etc. The selected strategy shall be passed by the process to the actual control processes for implementation according to the part of the network to which it is to be applied, i.e., roads, freeways, ramps, and parking lots. When part of the selected strategy, or at the request of the traffic operations personnel, the process shall send commands to the traffic sensor data process to change the operating parameters of video cameras used to provide traffic data. The process shall make it possible for the current strategy selection to be modified to accommodate the effects of such things as incidents, emergency vehicle green waves, the passage of commercial vehicles with unusual loads, equipment faults, and overrides from the traffic operations personnel. The selected strategy shall be sent to the process within the Provide Traffic Surveillance facility responsible for maintaining the store of long-term data.
Determine indicator state for road management (P-Spec 1.2.2.2)	This process shall be responsible for implementing selected traffic control strategies and transit priority on some or all of the indicators covering the road (surface street) network served by the Manage Traffic function. It shall implement the strategies only using the indicators (intersection and pedestrian controllers, variable message signs, etc.) that are specified in the implementation request and shall coordinate its actions with those of the processes that control the freeway network and the ramps that give access to the freeway network.
Output control data for roads P-Spec 1.2.4.1)	This process shall be responsible for the transfer of data to processes responsible for controlling equipment located at the roadside within the road (surface street) network served by the Manage Traffic function. These data shall contain outputs for use by roadside indicators, such as intersection and pedestrian controllers, variable message signs, etc. Data for use by in-vehicle signage equipment shall be sent to another process for output to roadside processes. All data shall have been sent to this process by processes within the Manage Traffic function. This process shall also be responsible for the monitoring of input data showing the way in which the indicators are responding to the data that they are being sent, and the reporting of any errors in their responses as faults to the Collect and Process Indicator Fault Data facility within the Manage Traffic function. All output and input data shall be sent by the process to another process in the Manage Traffic function to be loaded into the store of long-term data.

(Source: FHWA, *Developing Traffic Signal Control Systems* . . . 1998).

major applications. Situations where specific methodology issues and applications can be transfused from one field to a significantly different one appear to be the exception rather than the rule. However, systems engineering applications may be categorized as follows:

- Applications that are new or unique and that require development of new hardware and software technology. These applications may require the use of additional systems engineering techniques, such as charts and matrices, which couple physical principles to requirements. These systems often use new software techniques and algorithms. Military and space-related projects often fall into this category.
- Applications where the technology has basically been refined to practice and is commonly available.

In this case, the systems engineering decisions center on the selection of appropriate technologies and procedures from the available set. Nonresearch-oriented traffic signal systems generally fall into this category.

Users and suppliers of systems often have somewhat different views of systems engineering processes; users typically focus on life-cycle efficiencies for systems that meet their specific requirements and suppliers generally emphasize providing and supporting systems that satisfy most users, and implementing them in a reliable and cost-efficient manner.

From the user's perspective, most nonresearch-oriented traffic signal systems projects generally employ existing equipment and software technology, and select from

TABLE 2
 BASIC ELEMENTS IN THE TRANSPORTATION PLANNING PROCESS APPLIED
 TO CONSIDER THE FEASIBILITY OF A NEW BRIDGE

Process	Application to Bridge Study
Situation definition	<ul style="list-style-type: none"> • Inventory transportation facilities • Measure travel patterns • Review prior studies
Problem definition	<ul style="list-style-type: none"> • Define objectives <ul style="list-style-type: none"> – Reduce travel time • Establish criteria <ul style="list-style-type: none"> – Average delay time • Define constraints • Establish design standards
Search for solutions	<ul style="list-style-type: none"> • Consider options <ul style="list-style-type: none"> – Locations and types – Tunnel or don't build – Toll charges
Analysis of performance	<ul style="list-style-type: none"> • For each option determine <ul style="list-style-type: none"> – Cost – Traffic flow – Impacts
Evaluation of alternatives	<ul style="list-style-type: none"> • For bridge project determine <ul style="list-style-type: none"> – Benefits vs. cost – Profitability – Cost-effectiveness
Choice of project	<ul style="list-style-type: none"> • Consider factors involved <ul style="list-style-type: none"> – Revenue cost forecast – Site location – Political judgment
Specification and construction	<ul style="list-style-type: none"> • Design of bridge <ul style="list-style-type: none"> – Superstructure – Piers, foundation • Construction plans <ul style="list-style-type: none"> – Contractor selection • Transfer of completed bridge to authority operation and maintenance

(Source: Garber and Hoel, *Traffic and Highway Engineering*, 2nd ed., 1999). Reprinted with permission of Brooks/Cole, an imprint of the Wadsworth Group, a division of Thomson Learning.

among systems and components provided by the industry. Although many traffic signal systems projects (other than research projects) have some design requirements that may be unique, these requirements are usually adaptations of existing technologies, products, and procedures.

Garber and Hoel (1999) identify the basic elements of transportation planning through project construction. The left column of Table 2 shows the general elements of that process, and the right column shows the process as applied to the feasibility of constructing a new bridge. This process is generally relevant to traffic signal systems.

TRAFFIC SIGNAL SYSTEMS ENGINEERING

PURPOSE

This chapter presents an overview of various systems engineering processes for developing traffic signal systems based on a review of pertinent literature and current methodologies employed by state and local organizations. The chapter identifies major sources of available, valuable information on overall traffic systems engineering processes and summarizes useful steps and techniques, methodologies, goals and problem definition, and common constraints. Subsequent chapter sections provide information on systems engineering methodologies for upgrading traffic signal control systems, evaluating the need for a traffic signal, establishing signal coordination and interconnection, and equipment selection. The chapter includes a review of alternatives evaluation techniques and related criteria, focusing primarily on utility-cost and benefit-cost analysis. Finally, the chapter concludes with detailed discussions on

traffic systems operations and logistics requirements, covering maintenance activities and training, in addition to project evaluation which, in turn, provides information on various benefits measures and the application of common evaluation methodologies.

BACKGROUND

Engineers responsible for the development of traffic signal systems have, in some instances, employed many of the systems engineering processes described in the previous chapter. The processes have more often been employed in an informal way, based on judgment and experience rather than application of a formal methodology. The basic systems engineering paradigm shown in Figure 7 appears to be applicable to traffic signal systems.

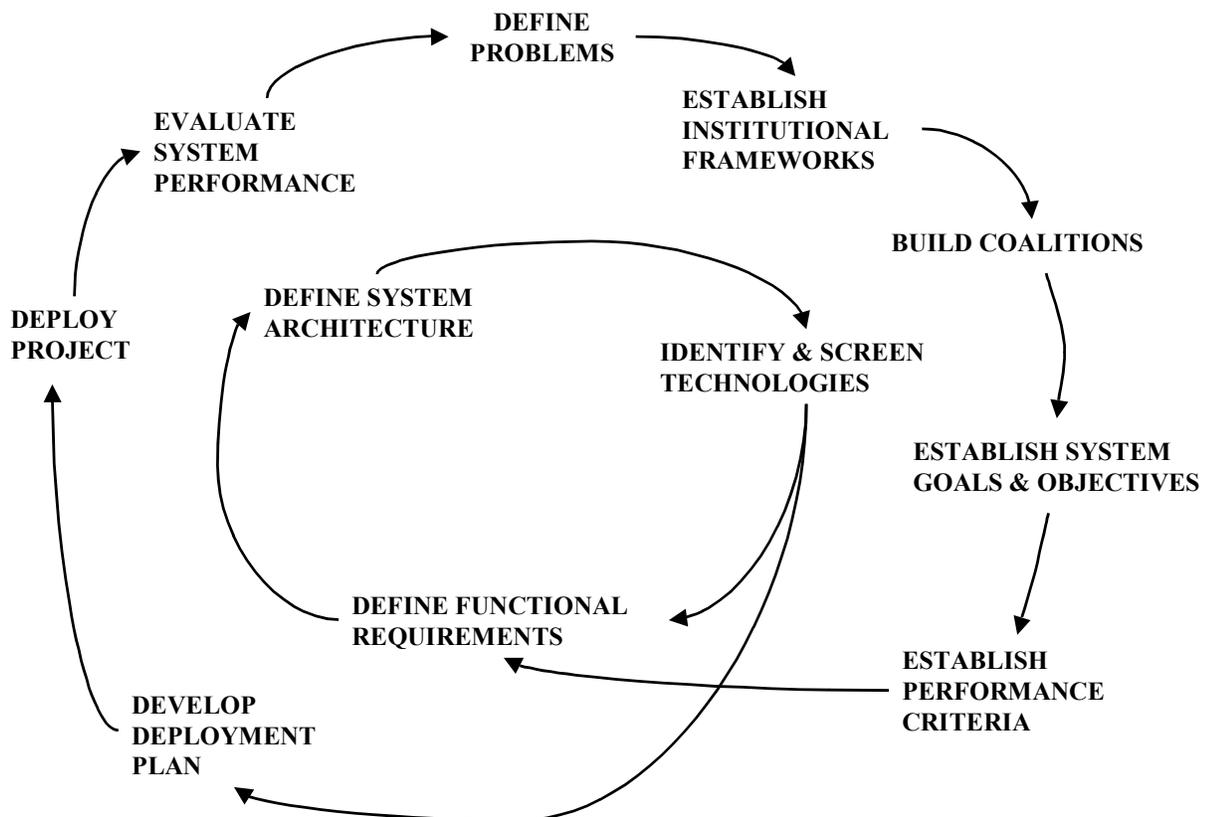


FIGURE 7 Steps performed in a typical systems engineering analysis (Carvell et al. 1997).

TABLE 3
SUMMARY OF TRAFFIC SIGNAL SYSTEM BENEFITS

Parameter	Benefit
Travel time	Decrease 8–15%
Travel speed	Increase 14–22%
Vehicle stops	Decrease 0–35%
Delay	Decrease 17–37%
Fuel consumption	Decrease 6–12%
Emissions	Decrease CO emissions 5–13%
	Decrease HC emissions 4–10%

Notes: CO = carbon monoxide; HC = hydrocarbons.

(Source: FHWA, *Intelligent Transportation Infrastructure Benefits* 1996).

In recent years the National ITS Architecture processes (*Developing Traffic Signal Control Systems* . . . 1998; *The National ITS Architecture* 1999) have influenced the development of traffic signal systems. The National Architecture is concerned with institutional and other relationships affecting system goals and objectives and the relationship of traffic signal control to other ITS functions. The National Architecture strongly influences the standards used to transmit information among the management centers and from the management centers to the field equipment.

Improved traffic signal systems have resulted in the benefit ranges shown in Table 3. The potential range of benefits is sufficiently attractive to warrant the expenditure of significant effort to implement procedures to improve performance at an acceptable cost.

GENERAL METHODOLOGIES

General Approach to Traffic Signal Systems Engineering

A review of engineering processes for developing traffic signal systems was conducted. Much of the literature relating to system methodologies for addressing traffic signal control systems describes these methodologies in fairly general terms.

The major sources of information on overall traffic systems engineering processes were found in the three versions of the FHWA-sponsored *Traffic Control System Handbooks* (Pinnell et al. 1976; Wilshire et al. 1985; Gordon et al. 1996). The first handbook (Pinnell et al. 1976) provides a comprehensive general process treatment, and is organized around the paradigm of viewing systems engineering as a continuous process (Figure 8). The handbook identifies the basic steps as

- Goal setting,
- Data collection,
- Problem definition, and
- Synthesis.

Candidate system objectives are identified in detail. These are then quantitatively related to functional subsystems. Func-

tional subsystem requirements and constraints are introduced. Synthesis techniques are borrowed from a nontraffic-related synthesis approach and include (Alger and Hays 1964)

- Understanding your problem,
- Establishing a creative attitude,
- Reviewing historical information,
- Individual creative effort, and
- Group creative effort.

Some guidance in system selection is provided by the second and third handbooks (Wilshire et al. 1985; Gordon et al. 1996). Table 4 summarizes the approaches of these references.

The *Freeway Management Handbook* (Carvell et al. 1997) describes systems engineering processes specific to freeway systems. That handbook also outlines the elements of an implementation plan (Table 5) that can serve as a checklist for systems engineering processes.

These handbooks discuss processes as they apply to the project life cycle, including consideration of operational, logistics, and evaluation issues.

Figure 9 depicts the systems engineering process used to develop the National ITS Architecture.

The FHWA publication *Integrating Intelligent Transportation Systems Within the Planning Process: An Interim Handbook* (Smith 1998) emphasizes problem definition, planning process impacts, and the relationship to the National ITS Architecture.

On January 8, 2001, the FHWA published its Final Rule on “Intelligent Transportation System Architecture and Standards,” in the *Federal Register*. All ITS projects not in final design by April 8, 2001, must be based upon a systems engineering analysis on a scale commensurate with the project’s scope and use U.S. DOT-adopted ITS standards as appropriate.

The definition of systems engineering analysis is “A structured process for arriving at a final design of a system”

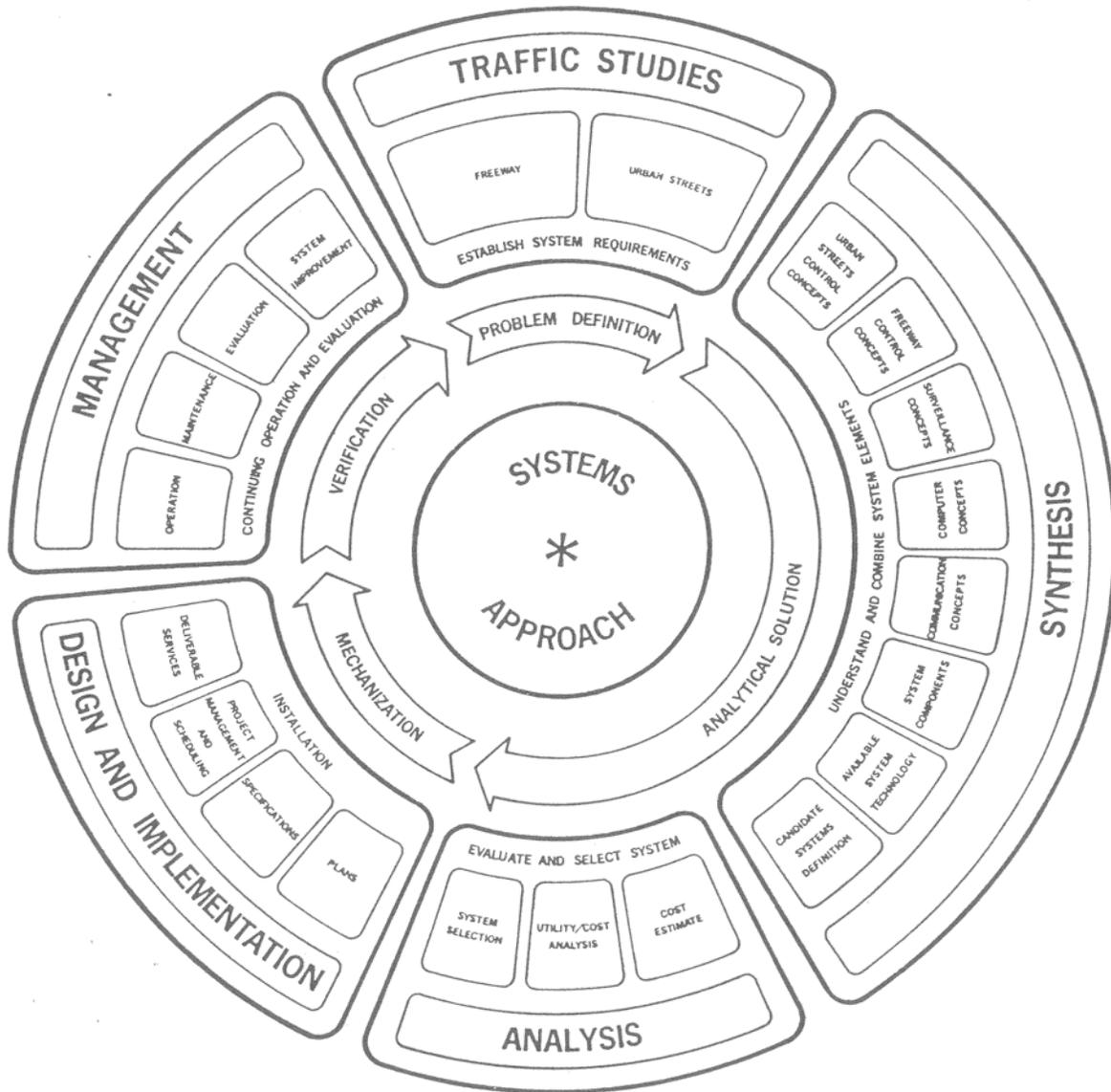


FIGURE 8 Traffic control systems engineering (Pinnell et al. 1976).

TABLE 4
METHODOLOGIES FOR DEVELOPMENT OF REQUIREMENTS AND SYSTEM ALTERNATIVES

Requirement	Overview
Define system requirements	<ul style="list-style-type: none"> • Requirements originate from <ul style="list-style-type: none"> – traffic growth or changes in traffic patterns – equipment that is obsolete or requires excessive maintenance • Requirements development team includes <ul style="list-style-type: none"> – management – planning – design – operations – maintenance
Identify alternative systems	<ul style="list-style-type: none"> • Information sources include <ul style="list-style-type: none"> – manufacturers – users – system houses – consultants – researchers – interested individuals

TABLE 5
ELEMENTS OF A TYPICAL IMPLEMENTATION PLAN

Element	Components
Needed Legislation	
System design	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • Division of responsibilities • Scheduling and establishing mileposts • Conflict mitigation • Coordination with other projects
System start-up plan	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • Evaluation <ul style="list-style-type: none"> – system evaluator – method of evaluation – cost of evaluation • Maintenance plan <ul style="list-style-type: none"> – 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 agreements	<ul style="list-style-type: none"> • 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	

(Source: Carvell et al. 1997).

(“Federal Transit Administration . . .” 2001). It evaluates a number of alternatives to meet the design objectives considering total life-cycle costs, technical merit, and relative value of each. A systems engineering analysis for ITS shall be on a scale commensurate with the project scope and at minimum shall include

- How the project fits into the regional ITS architecture (or applicable portions of the National ITS Architecture),
- Identification of roles and responsibilities of participating agencies,
- Requirements definition,
- Analysis of alternative system configurations and technology options,
- Procurement options,

- Identification of applicable ITS standards and testing procedures, and
- Procedures and resources necessary for operations and management of the system.

Further guidance is to be found in “Incorporating ITS into the Transportation Planning Process: Practitioner’s Handbook” (Mitretek Systems and PB Farradyne 2002).

Goals and Problem Definition

General systems engineering methodologies usually call for the identification of project goals or problems to be addressed. The National ITS Architecture defines these goals and goal setting techniques in a broad manner for all ITS

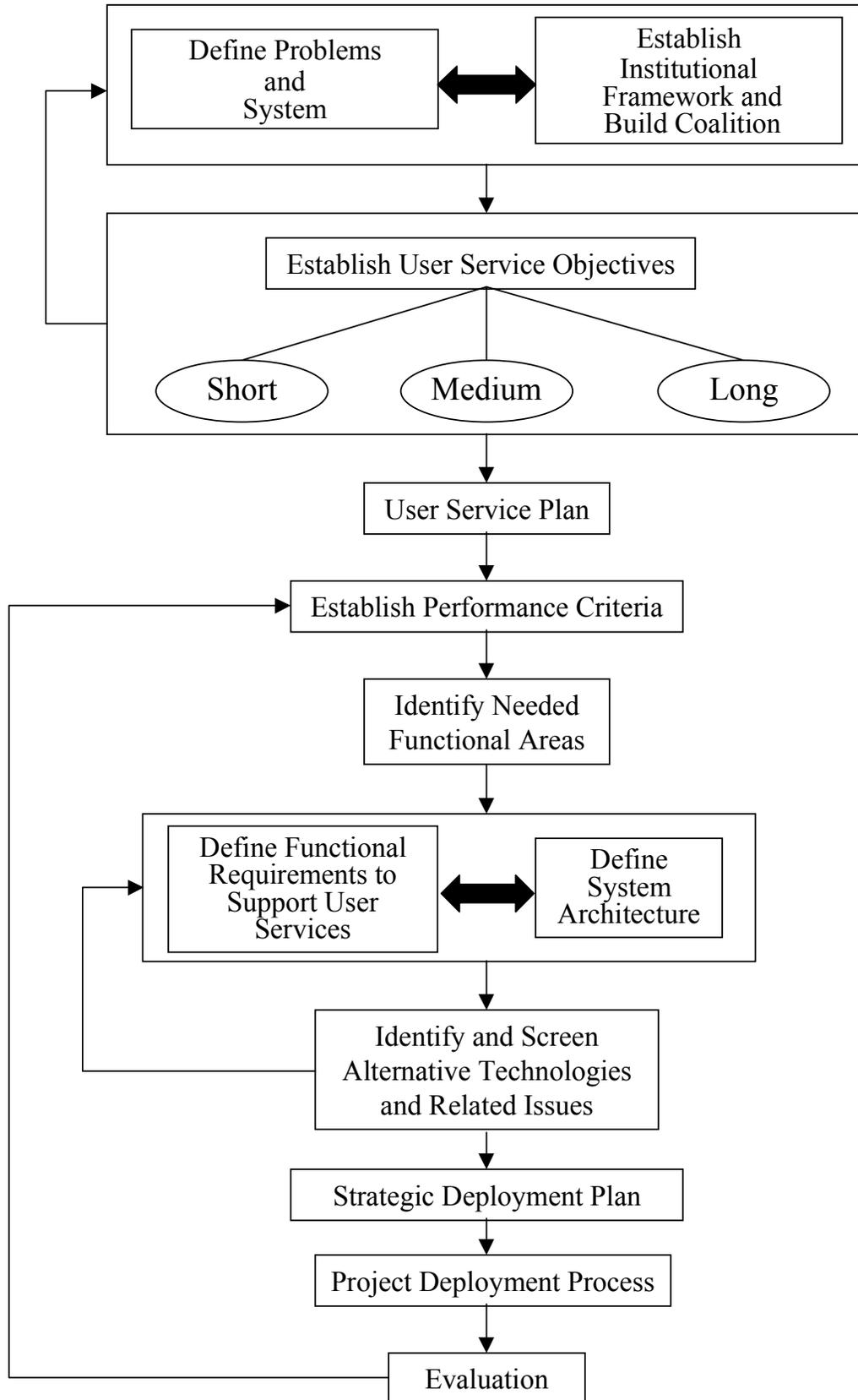


FIGURE 9 Systems engineering process used to develop National ITS Architecture (*Manual on Uniform Traffic Control Devices 2000*).

applications (*The National ITS Architecture* 1999). For traffic signal systems applications the following listings were compiled from various references.

- Improvement of services to the public.
 - Reduce recurrent congestion. Congestion may be spot congestion or may apply to arterials or areas.
 - Reduce nonrecurrent congestion. Congestion may be spot congestion or may apply to arterials or areas.
 - Reduce the accident rate at a spot location, on arterials, or in areas.
 - Reduce emissions and fuel consumption.
 - Serve as a diversion route within a local corridor.
 - Interoperate with other ITS in the same or other jurisdictions.
 - Facilitate the provision of emergency community services.
 - Facilitate railroad crossing preemption.
 - Facilitate signal priority for transit vehicles.
 - Facilitate pedestrian safety and mobility at traffic signals.
- Improvement of agency operations.
 - Reduce cost and improve performance of traffic management operations and equipment maintenance. Facilitate field equipment interchangeability.
 - Provide data for planning.
 - Improve public relations.

Processes that facilitate the identification of goals and problems include (*Developing Traffic Signal Control Systems* . . . 1998)

- Traditional transportation planning processes,
- Public questionnaires,
- Problems/needs identification studies, and
- ITS early deployment planning processes.

Constraints

The fulfillment of goals and the approaches to satisfy specific functional requirements are often constrained by resource, institutional, and legacy issues. In some cases the necessity to resolve problems may justify the relaxation of constraints. Absent this situation, the use of constraint analysis has the potential to simplify the selection of design alternatives by eliminating alternatives lying outside constraint boundaries. Some of the more common constraints are

- Resource constraints
 - Capital funding,
 - Funding for operations,
 - Funding for maintenance, and
 - Staffing levels and capabilities.

Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) regulations require that both long- and short-range plans be financially constrained to reflect revenues reasonably expected to be available over the time period they cover (Smith 1998).

- Institutional constraints
 - Funding through long-term planning processes,
 - Requirements to use agency-specific standard specifications,
 - Requirements to use National ITS Architecture standards and protocols,
 - Requirements to provide interoperability with other ITS in the same or other jurisdictions,
 - General design constraints,
 - Preservation of existing utilities,
 - Right-of-way constraints, and
 - Economic, social, environmental, and community considerations.
- Legacy constraints
 - Requirements to use existing equipment to the extent possible, and
 - Requirements for new equipment to be compatible with existing equipment.

It is important to identify constraints early in the systems engineering process. Such early identification will result in either of the following situations:

- The potential benefits of the project or design approach indicate that a serious attempt be made to relieve the constraint.
- The project must be subject to the constraints. These constraints may eliminate alternatives from further consideration.

REQUIREMENTS FOR UPGRADING EXISTING AND NEW SYSTEMS

Planning Structure for Identification of Requirements

Most traffic signal control systems, with the exception of systems for newly planned communities or facilities, currently exist in some sense (i.e., some form of signal control is currently present). The systems engineering process logically relates the goals discussed earlier to project requirements. Most of the available systems engineering methodologies address these requirements.

Requirements that span these goals may be expressed in a number of ways. The following list contains one top-level requirements breakout structure and is intended to assist the reader in locating a discussion of a specific requirement.

- **Functional Requirements**

- F 1. Satisfy traffic signal requirements at the intersection.
 - F 1.1 Provide traffic signal at this location, if necessary.
 - F 1.2 Retime signal, if necessary.
- F 2. Provide appropriate type of signal coordination, if necessary.
 - F 2.1 Determine whether coordination is appropriate for intersection.
 - F 2.2 Provide appropriate type of coordination strategies:
 - a. Select time-based coordination, physical coordination, conventional traffic-responsive operation, or adaptive system operation as basis for system operation.
 - b. Define interoperability requirements.
 - c. Identify candidate systems that can satisfy these requirements.
- F 3. Satisfy intersection control requirements.
 - F 3.1 Provide appropriate intersection control strategy.
 - F 3.2 Satisfy interchangeability requirements.
 - F 3.3 Provide preemption functions as necessary.
 - F 3.4 Provide transit priority functions as necessary.
- F 4. Service functions.
 - F 4.1 Provide planning data.
 - F 4.2 Facilitate system database preparation including development of signal timing plans.
 - F 4.3 Manage appropriate logistics functions (inventory, maintenance, etc.).

- **System Design Requirements**

- S 1. Design central control equipment.
 - S 1.1 Design central computer complex, servers, and workstations (develop requirements to satisfy Requirements F 2.2 and F 3.2.).
 - S 1.2 Design displays and controls.
- S 2. Design communications to the field.
 - S 2.1 Determine whether interconnect (wireline or wireless) is required to perform the necessary system functions. If an interconnected system currently exists, determine if the communications system needs replacement because it cannot be economically operated or maintained.
 - S 2.2 Determine appropriateness of the current communications topology to Requirement F 2.2.
 - S 2.3 Determine appropriateness of the current media and hardware to Requirement F 2.2.
 - S 2.4 Determine appropriateness of the current communication protocols to Requirements F 2.2 and F 3.2.

S 2.5 Develop requirements if a new communication system is needed.

- S 3. Design field equipment.
 - S 3.1 Select controllers.
 - a. Determine the appropriateness of the intersection equipment (local controllers, local detectors, and system detectors) for current and future needs.
 - b. Assess need to replace intersection equipment because it cannot be economically operated or maintained.
 - c. Assure that interchangeability requirements are appropriately supported.
 - d. Assess need to plan for provision of special purpose equipment such as audible signals.
 - S 3.2 Select detectors.
 - a. Select technology for system and local detectors.
 - S 3.3 Determine preemption provisions.
 - a. In conjunction with appropriate agencies, select technology for railroad and/or emergency vehicle preemption.
 - S 3.4 Provide signal priority provisions for transit.
 - a. In conjunction with appropriate agencies, select technology for signal priority for transit.

- **Project Management Requirements**

- M 1. Select a system design and procurement approach.
- M 2. Develop project implementation and management plan.

- **Operations Requirements**

- O 1. Develop and implement a staffing plan for day-to-day operations and for recurrent support needs.
- O 2. Define requirements to be included in Requirement F 4.2.

- **Logistics Requirements**

- L 1. Establish maintenance needs.
 - L 1.1 Develop and implement a maintenance plan.
 - L 1.2 Develop and implement a maintenance staffing plan.
 - L 1.3 Develop and implement a plan for obtaining necessary maintenance personnel.
 - L 1.4 Define requirements to be included in Requirement F 4.2.
 - L 1.5 Identify spare parts and special test equipment to be included in project procurement.

- L 2. Develop training.
 - L 2.1 Develop and implement a plan for training maintenance and operations personnel.
 - a. Identify special skills required for maintenance that current system does not require.
 - L 2.2 Define requirements to be included in Requirement F 4.2.
- L 3. Define documentation requirements and procure with system.

• Evaluation Requirements

- E 1. Develop a plan to evaluate the accomplishment of project goals.
- E 2. Define measures of effectiveness for the accomplishment of project goals.
- E 3. Develop and implement a plan to evaluate the project's progress and to modify the implementation and management plan if necessary.

The following sections discuss existing methodologies designed to assist traffic signal systems engineers and managers in addressing many of these requirements.

Processes and Methodologies for Traffic Signal Systems Engineering

Requirement F 1.1—Need for Traffic Signals

The need for a traffic signal is identified by the *Manual on Uniform Traffic Control Devices* (MUTCD; 2000). The manual provides a number of warrants based on vehicular and pedestrian volumes. It also recommends that factors such as safety and flow progression be taken into account. Future manual revisions will formalize these factors.

It may also be necessary to provide a process for reviewing the need for existing signals in some areas as changes in land use or other factors may eliminate the need for certain signals. Periodic analysis using highway capacity software resulting in very low delays or very short cycles may serve as a trigger to reconsider warrants for the signal.

Some agencies have incorporated warrants into a formal agency planning and signal acquisition process. The process used by the Arizona Department of Transportation (DOT) is summarized in Figure 10. An Arizona DOT report (2000) describes the traffic signal needs, phasing, clearance interval computations, and signal design process used by the agency. Numerous publications available from the Institute of Transportation Engineers provide information on various aspects of basic interaction in signal design.

Requirement F 1.2—Signal Timing

With the exception of adaptive traffic control systems, traffic systems require retiming of the signals from time to time.

The literature provides ample evidence to indicate that signal retiming provides very important and cost-effective benefits (Wagner 1980; Polanis 1984; Berg et al. 1986; Fambro 1992; Skabardonis et al. 1998). Use of multiple timing plans can provide benefits over the use of a single timing plan. Skabardonis et al. (1998) estimated the improvement in using three timing plans instead of one as an average of 16% delay reduction and 4% stops reduction on arterials. Delay and stops reduction in grids was 7% and 6%, respectively. Factors that lead to the need for signal retiming may include

- Changes in local or area-wide traffic demands,
- Local land-use changes, and
- Need to provide transit priority.

Traffic signal systems engineers use these factors as well as the following to identify the need for signal retiming:

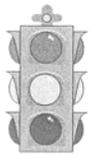
- Accident experience,
- Observations of signal timing performance and congestion patterns; formal measurements may result from these observations,
- Traffic count programs; growth factors may point to need for retiming, and
- Comments and complaints by the public.

Signal timing plans are commonly prepared by using programs designed for this purpose, including

- WHICH (McTrans 1999E)—Isolated intersection timing.
- TRANSYT 7F (McTrans 1999D)—Arterial and grid timing.
- PASSER II-90 (McTrans 1999B)—Arterial timing.
- PASSER III-98 (McTrans 1999C)—Diamond intersection timing.
- PASSER IV-96 (McTrans 1999A)—Multi-arterial network timing.
- SYNCHRO Version 4.0 (Trafficware Corp. 1999)—Arterial and grid timing.

The input database for these programs requires the collection of intersection turning movement data for each timing plan. This may entail a significant expense.

An important issue is the determination of the number of timing plans required and the time period over which they should be employed. Many jurisdictions use three timing plans reflecting the weekday peak periods and an off-hour (perhaps midday). In many cases, this fails to appropriately reflect actual traffic variations. Possible techniques for addressing this issue include



TRAFFIC SIGNAL PROCESS

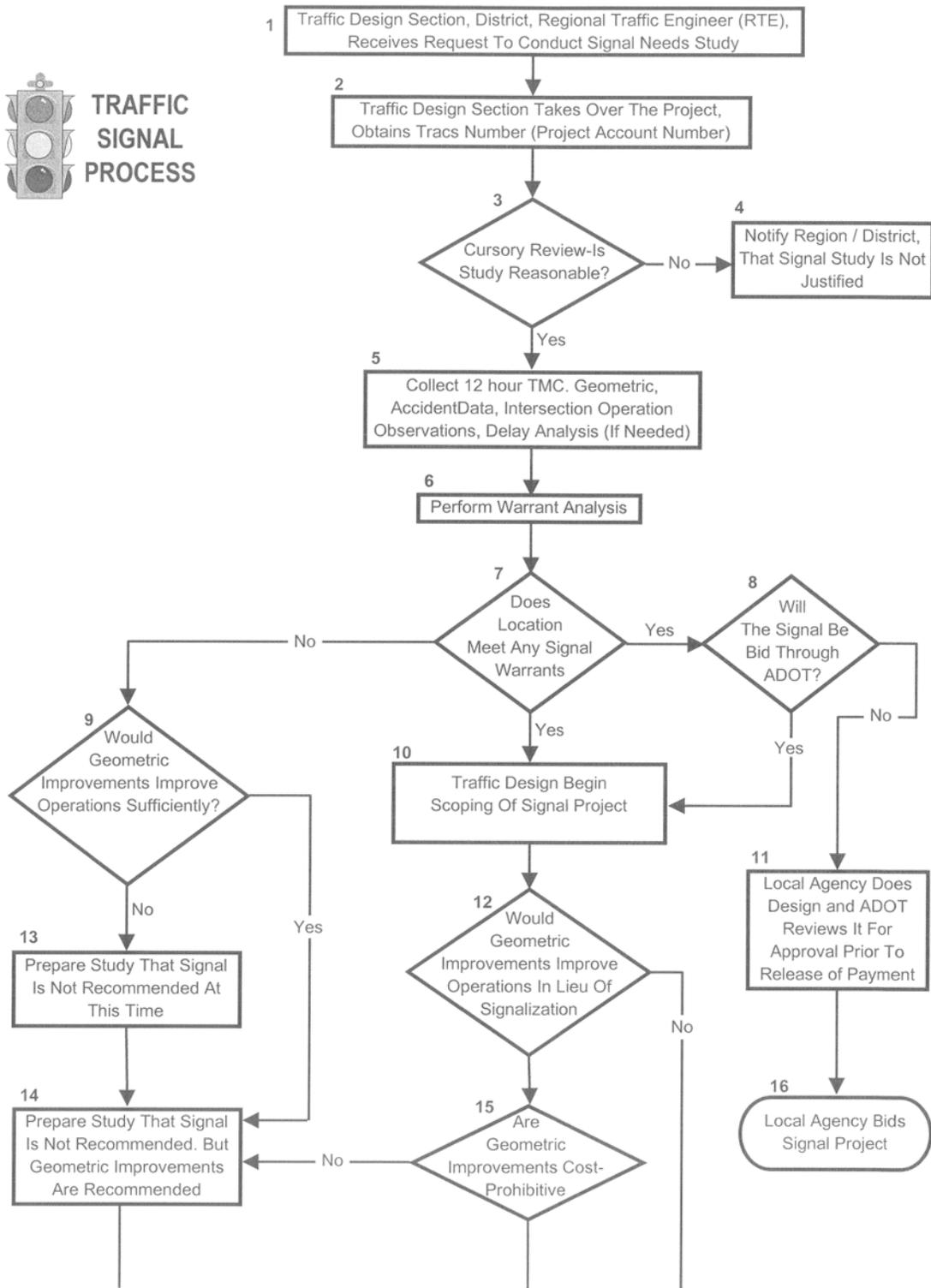


FIGURE 10 Arizona DOT traffic signal sequence (Improved Traffic Signal Process 1996).

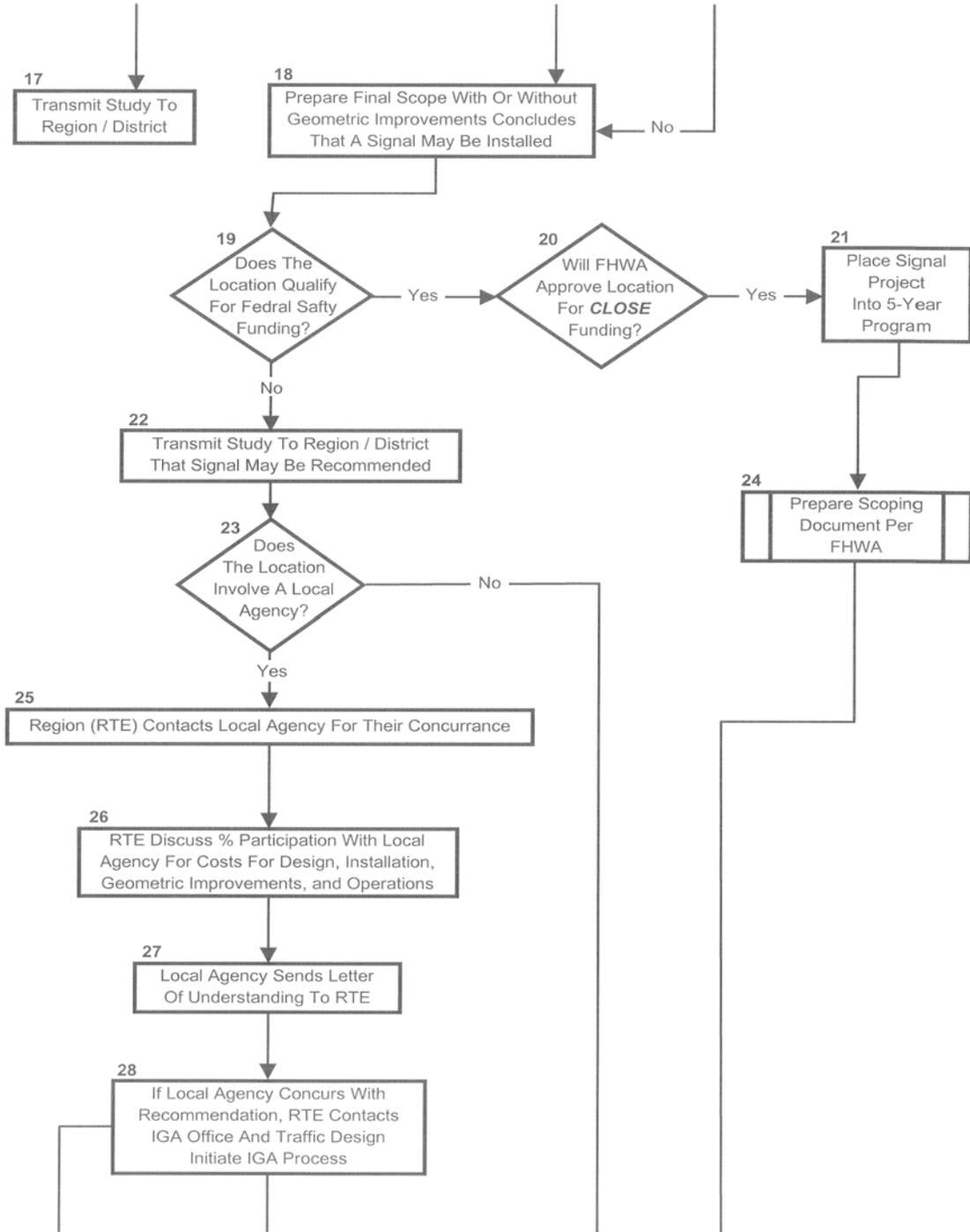


FIGURE 10 (Continued).

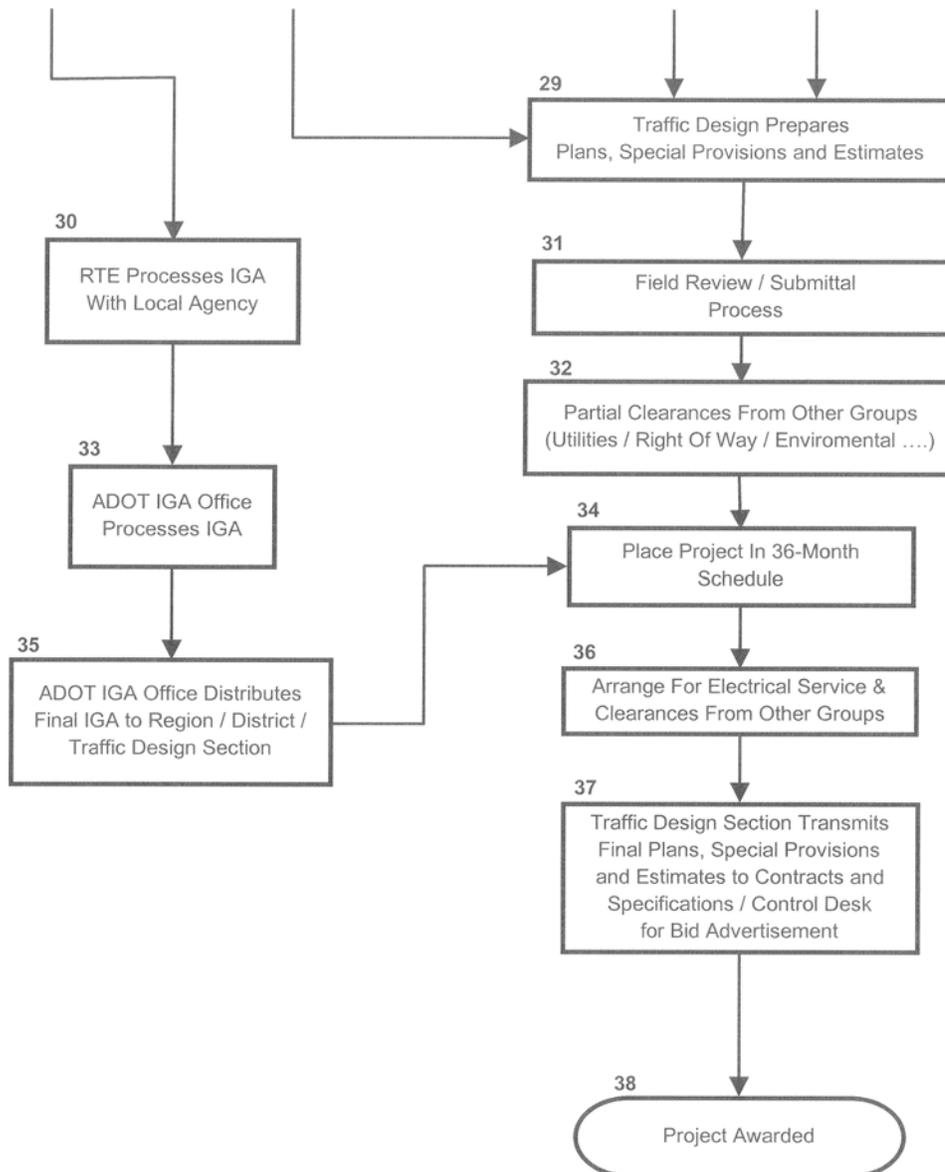


FIGURE 10 (Continued).

- Semi-quantitative use of historic volume and occupancy data from traffic system detectors or volume data from machine counts to identify the major trends.
- Computer analysis of historic volume and occupancy data from traffic system detectors (Gordon 1988).

Procedures for timing fully actuated and semi-actuated controllers are described in the *Highway Capacity Manual* (2000, pp. 16-101-16-116).

Requirement F 2.1—Requirements for Signal Coordination

Although coordination of adjacent signals often provides benefits, in each case the traffic systems engineer must

decide whether better performance will be achieved with coordinated or isolated operation.

When a platoon of vehicles is released from a traffic signal, the degree to which this platoon has dispersed at the next signal (difference from profile at releasing signal) in part determines whether significant benefits can be achieved from signal coordination.

Two general techniques are commonly used to determine coordination needs: information from prior research and experience, and simulation.

Information from Prior Research and Experience The TRANSYT platoon dispersion model is commonly used to

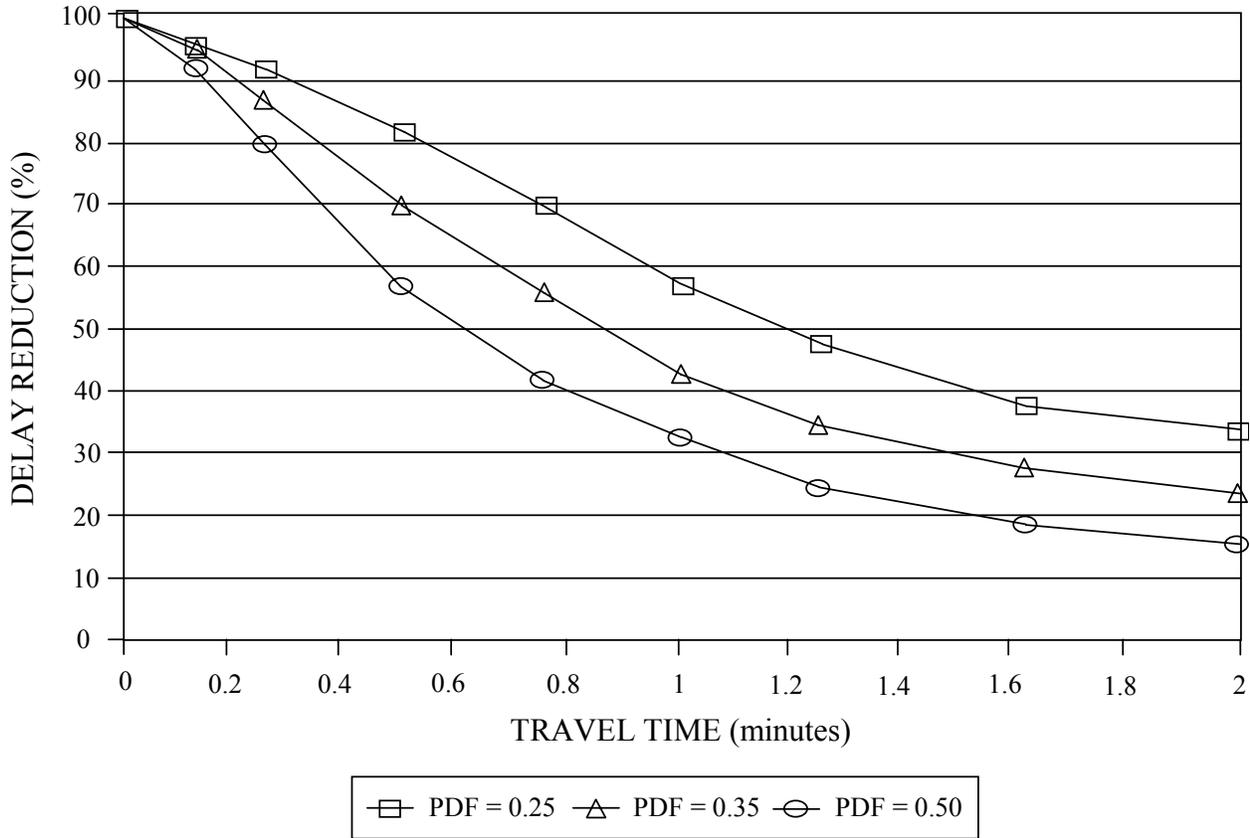


FIGURE 11 Benefits of signal coordination (Skabardonis et al. 1998).

TABLE 6
PLATOON DISPERSION FACTOR (PDF) CHARACTERISTICS

PDF Value	Roadway Characteristics	Conditions
0.5	Heavy friction	Combination of parking, moderate to heavy turns, moderate to heavy pedestrian traffic, narrow lane width. Traffic flow typical of urban CBD.
0.35	Moderate friction	Light turning traffic, light pedestrian traffic, 11 to 12 ft (3.4 to 3.7 m) lanes, possibly divided. Typical of well-designed CBD arterial.
0.25	Low friction	No parking, divided, turning provisions 12 ft (3.7 m) lane width. Suburban high type arterial.

Note: CBD = central business district.
(Source: Gordon et al. 1996)

represent this effect (Robertson 1969). In this model, platoon dispersion is a function of travel time to the downstream signal and roadway impedance to traffic flow or “friction.”

Figure 11 depicts the reduction in delay as a function of travel time and platoon dispersion factor (PDF) based on the TRANSYT model. PDF characteristics are shown in Table 6.

A number of simple criteria have been used that do not directly incorporate a platoon dispersion model, including

reduction in the queue (Robertson and Hunt n.d.), given by Eq. (1).

$$K = Q/(200(1 + t)) \tag{1}$$

where

- K = reduction in the queue (number of vehicles),
- Q = travel volume [number of vehicles/h (VPH)],
- and
- t = travel time between intersections (minutes).

- Criterion for good progression (Christopher and Kiddle 1979). Good progression when signal spacing is fairly uniform and $0.40 < \text{travel time/cycle length} < 0.60$.
- Criterion for coordinating signals (Wilshire et al. 1985). Coordinate signals within 0.8 km (0.5 mi).
- Criterion for coordinating signals (Gordon et al. 1996). Coordinate signals when spacing (ft) < 70 [desired arterial speed (ft/s)].
- Criterion for coordinating signals (Orcutt 1993), illustrated by Eq. (2).

$$I = V/L, I > 0.5 \quad (2)$$

where

V = two-way, peak-hour link volume (VPH); and
 L = link length (feet).

Chang and Messer (1986) developed the inter-coordination desirability index described in Eq. (3).

where

$$I = \left(\frac{0.5}{1+t} \right) * \left(\frac{q_{MAX}}{q_r} - (N-2) \right) \quad (3)$$

I = inter-coordination desirability index;
 t = link travel time (minutes);
 q_{MAX} = straight through flow from upstream intersection (VPH);
 q_T = sum of traffic flow at the downstream approach from the right turn, left turn, and through movements of the upstream signals, divided by the number of arrival links at the upstream intersection; and
 N = number of arrival lanes feeding into the entering link of the downstream intersection.

I may range from 0 to 1.0. Interconnection is recommended when I exceeds 0.35.

These criteria may also be employed to establish boundaries between sections of coordinated signals.

Simulation This is often used to determine coordination requirements and benefits, particularly when performed in connection with retiming of traffic signals. The systems engineer may employ a general model such as CORSIM (CORridor SIMulation), a widely used FHWA nonproprietary simulation model, together with a signal-timing program, or may use the evaluative features of a signal-timing program such as TRANSYT 7F. In the latter case, coordination requirements

and section boundary identification may be directly coordinated with the signal retiming effort.

A key issue is whether a major intersection operating at near capacity should be coordinated with a series of minor intersections (which by themselves might operate at a lower cycle length) or whether it should operate as an isolated intersection with its own cycle (Skabardonis et al. 1998).

Requirement F 2.2—Coordinated Traffic Control Systems

Systems engineering and design may be influenced by the following:

- Characteristics of systems provided by the available suppliers. Traffic signal systems engineering consists, to a large extent, of the selection of technologies from those provided by industry. Although relatively minor software changes are frequently made to satisfy unique requirements, the basic system usually includes a software package provided by the supplier.
- Requirements to interface with legacy field equipment or legacy communications.

Coordination may be achieved in the following ways:

- Time base coordination or
- Coordination through virtual or physical interconnection.

Figure 12 provides an overview of the evolution of interconnected traffic signal systems from a chronological perspective. The arrows emerging at the right of the figure represent the four currently surviving interconnected architectures.

Table 7 identifies a hierarchy of coordinated traffic control systems. These are discussed in terms of their capability level in the following sections.

Level 1—Time Base Coordination(TBC) Modern intersection controllers provide coordinated signal timing plans without the need for a wireline or wireless communication technique. Operation of TBC with up to three weekday timing plans is common. Although TBC entails a relatively low capital cost and is commonly used for backup of interconnected systems when the central computer or communication fails, the system designer must consider the following limitations before selecting this approach for primary control:

- Equipment status is not provided; thus, equipment failure or failure to display the appropriate signal timing cannot be automatically identified at the traffic management center (TMC) or in the maintenance facility.

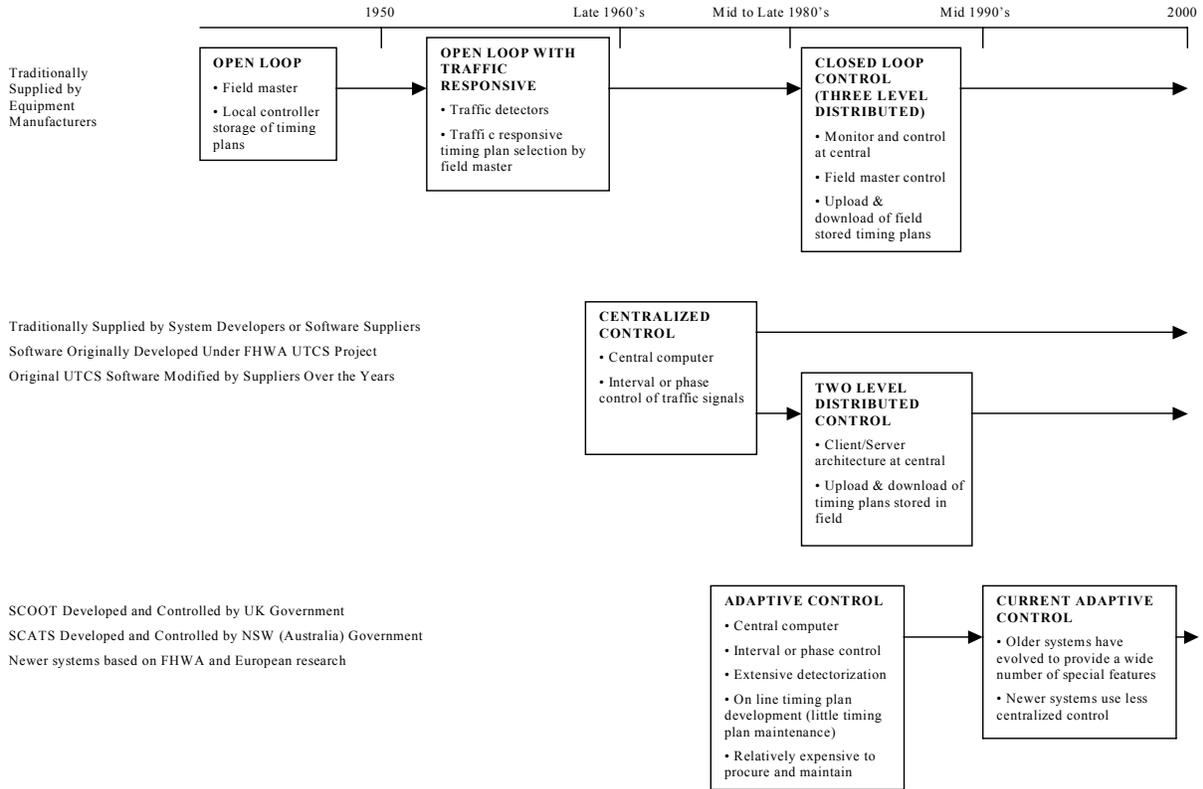


FIGURE 12 Interconnected traffic control system chronology.

TABLE 7
COMPLEXITY HIERARCHY OF TRAFFIC CONTROL SYSTEMS

Type of System	Features	Implementation Requirements
Level 1—Time base coordination <ul style="list-style-type: none"> Time of day plans Local intersection strategies 	<ul style="list-style-type: none"> Provides basic coordination 	<ul style="list-style-type: none"> Simple to implement. TBC provided by modern controllers Requires timing plan maintenance
Level 2—Interconnected control <ul style="list-style-type: none"> Time of day or operator-selected timing plans Local intersection strategies 	Level 1 + <ul style="list-style-type: none"> Provides intersection and equipment status Allows download of timing plans and changes Provides record of system operation 	Level 1 + <ul style="list-style-type: none"> Wireline or wireless interconnect Two or three level distributed control or central control Few or no system detectors
Level 3—Conventional traffic-responsive control <ul style="list-style-type: none"> Area traffic-responsive control Critical intersection control (centralized architecture only) Local intersection strategies 	Level 2 + <ul style="list-style-type: none"> Section-wide traffic responsive operation Can display and record traffic conditions Provides data to analyze and assess need for and nature of timing plan changes 	Level 2 + <ul style="list-style-type: none"> Modest level of system detectorization Additional database development
Level 4—Adaptive control <ul style="list-style-type: none"> Intracycle control or control by signal phase Imbeds features of central control and local intersection control 	Level 2 + <ul style="list-style-type: none"> Rapid traffic-responsive operation using microscopic data Subsumes conventional local intersection control Simplifies timing plan maintenance and database update Can display and record traffic conditions 	Level 2 + <ul style="list-style-type: none"> High level of system detectorization May need special controller interfaces System design and operation more complex and may require higher skill level

Notes: TBC = time base coordination.

TABLE 8
TIMING PLAN (TP) INITIATION SCHEDULE FOR WHITE PLAINS, NEW YORK

Time of Day	Section Type			
	Section 1 CBD Grid	Section 2 Arterial	Section 3 Arterial	Section 4 Arterial
24:00 (continued)	TP1	TP1	TP1	TP1
07:30	TP2	TP2	TP2	TP2
08:45	TP3	TP3		
09:15			TP3	
09:30				TP3
11:00	TP4			
11:45		TP4	TP4	TP4
15:30			TP5	
16:00	TP5			
16:15				TP5
18:30	TP6	TP5	TP6	TP6
20:30		TP1		
20:45	TP1		TP1	
21:30				TP1

Note: CBD = central business district.

(Source: Dunn Engineering Associates, *Evaluation Report* . . . 1991)

- Timing plans cannot be selected by or changed from the TMC. Implementation of a new or modified timing plan requires a visit to the intersection.
- Section-wide, traffic-responsive operation cannot be achieved.
- No record is available of equipment operation or traffic conditions.

These limitations lead to fewer motorist benefits, particularly when the additional response time to resolve equipment or timing failures is considered. Limitations may also affect the cost of operations and maintenance.

Interconnected Systems Wireline or wireless techniques may be used to achieve interconnection. These systems are represented in Table 7 as Levels 2, 3, and 4.

- Levels 2 and 3—These levels physically differ by the density of system detectors provided. Level 2 resolves the deficiencies of TBC described previously. Level 3 provides the capability to achieve the following:
 - Traffic-responsive timing plan selection on a section basis using conventional strategies.
 - Traffic data to establish timing plans specifically tailored to recurrent traffic variations. This requires additional systems and traffic engineering capability. Considerably more than the three traditional timing plans may be feasibly provided. Assists to develop the number and operating periods for timing plans exist (Gordon 1998). A typical result of an analysis using this tool is shown in Table 8.
 - Enables a system operator to monitor traffic conditions and select an alternative timing plan, change a controller's timing, or take other appropriate action.

Table 9 summarizes the characteristics of the Level 2 and Level 3 systems described here including

- Two-Level Distributed Control—This architecture features a central computer and intersection controller. Signal timing plans are downloaded to the intersection controller and stored there so that they can be used as required by the control strategy in effect. Data from system detectors are preprocessed by the intersection controller and uploaded to the central computer. Traffic-responsive section timing plans are selected by the central computer, often using the Urban Traffic Control System (UTCS) signature matching algorithm (Gordon et al. 1996).
- Three-Level Distributed Control (Closed Loop)—In this architecture a unit commonly known as a “field master controller” lies between the central computer and intersection controller. The field master may be located physically at the TMC or in the field. Signal timing plans are transferred from the central computer to the field master and then to the intersection controller. They are stored in the intersection controller so that they can be used as required by the control strategy in effect. System detector data are preprocessed by the intersection controller and further processed by the field master. These data are then transferred to the central computer. Traffic-responsive area timing plans are selected by the field master based on volume and occupancy detector threshold values for cycle, split, and offset. Guidance for the location of system detection is provided by Balke et al. (1997).
- Centralized Control—This architecture is characteristic of the traditional UTCS-type systems. Signal control is based on background timing plans residing in the central computer. Interval or phase changes are communicated to the intersection controller. Detector

TABLE 9
MAJOR CHARACTERISTICS OF LEVEL 2 AND LEVEL 3 TRAFFIC CONTROL SYSTEMS

System Characteristic	System Type		
	Two-Level Distributed	Closed Loop (Three-Level Distributed)	Central System
Upload/download of timing plans	Yes	Yes	Not necessary
Second by second signal control	No	No	Provided by interval or phase control of timing plans
Second by second monitoring of field equipment	Sometimes	Sometimes	Yes
Timing plan storage in controller required	All plans	All plans	Backup plans
Conventional MOE generation, graphics, reports, communications monitoring, failure checking, archiving, etc.	Yes	Yes	Yes
Field master	No	May be in field or at central	No
Timing plan maintenance required	Yes	Yes	Yes
Number of detectors in field	Low for Level 2, moderate for Level 3	Low for Level 2, moderate for Level 3	Low for Level 2, moderate for Level 3
Section traffic-responsive control	Level 3: Usually uses UTCS first general algorithm	Level 3: Usually uses cycle, split, and offset selection by threshold	Level 3: Usually uses UTCS first general algorithm
CIC capability (cycle-based split changes)	No	No	Capability with Level 3 detectorization

Notes: MOE = Measure of effectiveness; UTCS = urban traffic control system; CIC = critical intersection control.

data and field equipment status is polled by the central computer at frequent intervals. Traffic-responsive area timing plans are selected by the central computer using the UTCS signature matching algorithm. A cycle by cycle critical intersection control (CIC) capability is provided for use at intersections with high volume-to-capacity ratios that do not use conventional local actuation (Gordon et al. 1996).

Although stemming from different genealogies, current two-level and three-level distributed control systems are seen to have quite similar characteristics (see Table 25). They differ primarily in the way controllers are organized into traffic control sections and in the organization of communication channels. The traffic-responsive control algorithms are also different.

Level 3 systems require considerable maintenance of their databases. In particular, the following functions must be maintained:

- Updating of timing plan sequences. Traffic-responsive operations also require the development of signatures or detector thresholds.
- Partial or complete automation of timing plan development with particular attention to avoiding manual collection of turning movement counts (Rowe 1991).
- Migration of timing plans and detector signatures into the traffic control system database.

The provision of system support in these areas has been referred to as UTCS 1.5 Generation Control. Some system suppliers provide the capability to address some of these requirements (Yagoda 1982; JHK & Associates 1996).

- Level 4—This level consists of a family of techniques that collectively have been termed “adaptive systems.” Typically, adaptive systems apportion intersection green time based on prediction of platoon arrivals. Timing decisions are made within the traffic cycle or during each signal phase. Adaptive systems not only have the capability to respond to traffic variations by rapidly changing timing, but they also do not require the same level of manual participation in database and signal timing revisions necessary in Level 3 systems.

These systems typically use traffic information at or near the intersection in addition to information remote from the intersection. Strategies differ significantly with the type of adaptive system. Although adaptive systems have the potential to reduce the database maintenance effort required by Level 2 or Level 3 systems, the level of expertise required to design, deploy, initialize, and maintain these systems is often much greater than that required for the other levels. Adaptive systems may require additional or modified intersection controller equipment.

The following adaptive systems are available from suppliers in the United States and provide information on the control strategies.

- SCOOT (Robertson 1987; Bretherton and Bowen 1990).
- SCATS (Lowrie 1991).
- OPAC (Gartner et al. 1991).
- RHODES (Head et al. 1998).
- ATCS (ATCS . . . 1998).

Interoperability Traffic signal systems may be required to interoperate with other ITS for the following reasons:

- To provide signal timing plans on diversion routes in response to freeway incidents,
- Coordinate signals along arterials that cross jurisdictions, and
- Share operations and/or maintenance responsibilities among jurisdictions.

Although in some cases these functions may be performed manually, in other cases data flows among systems using protocols common to these systems may be employed. Memoranda of understanding or other agreements may be required to provide the institutional basis for data or command transfer.

Selection Methodology Once having decided that signal coordination is required, the systems engineering team must select the appropriate level of coordination. Many operating agencies feel that Level 2 operation is an appropriate minimum requirement (see chapter five). Monitoring of equipment and timing operations has demonstrated significant benefits (Rowe 1991). In some cases, standard specifications for interconnected systems have been prepared by states and policy dictates their use on major arterials (“EBM-CL-1 . . .” 1996). Some agencies require monitoring for equipment failure even when signals are not interconnected. Not infrequently, the selection between Level 1 and Level 2 design depends on the availability of funding.

No methodology for quantifying the benefits of the Level 2 over Level 1 or providing a basis for selection has been found in the literature.

Hanbali and Formal (1997) have reported on the benefits from Level 3 operation relative to Level 2 in terms of congestion and safety. Rowe (1991) states that “It has been found to be an improvement over time-of-day timing plan selection in those instances where day-to-day variations are significant.” Similarly, the use of CIC showed significant levels of delay reduction (Skabardonis et al. 1999).

The literature does not, however, quantify the benefits of moving from Level 2 to Level 3 in sufficient detail to be used for system selection purposes, nor are guidelines to be found in the literature.

The benefits in moving from Level 3 to Level 4 have been estimated as up to 7% in delay (*Workshop . . .* 2001). In addition, considerable research has been performed in moving from Level 2 to Level 4 (Robertson 1987; Bretherton and Bowen 1990; Lowrie 1991; Yedlin 1994; Andrews et al. 1997; Head et al. 1998). The research

shows a considerable range of benefits (from more than 20% improvement in delay to significant harm). Benefits using SCOOT have been reported as 12%, plus 3% each year since the updating of fixed-time plans (*Workshop . . .* 2001). The results vary with the algorithm, test site conditions, quality of signal timing before improvement, and test methodology. Although sometimes impressive, the results do not provide the systems engineer with a sufficient a priori basis for either selecting Level 4 (as compared with Levels 2 or 3) or selecting the appropriate Level 4 strategy.

Simulation does, however, offer the possibility of comparatively evaluating Levels 2, 3, and 4 and selecting strategies for the particular site to be controlled. Although CORSIM can be used for this purpose (Head et al. 1998; Abdel-Rahim and Taylor 2000), considerable effort is required to program the control algorithms themselves and to provide the interface to CORSIM. Other simulations have also been used for this purpose (Stewart et al. 1998). The skills required to implement this effort probably exceed the capabilities of most jurisdictions and consultants.

In summary, benefit-based guidelines for selecting among Levels 2, 3, or 4 currently do not exist. Simulation for benefit estimation, although possible, is difficult for nonresearch-oriented practitioners and may be quite costly.

Requirement S 2—Communication Subsystems

Requirements and Measures of Performance Most agencies use system reliability as the primary measure of performance for their communications system. System reliability is measured in two ways (Carvell et al. 1997).

- Transmission errors—Transmission errors are measured in bit error rate (BER). BER is the ratio of incorrectly transmitted bits to correctly transmitted bits. Values of approximately 10^{-6} or better for end-to-end communications represent an acceptable BER for most computer and traffic control communications systems (Gordon et al. 1993). Most systems have processes to detect errors in communication signals.
- System uptime—System uptime is another common measure of the performance of a communications system. System uptime represents the portion of the normal operating time of the system during which a link or the entire communications system is functioning properly (Carvell et al. 1997).

Using these measures, the system designer must select equipment approaches that satisfy these requirements. For example, providers of fiber optics communication equipment can supply redundant ring modems. Using this equipment and additional fibers, failure of a single modem in a chain of controllers will affect only that controller and

not the controllers physically downstream of the failed controller. The use of wireless techniques such as spread spectrum radio may require additional repeaters to obtain similar system reliability.

Traffic Control Communication Protocols and Interfaces Appendix E describes various interface alternatives for communicating with controllers. Modern systems generally use a modem that is either incorporated into the controller unit or is external to it. In the latter case, communication between the modem and controller is accomplished using serial ports.

A Kimley-Horn and Associates report (1995) summarizes the communications systems and protocols used by a number of traffic systems.

Communication systems require a protocol to transfer data between the controller and the central computer or field master. The protocol establishes the set of rules by which information is communicated. At this writing most systems use protocols that are proprietary to the controller supplier or the system supplier. In systems that use NEMA-type controllers, this essentially limits the user to one controller supplier. Controller *interchangeability* is not possible under these circumstances.

To address this problem, some system suppliers developed a protocol that was made available to controller suppliers (*Protocol—90 . . . 1992*). This protocol enables users of that supplier’s central system to employ controllers from multiple suppliers.

To facilitate interchangeability among all system suppliers and controller equipment suppliers and to foster *interoperability* (the ability to use many different types of devices on the same communications channel) the NTCIP (National Transportation Communications for ITS Protocol) was established. This standard set is incorporated into the National ITS Architecture. *The NTCIP Guide* (1999) provides an overview of this protocol. NTCIP provides a set of protocols for communication from control centers to other devices besides traffic signal controllers. The NTCIP standards framework is a comprehensive set of compatible standards for communication between ITS centers and devices. Figure 13 depicts the NTCIP standards framework. *The NTCIP Guide* also provides guidance for determining the communication channel data loadings engendered by NTCIP. The framework provides for communication between control centers, using either the DATEX standard or the CORBA approach.

In addition to the mandatory and optional objects (messages) specified by NTCIP, the standard also provides for

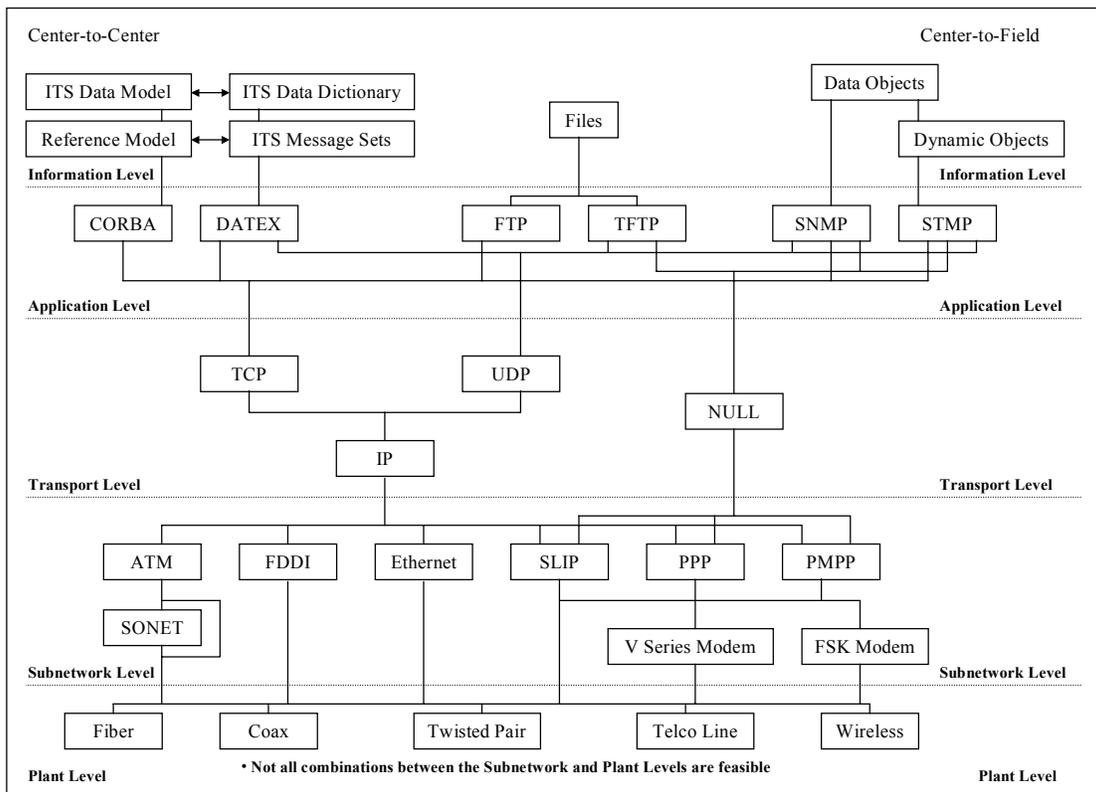


FIGURE 13 NTCIP standards framework (*The NTCIP Guide* 1999).

proprietary objects. The effect is to provide for a core set of functions to provide interchangeability and interoperability, and another set of functions that permits suppliers to differentiate their products.

NTCIP is currently in a relatively early stage of implementation for communication to traffic signal controllers. Early implementation projects have identified problems that are currently being addressed (*The NTCIP Guide* 1999).

Media and Equipment Technology Current traffic signal systems use a variety of media including copper and fiber optic-based communication cable, coaxial cable, and several forms of wireless communication. Media may be owned, leased, or utilized on a per message basis.

Where closed-circuit television (CCTV) is extensively employed on surface streets, the CCTV communication requirements often dominate the selection of media and technology. It may be necessary to consider requirements for media to be shared with other municipal services or with other telecommunications service providers.

Burchett (1998) reviewed several case studies that provide fiber optic communications for traffic systems in combination with other municipal services. The plant level of Figure 13 (at bottom) identifies basic classes of communications media.

The *Communications Handbook for Traffic Control Systems* (Gordon et al. 1993) provides a methodology and procedure for selection of communications system media and topology (see following subsection). The methodology as provided does not incorporate some of the media and communication services that have become prominent since its publication, but is sufficiently flexible to provide for its incorporation.

The third *Traffic Control Systems Handbook* (Gordon et al. 1996) and the *Freeway Management Handbook* (Carvell et al. 1997) update the technologies. The latter reference also provides guidance on communication performance criteria and communication topologies.

Physical Architecture and Topology The systems designer is responsible for selecting the forms of physical interconnection that will be used. Two interconnection attributes are

- Physical Architecture—Although many small- and medium-size traffic signal systems often use a single communications link from the control center to the intersection controller, closed-loop systems and large systems often find it necessary to utilize different types of media, data rates, or changes in the character

of the information as data moves between the control center and the field controller. The various schemes and combinations may be referred to as the “physical architecture.” Figure 14 depicts some of the physical architectures as shown in the *Communications Handbook for Traffic Control Systems*. The identification of the appropriate physical architecture is done in combination with technologies, traffic signal systems architectures, data rate requirements, and institutional issues. The *Communications Handbook for Traffic Control Systems* describes a formal process for architecture and technology selection (see Appendix F).

- Topology—Starting at the control center, field master, field multiplexer, or communications hub, physical interconnections to the downstream devices may take several forms (topologies).

Figure 15 illustrates a number of these topologies. Selection of a topology depends on the required transmission error rate and system uptime as well as on the physical locations of the controllers. The communication selection procedure in the *Communications Handbook for Traffic Control Systems* does not directly address topology selection.

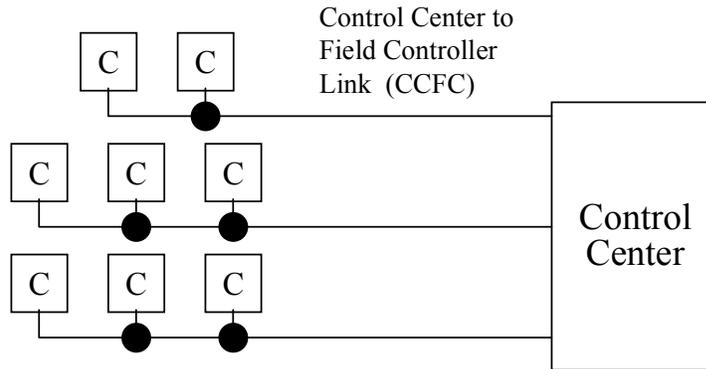
The FHWA report *Communications for Intelligent Transportation Systems, Successful Practices, A Cross-Cutting Study* (2000), describes the alternatives for selecting organizations to perform the communications system design. It also describes the relationships between communications design and the National ITS Architecture, particularly with regard to requirements for interoperability among agencies.

Although the ITS Communication Document incorporated in the National ITS Architecture has a great deal of background information on communication requirements and technology for many ITS services, it is not easily focused to assist the systems engineer in the selection of communications for traffic signal systems (*The National ITS Architecture* 1999).

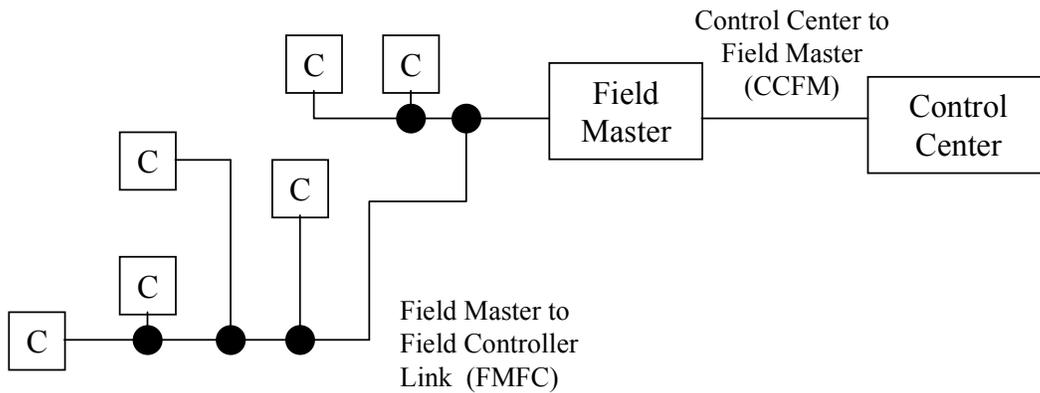
In larger traffic signal systems and in signal systems that share communications networks with other functions it may be difficult to perform a communications traffic loading model analytically. Commercial simulation packages may be used to perform this function. OPNET is an example of a simulation that is commonly used by the telecommunications industry (OPNET 2000).

During the past decade a considerable number of telecommunications products and services have come on the market and it is expected that this trend will continue. In some cases manufacturers have adapted these technologies for specific use in traffic signal systems. The most current sources of information are likely to be traffic signal industry-oriented publications and manufacturer representatives.

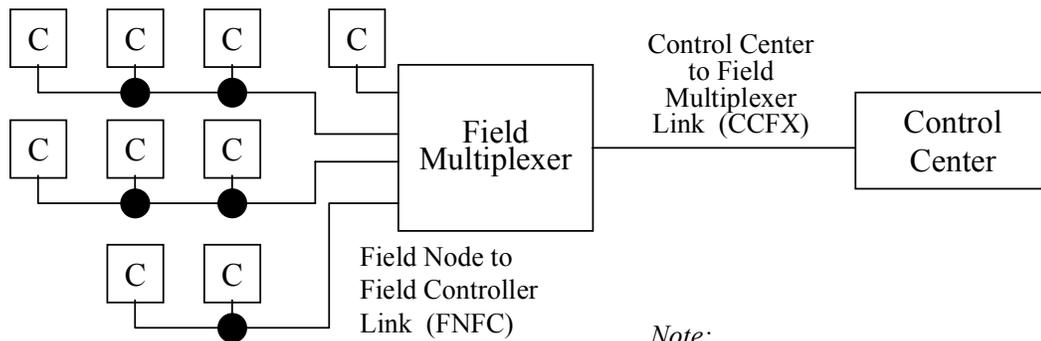
A. CENTRAL ARCHITECTURE



B. DISTRIBUTED ARCHITECTURE



C. COMMUNICATIONS TRUNKING ARCHITECTURE



Note:

All links that interface with field controllers may be multiplexed

FIGURE 14 Representative physical architectures (Gordon et al. 1993).

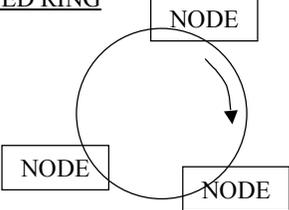
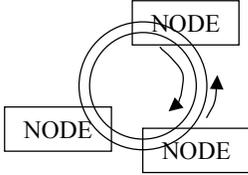
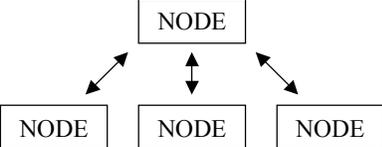
<p><u>UNPROTECTED RING</u></p> 	<p><u>BACKBONE NETWORK</u> HANSHIN EXPWY (DATA)</p>	<p><u>DISTRIBUTION NETWORK</u></p>
<p><u>PROTECTED RING</u></p> 	<p>HIGHWAY 401 (DATA) I-70 TUNNEL SEATTLE</p>	
<p><u>LINEAR DROP</u></p> 	<p>HOUSTON SEATTLE SAN ANTONIO SHIRLEY HWY EXTENSION</p>	<p>HWY 401 (CONTROLLERS) SEATTLE</p>
<p><u>STAR</u></p> 	<p>HIGHWAY 401 (VIDEO) ATSAC HOUSTON SAN ANTONIO (INITIAL INSTALLATION, ULTIMATE CONFIGURATION WILL BE PROTECTED RING)</p>	<p>HIGHWAY 401 SHIRLEY HWY EXTENSION I-70 TUNNEL HANSHIN (DATA, VIDEO) ATSAC MASSEY TUNNEL HOUSTON SEATTLE SAN ANTONIO</p>

FIGURE 15 Traffic control system communications network topologies (Gordon et al. 1993).

Requirements S 3.1 and S 3.2—Intersection Field Equipment Subsystem

This basically consists of intersection traffic control system equipment, cabinets, and traffic detectors for local intersection control and coordinated system control. The design of intersection traffic controllers and cabinets in the United States is highly influenced by equipment standards. A number of alternatives are available for traffic detectors.

Available Standards Almost all of the available traffic signal controllers conform to one of the following families of standards, and the systems engineer is, in essence, required to select from among these families.

- National Electrical Manufacturer's Association (NEMA) Standards Family.
- Model 170 Standards Family consisting of Model 170, 170E, 2070, 2070N, Advanced Transportation Controller. The Model 179 used in New York State and several other locations is also a member of this family.

NEMA Standards Family This specification family describes the functional characteristics of traffic control equipment as well as electrical interfaces and certain

physical standards (*NEMA Traffic Control Systems* 1983; *Traffic Controller Assemblies* 1992; *Traffic Controller Assemblies . . .* 1998). The specifications provide minimum performance requirements. Suppliers provide equipment that conforms to or exceeds these requirements. The NEMA standards also include specifications for inductive loop detectors.

Model 170 Standards Family This controller family started with the Model 170 controller and includes Model 170E. A major upgrade has recently been implemented (Models 2070 and 2070N).

These specifications describe equipment requirements in sufficient detail so that interchangeable equipment may be procured from alternate sources (*Transportation Electrical . . .* 1997). Because the specifications do not include applications software functionality (as does the NEMA family), firmware must be acquired by the user. Suppliers are available to provide this firmware.

Specifications developed by Caltrans are commonly used by many agencies responsible for traffic signal systems. Caltrans specifications also provide for inductive loop detectors and magnetic detectors.

An initiative is currently under way to develop specifications for an Advanced Transportation Controller (Joint Committee on the ATC 2000). It is intended to provide an open architecture platform and will accommodate both NEMA family and Model 170 family users.

Controller Selection Methodology Although the literature provides little formal guidance on the selection of a controller family, traffic engineers often have the knowledge (based on experience, supplier contacts, and supplier literature) to select a controller family and the important variations within that family. Anecdotal evidence points to the importance of the following factors in the selection process:

- Legacy issues and compatibility with existing equipment are very important to many agencies in controller family selection.
- Organizations desiring to standardize on designs to improve logistics and to provide an opportunity for competitive bidding to an open specification may prefer the Model 170 family.
- Organizations that may require considerable technical and product support and that may desire to use the supplier as a “systems house” may prefer the NEMA family.

Traffic Detectors Prior to 1990, traffic-responsive signal timing-plan selection and on-line timing-plan generation almost exclusively used the inductive loop detector. Local actuation primarily depended on the inductive loop detector, but magnetometers, pressure detectors, and microwave detectors were also used. Since that time, a number of agencies have begun to seriously consider and to use other recently developed detector technologies.

Tradeoffs for selecting detectors are provided in some of the FHWA handbooks (Gordon et al. 1996; Carvell et al. 1997), as well as other material. FHWA and other agencies have published results comparing test data for various detectors (Klein and Kelley 1995). Klein (2001) provides a reference for detector technology, as well as the analysis and algorithms for estimating state variables. An extensive set of references on detectors and related technologies is also provided. Tables 10 and 11 show trade-off information.

Because operational characteristics and performance capabilities for emergent detector technologies change rapidly, the systems engineer must be sure that the information sources reflect current developments.

Requirement F 3.1—Local Intersection Control Strategies

If adaptive system coordination (Level 4 coordination) is selected, the adaptive strategy essentially determines the strategy for operating and instrumenting the local intersection. For each of the other levels of coordination, as well as

for noncoordinated signals, the following combinations are usually employed:

- Isolated intersections—Pretimed or fully actuated operation is conventionally used. Tarnoff provides guidelines for selecting between these alternatives (Tarnoff and Parsonson 1981). Skabardonis recommends the use of fully actuated operation at an intersection that operates close to saturation and with complicated geometrics or phasing (Skabardonis et al. 1998).
- Coordinated intersections—Pretimed or semi-actuated operation is conventionally used. Skabardonis provides guidelines based on volume-to-capacity ratio and arterial-volume-to-cross-street volume ratio as well as other factors for the selection of signal control strategy (Skabardonis et al. 1998). Also, Chang describes a set of guidelines for strategy selection (Chang 1996).

Requirement F 3.3—Preemption

Signal preemption is provided for two purposes, railroad grade crossing signal preemption and emergency vehicle signal preemption. Modern traffic controllers are designed to support preemption equipment and provide preemption timing sequences (*Traffic Controller Assemblies . . .* 1998).

Railroad Grade Crossing Preemption The need for preemption is established by the MUTCD (2000). Additional guidance for the need and functional operation of preemption is provided by the Institute of Transportation Engineers (ITE) Technical Council Committee TENC-4M-35 (*Pre-emption of Traffic . . .* 1997) and by Marshall and Berg (1997).

Emergency Vehicle Preemption This section is largely based on material in a Dunn Engineering Associates (*Route 5 Corridor Project—Task 4 . . .* 1999) report.

The following issues should be addressed by jurisdictions potentially interested in the provision and use of emergency vehicle preemption service:

- Identification of the types of emergency vehicles and the agencies that operate them that desire preemption and are candidates. Police vehicles, fire department vehicles, and ambulances are typical candidates for emergency vehicle preemption.
- Willingness of the agencies desiring emergency vehicle preemption to equip their vehicles with other than existing sirens and maintain the equipment.
- Relationship to centrally controlled preemption. Some traffic systems employ a centrally controlled fire run preempt sequence. The relationship of these controls to vehicle-based preemption must be established.

TABLE 10
STRENGTHS AND WEAKNESSES OF COMMERCIALY AVAILABLE SENSOR TECHNOLOGIES

Technology	Strengths	Weaknesses
Inductive loop	<ul style="list-style-type: none"> • Flexible design to satisfy large variety of applications • Mature, well-understood technology • Large experience base • Provides basic traffic parameters (e.g., volume, presence, occupancy, speed, headway, and gap) • High frequency excitation models provide classification data 	<ul style="list-style-type: none"> • Installation requires pavement cut • Decreases pavement life • Installation and maintenance require lane closure • Wire loops subject to stresses of traffic and temperature • Multiple detectors usually required to monitor a location • Accuracy may decrease when design requires detection of a large variety of vehicle classes
Magnetometer (two-axis fluxgate magnetometer)	<ul style="list-style-type: none"> • Less susceptible than loops to stresses of traffic • Some models transmit data over wireless radio frequency link 	<ul style="list-style-type: none"> • Installation requires pavement cut • Decreases pavement life • Installation and maintenance require lane closure • Models with small detection zones require multiple units for full lane detection
Magnetic (induction or search coil magnetometer)	<ul style="list-style-type: none"> • Can be used where loops are not feasible (e.g., bridge decks) • Some models installed under roadway without need for pavement cuts • Less susceptible than loops to stresses of traffic 	<ul style="list-style-type: none"> • Installation requires pavement cut or tunneling under roadway • Cannot detect stopped vehicles unless special sensor layouts and signal processing software are used
Microwave radar	<ul style="list-style-type: none"> • Typically insensitive to inclement weather at the relatively short ranges encountered in traffic management applications • Direct measurement of speed • Multiple-lane operation available 	<ul style="list-style-type: none"> • Continuous wave Doppler sensors cannot detect stopped vehicles
Active infrared	<ul style="list-style-type: none"> • Transmits multiple beams for accurate measurement of vehicle position, speed, and class • Multiple-lane operation available 	<ul style="list-style-type: none"> • Operation may be affected by fog when visibility is less than ≈ 20 ft or blowing snow is present
Passive infrared	<ul style="list-style-type: none"> • Multizone passive sensors measure speed 	<ul style="list-style-type: none"> • Passive sensor may have reduced sensitivity to vehicles in its field-of-view in heavy rain and dense fog • Some models not recommended for presence detection
Ultrasonic	<ul style="list-style-type: none"> • Multiple-lane operation available • Capable of overheight vehicle detection • Large Japanese experience base 	<ul style="list-style-type: none"> • Some environmental conditions such as temperature change and extreme air turbulence can affect performance. Temperature compensation is built into some models • Large pulse repetition periods may degrade occupancy measurement on freeways with vehicles traveling at moderate to high speeds
Acoustic	<ul style="list-style-type: none"> • Passive detection • Insensitive to precipitation • Multiple-lane operation available 	<ul style="list-style-type: none"> • Cold temperatures have been reported as affecting data accuracy • Specific models are not recommended with slow moving vehicles in stop-and-go traffic
Video image processor	<ul style="list-style-type: none"> • Monitors multiple lanes and multiple zones/lane • Easy to add and modify detection zones • Rich array of data available • Provides wide-area detection when information gathered at one camera location can be linked to another 	<ul style="list-style-type: none"> • Inclement weather such as fog, rain, and snow; vehicle shadows; vehicle projection into adjacent lanes; occlusion; day-to-night transition; vehicle/road contrast; and water, salt, grime, icicles, and cobwebs on camera lens can affect performance • Requires 50- to 60-ft camera mounting height (in a side-mounting configuration) for optimum presence detection and speed measurement • Some models susceptible to camera motion caused by strong winds • Generally cost-effective only if many detection zones within the field-of-view of the camera or specialized data are required

(Source: Klein 2001).

TABLE 11
TRAFFIC OUTPUT DATA (TYPICAL), COMMUNICATIONS BANDWIDTH, AND COST OF COMMERCIALY AVAILABLE SENSORS

Technology	Output Data			Occu- pancy	Classifi- cation	Multiple-Lane, Multiple-Detection Zone Data	Communication Bandwidth	Sensor Purchase Cost ^a (each in 1999 U.S. \$)
	Count	Presence	Speed					
Inductive loop	▶	▶	▶ ^b	▶	▶ ^c		Low to moderate	Low ^d (\$500–\$800)
Magnetometer (two-axis fluxgate)	▶	▶	▶ ^b	▶			Low	Moderate ^d (\$1,100–\$6,300)
Magnetic (induction coil)	▶	▶ ^e	▶ ^b	▶			Low	Low to moderate ^d (\$385–\$2,000)
Microwave radar	▶	▶ ^f	▶	▶ ^f	▶ ^f	▶ ^f	Moderate	Low to moderate (\$700–\$3,300)
Active infrared	▶	▶	▶ ^g	▶	▶	▶	Low to moderate	Moderate to high (\$6,500–\$14,000)
Passive infrared	▶	▶	▶ ^g	▶			Low to moderate	Low to moderate (\$700–\$1,200)
Ultrasonic	▶	▶		▶			Low	Low to moderate (Pulse model: \$600–\$1,900)
Acoustic array	▶	▶	▶	▶		▶ ^h	Low to moderate	Moderate (\$3,100–\$8,100)
Video image processor	▶	▶	▶	▶	▶	▶	Low to high ⁱ	Moderate to high (\$5,000–\$26,000)

^aInstallation, maintenance, and repair costs must also be included to arrive at the true cost of a sensor solution as discussed in the text.
^bSpeed can be measured by using two sensors a known distance apart or estimated from one sensor and the effective detection zone and vehicle lengths.
^cWith specialized electronics unit containing embedded firmware that classifies vehicles.
^dIncludes underground sensor and local detector or receiver electronics. Electronics options are available to receive multiple-sensor, multiple-lane data.
^eWith special sensor layouts and signal processing software.
^fWith microwave radar sensors that transmit the proper waveform and have appropriate signal processing.
^gWith multidetection zone passive or active mode infrared sensors.
^hModels with appropriate beam forming and signal processing.
ⁱDepends on whether higher-bandwidth raw data, lower-bandwidth processed data, or video imagery is transmitted to the traffic management center.
 (Source: Klein 2001).

- Identification of controllers to receive preemption and associated technologies and suppliers. Modern controllers have internal preemption capability, which is compatible with all preemption technologies. Preemption support for older controllers is provided by some manufacturers but not by others, possibly limiting the combinations of vendors and controllers available for preemption.
- Agreement must also be reached on the features to be incorporated. Although features such as reporting of preempted phases and preempting vehicles are available for certain preempt equipment, all traffic control systems do not necessarily support these features.
- Interjurisdictional preempt policy. Will emergency vehicles originating in one traffic jurisdiction be able to preempt signals in another traffic jurisdiction? Agreements for operation and equipment maintenance may be required. [Grayson (1999) describes a case study concerning issues involved for a police vehicle preemption project. Bullock et al. (1999) reports that emergency vehicle preemption impacts on arterial corridor flow are minor.]

- Technology alternatives. The following technologies have been implemented or are being proposed for preemption of traffic signals by emergency vehicles:
 - Optical-based preemption,
 - Siren-based preemption, and
 - Global Positioning System (GPS)/short-range radio-based preemption.

Suppliers’ material is the best source for the detailed characteristics for these technologies. Table 12 contains a comparison of optical and siren technology characteristics.

Requirement F 3.4—Transit Priority

Priority may be provided to transit vehicles by a number of passive and active strategies. Although these strategies have been extensively discussed in the literature, a comprehensive discussion with emphasis on active strategies is provided in the TCRP report *Improved Traffic Signal Priority for Transit* (1998). That report also contains an extensive set of references and provides a detailed review of

TABLE 12
COMPARISON OF PREEMPTION TECHNOLOGIES

Factor	Optical Technology	Siren Technology
Range	Up to 2,500 ft	Up to 1,500 ft
Risk	Most deployments	Considerably fewer deployments
Promote multi-agency use		Best—Preemption can be provided with current sirens
Control multi-agency use	Best	Theoretically can provide special sirens or encoding but not commonly done
Vehicle identification coding	Available if required (traffic systems and controllers may not support)	Claim to be developing
Interoperability among equipment manufacturers	Emitters generally interchangeable for low-end systems	Conventional sirens normally used with any supplier
Cost	<ul style="list-style-type: none"> • Cost for on-board equipment • Higher cost for intersection-based equipment 	<ul style="list-style-type: none"> • No additional on-board equipment required • Lower cost for intersection-based equipment
Routine maintenance	Optical surfaces require periodic cleaning	Best
Mounting	Mast arm. Poles may be used depending on visibility	Pole or mast arm
Support of internal preemption	Yes	Yes
Support of external preemption	Some suppliers can support many old controller types	Less support of older controllers

(Source: Dunn Engineering Associates, Route 5 Corridor Project—Task 4 . . . 1999).

signal priority strategies and their impacts on traffic controller timing changes to implement these strategies. Case studies are provided.

Signal priority may be provided by preemption, which is common in Europe. Most systems in the United States employ conditional priority strategies to prevent excessive congestion on nonpriority phases.

Goals of Transit Signal Priority These goals may include

- Decrease in average transit vehicle travel time resulting in shorter scheduled travel time and reduction in passenger travel time.
- Improved schedule adherence by providing priority to late transit vehicles. This results in reduction of passenger waiting time and improvement in perceived service reliability.
- Reduction in overall delay to riders in transit vehicles and in nontransit vehicles.
- Increase in traveler throughput.
- Improvement in transit modal split. This implies provision of benefits relative to automobile travel that are perceived by the public.

Constraints on Transit Signal Priority Successful implementation of transit priority generally depends on the cooperation and positive attitude on the part of the major stakeholders, including

- The traffic signal operating agency. Where the project involves multiple jurisdictions, the agencies must support a common signal priority technology.

- The transit authority.
- Transit riders and the motoring public.

A consensual approach among these stakeholders or their surrogates may result in the following types of constraints on priority operation:

- Limitations to traffic congestion induced by transit priority. This may result in limitations on the selection of priority intersections or the time periods during which priority is exercised.
- Frequency of priority grants.
- Limitation of one priority per intersection traffic cycle.
- Provision of priority when a certain net benefit level is achieved. This may limit its use under low ridership or deadheading conditions.

Elements of System Design The following elements of system design are interrelated and influence each other.

- Types of strategies—Signal priority strategies include the following:
 - Green extension,
 - Green advance (red truncation),
 - Green extension and advance,
 - Phase skipping,
 - Queue jump, and
 - Queue jump with green extension.
- Selection of transit routes for priority—The transit authority can provide data on high ridership routes and can identify candidate routes.
- Selection of priority intersections, priority phases, types of priority strategies, and priority periods—Priority intersections must satisfy the following conditions:

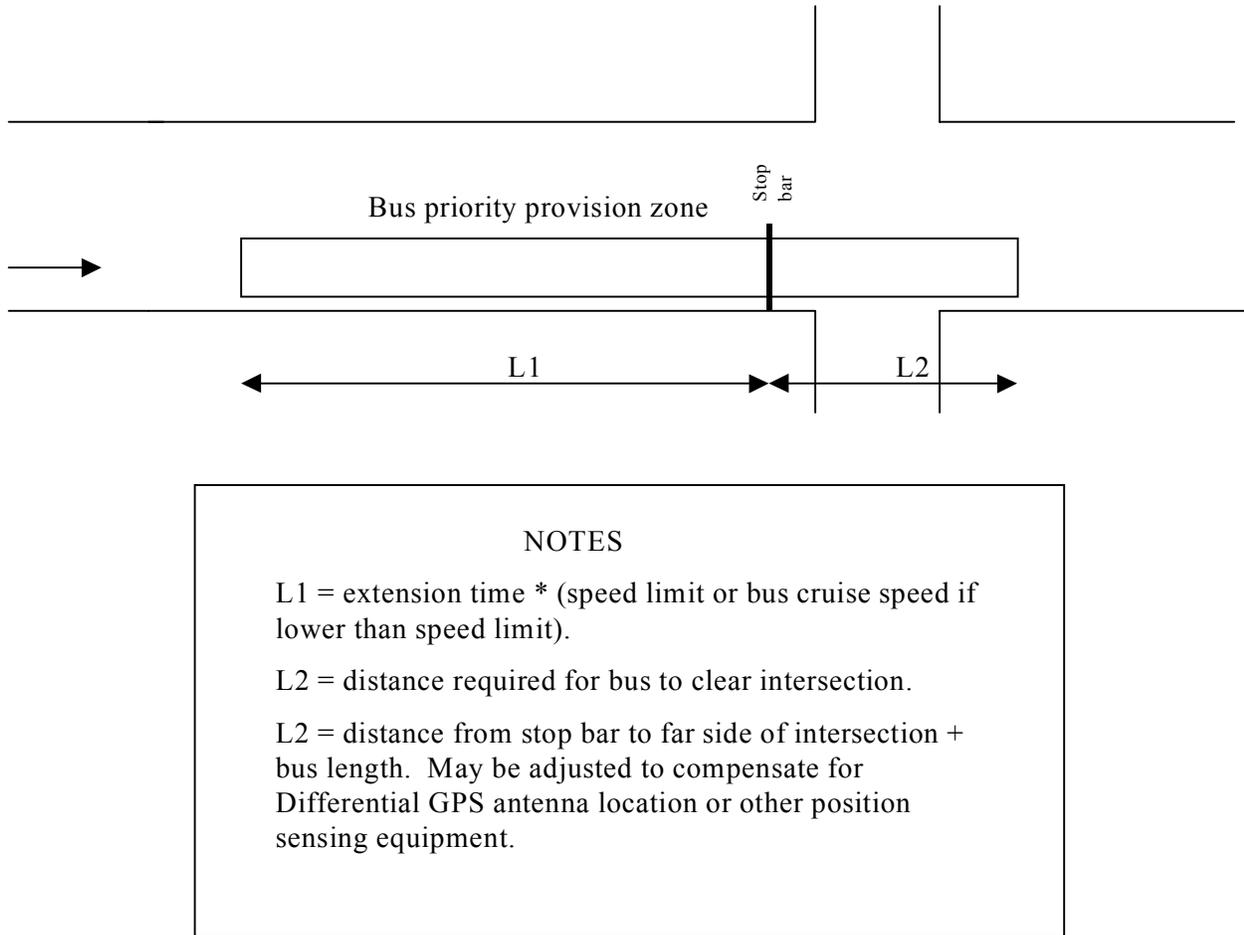


FIGURE 16 Bus priority provision zone.

- Signal priority must be capable of providing a meaningful benefit. For example, if the cross street to a major arterial being considered for priority has minimal vehicular and pedestrian volume and is semi-actuated, the signal remains green most of the time and the benefits of priority are minimal.
- Constraints on traffic impacts must be satisfied. For example, studies have shown that when the cross-street volume-to-capacity ratio does not exceed 0.8 to 0.85, the effects on cross-street delay are minor (Garrow and Machemehl n.d.). This may affect the time periods for which it is feasible to schedule priorities. Similarly, if priorities are to be granted by the elimination of turning phases or green time reduction, the effects of possible turning bay overloads should be considered.

A strategy type must be selected for each intersection (or for the route or system). The phases to be given priority and the phases to be shortened or eliminated must be identified. When phases are provided (including pedestrian phases), clearance periods must be satisfied.

Simulation is often a useful tool for evaluating the negative impacts of transit priority at an intersection.

- Technology selection—A typical arrangement for providing a green advance or green extension priority is shown in Figure 16. On entering the bus priority provision zone, a priority request would be provided. The priority request would be terminated when the bus leaves the priority provision zone. If a bus stop is located on Section L1 and the bus doors are open, the priority request is terminated and reinitiated when the doors close.

The implementation of these functions requires close coordination between the traffic signal agency and the transit system operator. Some transit properties operate or plan to operate “smart buses.” Smart bus items that may be of use for signal priority include

- Differential GPS receivers,
- On-board computers,
- Door status sensors,
- Dedicated short-range communications, and

- Data communications to dispatch center.

Equipment and software (available from a limited number of suppliers) must be provided to implement the following functions:

- Location of bus (e.g., differential GPS, signpost and/or dead reckoning, point detection of bus priority provision zone).
- Priority requests and priority request termination (on-board computer).
- Communication of request and request termination to intersection using dedicated short-range communication by optical or radio (e.g., spread spectrum radio) techniques. Central traffic control system architectures may use this technique or may provide priority timing commands from the central computer.
- Logic at the intersection to convert received priority commands to controller signals. Logging functions are also sometimes provided by this unit.
- Modifications of controller software to provide priority functions and sequences are required of systems that store timing plans at the intersection. Other systems may or may not require controller software modifications.

Monitoring requirements may include the logging of priorities granted and priority times provided.

Validation of System Design Prior to Implementation

Although a number of transit signal priority systems have been implemented, the improvement that they provide varies considerably because of variations in design approach and operational factors. Experience with such systems is less than with signal control systems, the design issues are of equal or greater complexity, fewer design guidelines and aids exist, and the equipment is less standardized.

Because transit signal priority projects tend to be complex, diverse, and costly, it is important for the design concept to be validated, to the extent possible, *prior to imple-*

mentation, to improve the probability of achieving expected performance. One method for concept validation is by simulation.

Although explicit capability does not exist in CORSIM (CORridor SIMulation), a widely used FHWA nonproprietary simulation model, to simulate bus priority, a procedure has been identified for using CORSIM to evaluate the effects of signal priority (Khasnabis et al. 1996). By using the graphics capability, the bus may be tracked through the signal system. If it stops during the red phase, the timing plan may be altered to simulate the effects of a priority. This may be done for each subsequent intersection for which the bus stops when no priority is provided. Although laborious, the process was successfully employed to estimate the benefits for a proposed system (*Route 5 Corridor Project—Task 2 . . . 1999A*).

Other approaches to validating the concept design include

- Use of proprietary simulation programs that support transit priority strategies,
- Peer review by engineers experienced in implementing signal priority for transit, and
- Implementation of a small pilot project. This approach has the disadvantage of incurring the equipment and software design and starting costs, which can be considerable.

Project Implementation Plan Although a number of stakeholders may be involved in establishing project goals and constraints for traffic signal systems, the design, installation operation, and maintenance of these systems usually resides with the traffic signal operating agency.

Because transit signal priority systems often involve shared responsibilities in these areas it is necessary to identify the responsibilities for the various project items. An example of responsibility allocation is shown in Table 13. Particularly strong coordination is required during the design activity to ensure compatibility among all items.

TABLE 13
EXAMPLE OF IMPLEMENTATION RESPONSIBILITIES

Item	Activity			
	Design	Installation	Operation	Maintenance
Concept Design	C			
Equipment				
Central transit system	C	B	B	B
On-board equipment	C	B	B	B
Curbside (wayside) communications and interface equipment	C	B	A	Curbside—A Depot—B Funding—B
Traffic controller	C	A	A	A
Operating Policies			C	
Evaluation			C	

Notes: A = traffic signal system agency responsibility; B = transit agency responsibility; C = joint responsibility.

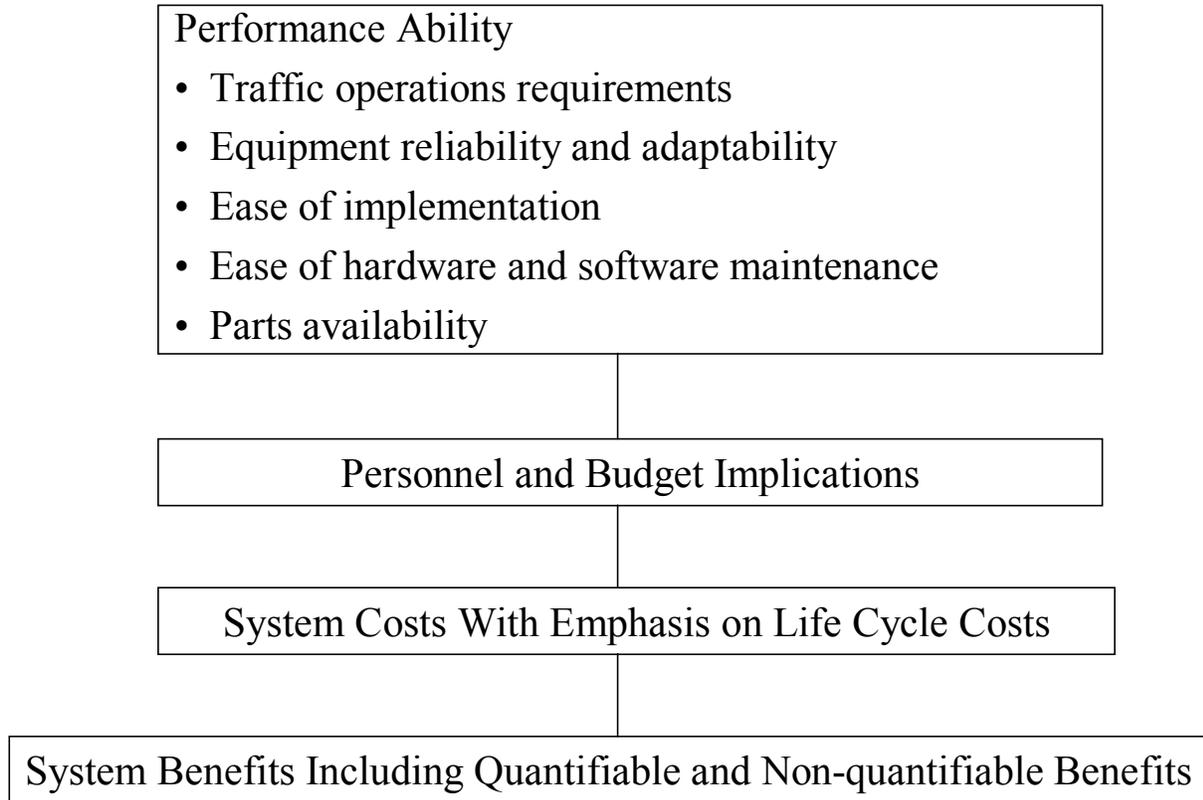


FIGURE 17 Criteria for analyzing alternative systems (Gordon et al. 1996).

ALTERNATIVES EVALUATION TECHNIQUES

The third *Traffic Control Systems Handbook* identifies the evaluation criteria shown in Figure 17.

Two types of analysis have traditionally been used to assist in system selection and evaluation, utility-cost analysis and benefit-cost analysis.

- Utility-cost analysis—Utility is computed by assigning a relative value to the importance of each evaluation factor. These importance values are multiplied by a relative value representing the ability of each candidate to satisfy the factor. These products are then summed for each candidate and plotted on utility and cost axes (Figure 18). The following discusses the figure.

The slope of the line indicates the utility-cost ratio, and the endpoint represents individual values of utility and cost for each alternative. In this manner, systems with nearly equivalent utility-cost ratios, such as Systems 1 and 2 can be readily compared. Notice also that the rectangle at each point represents the range of uncertainty associated with costs and utilities. Further, notice that Systems 3, 4, and 5 can be excluded from further consideration because they exceed acceptable cost or provide less utility than the lower cost systems (Gordon et al. 1996).

An example of the relative importance of each evaluation factor is shown in Table 14.

Utility-cost analysis is useful because it provides a reasonable basis for the selection of a system. Importance factors are usually identified by a consensus of transportation professionals. It is less useful in justifying the need for a system and its expected benefits to decision makers. In practice it often tends to emphasize those utilities important to the system operator and de-emphasize those important to the public.

- Life-cycle benefit-cost analysis—Life-cycle benefit-cost analysis provides a common frame of reference for capital costs and annual operations and maintenance costs. Total annual cost is an example of a common frame of reference. Benefits include reductions in congestion delay costs, accident costs, and fuel costs. When the benefit-to-cost ratio exceeds unity, the system is theoretically justified. Many practitioners, however, seek systems that considerably exceed this value.

A plot of candidate systems using benefit and cost axes provides a basis for evaluation. As for utility-cost analysis, the plot may be used to identify the dominance of one

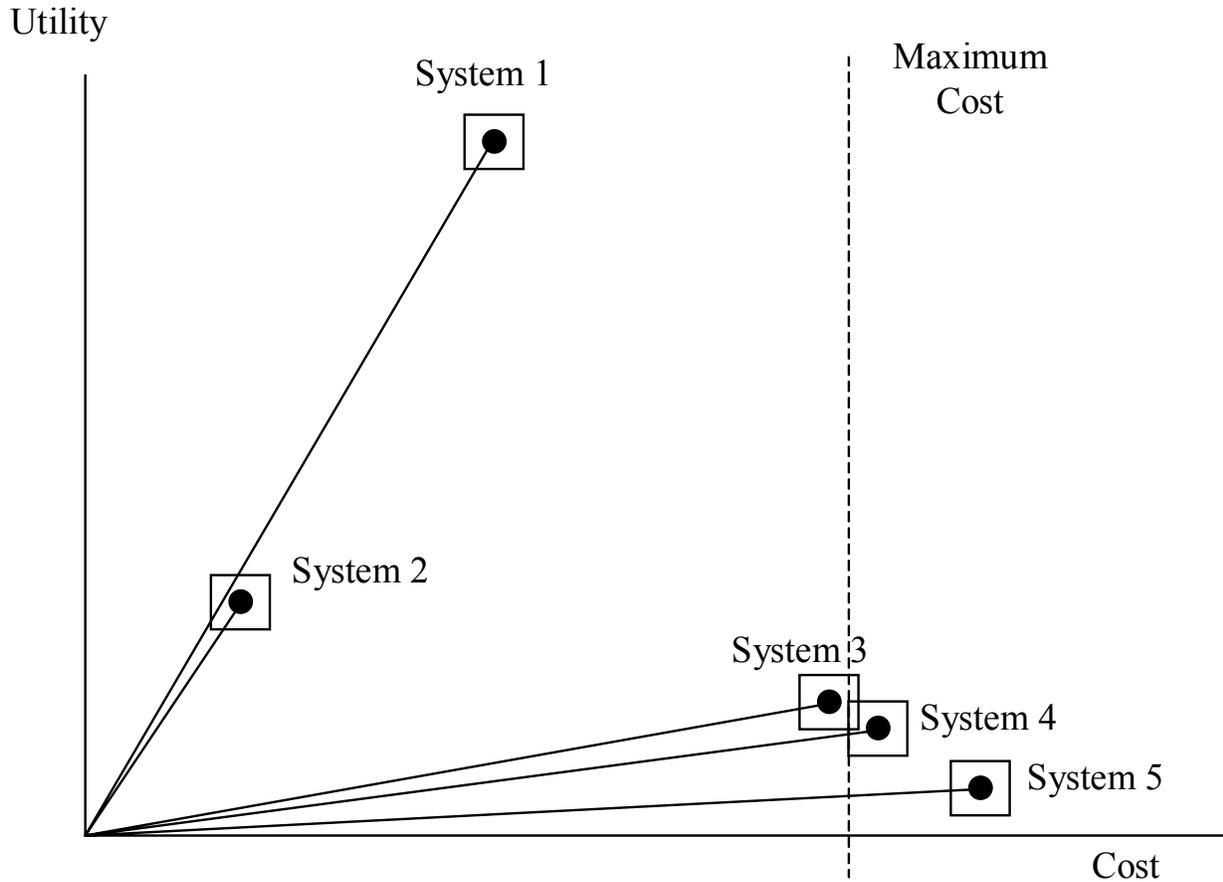


FIGURE 18 Utility–cost comparison of alternative systems (Gordon et al. 1996).

candidate over another or to eliminate candidates based on cost constraints.

Although benefit-cost analysis is traditionally used for the evaluation of transportation system improvements, the basic problem for traffic system evaluation stems from the difficulty in quantifying the benefits to the public or the cost reduction to operating and maintenance personnel for a number of the factors related to system design.

The third *Traffic Control Systems Handbook* provides a methodology for the benefit-to-cost computation (Gordon et al. 1996). The methodology requires the estimation of reductions in such parameters as delays and stops. Methods for obtaining these values include the use of values derived from experience on previous projects. An example of a set of values is shown in Tables 15 and 16. The following problems arise from the use of such values:

- Values reported in the literature reflect particular experiences. The conditions that these values reflect may not be true for the network under consideration.
- Other values besides those shown in Tables 15 and 16 have been reported in the literature.

Clark et al. (2000) describes a simulation-based methodology using a performance versus cost profile of candidate systems (Figure 19). Candidates below the “optimal frontier” are eliminated. Clark provides a ramp metering example to illustrate the technique.

Simulation-based techniques have been used for a number of projects. The thrust of the study is often to assess the performance of a planned major system upgrade. A recent example of such a study (*Route 5 Corridor Project—Task 2 . . . 1999B*) used the CORSIM (*Traffic Software Integrated System* 1998) model for this purpose. Signal timing programs such as TRANSYT 7F (McTrans 1999D) and SYNCHRO (Trafficware Corp. 1999) also have an evaluation capability. VISSIM is a simulation model used more widely overseas than in the United States (Bloomberg and Dale 2000).

The basic CORSIM program provides the ability to simulate arterial, grid, and corridor traffic flow using fixed timing plans with a variety of local intersection control strategies. CORSIM provides the common measures of effectiveness (e.g., stops, delays, and emissions). Transit vehicles may also be simulated, and measures of effectiveness are provided for these vehicles.

TABLE 14
UTILITY MEASURE WEIGHTS

Utility Measures	Weight
Adaptability (16.0)	
Incorporation of new control logic	4.6
Accommodation of traffic pattern shifts	5.2
Adjustment to physical changes	4.5
Incorporation of nontraffic control functions	1.7
Areawide Traffic Management (14.9)	
Special traffic functions	3.6
Special events	3.4
Coordinated controls of all signals	7.9
Implementation Characteristics (14.4)	
Implementation in phases on priority basis	5.3
Minimal degree of implementation complexity	2.8
Minimal impact on traffic	2.6
Use of existing equipment	3.7
Performance monitoring and operator interface (14.1)	
Dynamic display map	4.7
Operator console	4.6
Data logging and measure of effectiveness analysis	4.8
Reliability (19.5)	
Failsafe backup compatibility	5.1
Hardware failure monitoring and reporting	4.3
Software reliability	4.8
Ease of maintenance	5.3
Traffic Operations (21.1)	
Adequate number of timing plans with multiple zones	3.4
Isolated, arterial, and network control	3.6
Coordination of adjacent zones	3.9
Local intersection optimization	5.3
Selection of timing patterns by manual, time of day, or traffic responsive	4.9
Total	100.0

(Source: Wilshire et al. 1985).

TABLE 15
ANNUAL BENEFITS FROM OPTIMIZATION ON ARTERIAL

Coordination/Equipment Status	Stops (%)	Delay (%)	Fuel Consumption (%)
Uncoordinated arterial with existing equipment	10	24	8
Uncoordinated arterial with new equipment	18	21	14
Partially coordinated arterial with existing equipment	6	9	3
Partially coordinated arterial with new equipment	15	18	3
Coordinated arterial with existing equipment	16	23	17
Coordinated arterial with new equipment	14	23	12

(Source: Fambro 1992).

TABLE 16
ANNUAL BENEFITS FROM OPTIMIZATION ON NETWORK

Coordination/Equipment Status	Stops (%)	Delay (%)	Fuel Consumption (%)
Uncoordinated network with existing equipment	8	18	8
Uncoordinated network with new equipment	11.2	16.3	8.8
Partially coordinated network with existing equipment	4.4	20.5	8.7
Partially coordinated network with new equipment	16	26	11
Coordinated network with existing equipment	15	22	12
Coordinated network with new equipment	15	27	9

(Source: Fambro 1992).

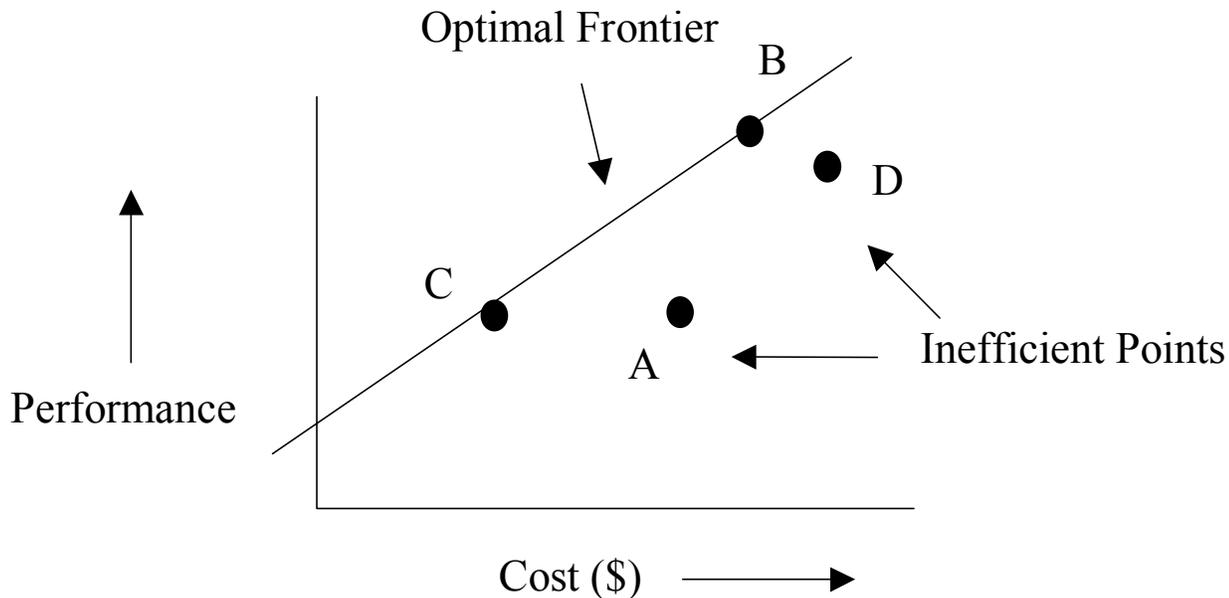


FIGURE 19 Optimal frontier (Clark et al. 2000).

Although it is possible to differentiate between traffic-responsive control strategies by providing externally provided software to CORSIM, it requires a high level of expertise and may be beyond the capability of most practitioners. Consultants specializing in these services are available.

The *Freeway Management Handbook* (Carvell et al. 1997) identifies the following additional techniques, and the following discussion is abstracted from that reference.

- Value engineering—Value engineering is an organized effort directed at analyzing the function of an item with the purpose of achieving the required function at the lowest overall cost (Miles 1972). The relationship between value and function is expressed in Eq. (4) (*Value Engineering Conference . . . 1980*):

$$\text{Value} = \text{Functional Performance}/\text{Cost} \quad (4)$$

A project team or expert panel approach is used in this analysis process, just as for a utility–cost evaluation. The principal difference between value engineering and utility–cost evaluation is in how item performance is accounted for in the analysis. Whereas the utility–cost approach assigns a subjective measure of utility to otherwise non-quantifiable performance measures, the value engineering approach depends on the ability of the analyst (or project team) to define a quantifiable measure of performance for the primary function(s) of the alternative being evaluated.

The *Handbook* provides a freeway-based example of value engineering.

- Sensitivity analysis—Key assumptions based on limited information may strongly influence the outcome of such techniques as value analysis. To avoid undue emphasis on these assumptions, sensitivity analysis repeats the value analysis based on alternative assumptions. The *Freeway Management Handbook* provides an example based on transit improvement alternatives. The *Handbook* references Heggie and Thomas (1982).

Processes and Methodologies for Traffic Signal Systems Engineering

Requirement M 1—System Procurement Methodologies

Smith (1998) identifies the following procurement approaches:

- Low bid—Single contract awarded to the lowest bidder, who is responsible for all tasks identified in the scope request.
- Two-step—Process that adds a formal technical pre-qualification step to the bid approach; sets of qualified contractors are then requested to submit a bid and/or proposal.
- Design/build—Process where a single entity, that is, designer/builder, is responsible for all work associated with the system development, including design, contracting, and system integration. Once completed, system is turned over to agency to operate and maintain; this generally results in reduced implementation time over normal processes.

TABLE 17
SUMMARY OF SYSTEM PROCUREMENT APPROACHES

Approach	Features
Engineer (consultant) contractor	<ul style="list-style-type: none"> • Costs less than systems manager approach because of competitive bidding for total installation • May result in lower design cost because less detail required for certain elements • Minimizes potential conflicts of interest
Systems manager	<ul style="list-style-type: none"> • Provides greater expertise in contract monitoring, equipment acceptance, and testing than many agencies can provide • Can easily modify functional requirements and provide additional features during implementation • Has greatest value for very large systems or systems having unique characteristics
Design/build	<ul style="list-style-type: none"> • Assures project cost limit prior to starting detailed design • Eliminates time between project phases thus leading to more rapid project completion • Requires sufficient level of technical definition prior to award to assure satisfaction of all functional requirements, operating features, and quality standards

(Source: Gordon et al. 1996).

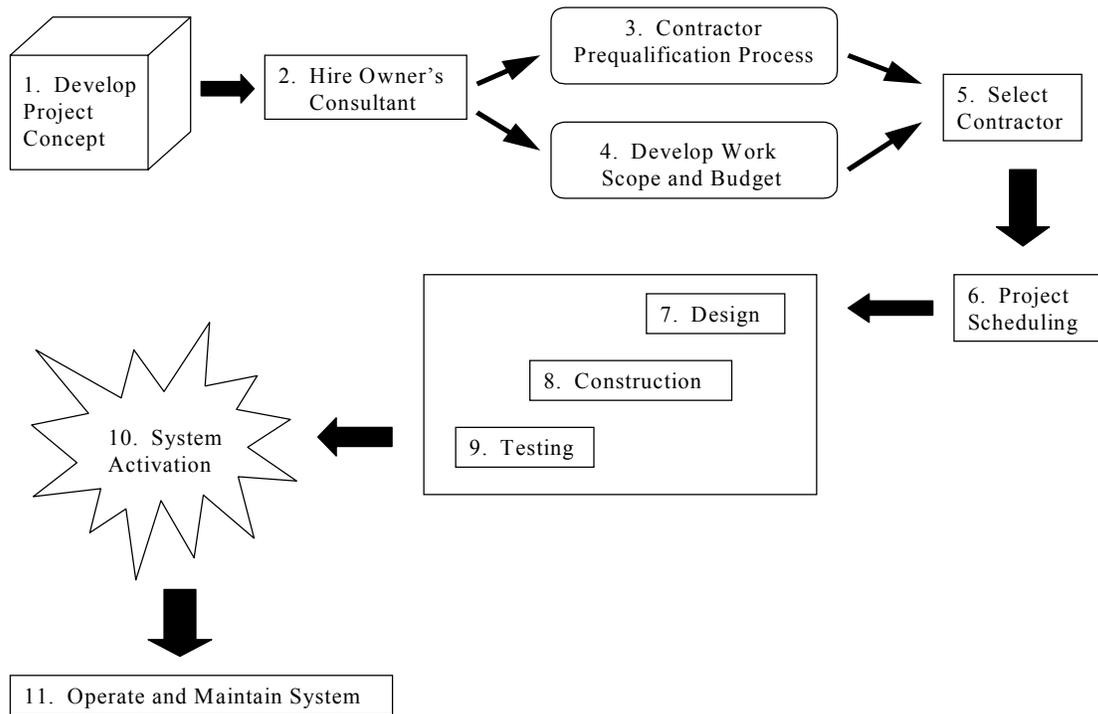


FIGURE 20 Model design/build process (Cronin 1996). (Used by permission of the Institute of Transportation Engineers).

- Sole source—Contract is awarded to a named supplier without competition. This process is usually oriented towards implementation of standard, off-the-shelf products and can be used to maintain continuity or compatibility of products.
- Systems manager—Primary system manager contract is awarded to design and manage the systems development process. Separate contracts are prepared and awarded for the development of individual components; however, the interface between the subsystems

is the responsibility of the systems manager/management consultant.

In addition to discussing some of these approaches, the third *Traffic Control Systems Handbook* (Gordon et al. 1996) provides a limited level of guidance in selecting an approach, as summarized in Table 17.

Cronin (1996) discusses a design/build model, an overview of which is shown in Figure 20.

TABLE 18
OPERATION AND MAINTENANCE ABILITY

Level	Currently (%)	Expected by 1998 (%)
Good (able to operate and maintain at a level that allows systems to achieve most of their potential)	56	70
Fair (only able to operate and maintain at a level to achieve a portion of their potential)	38	27
Poor (not able to operate and maintain these systems at a satisfactory level)	6	3

(Source: ITE, *Operation and Maintenance* . . . 1995).

OPERATIONS AND LOGISTICS REQUIREMENTS

A 1995 ITE report summarized the status of ITS operations and maintenance capability (*Operation and Maintenance* . . . 1995). Table 18 summarizes the nation's ability to operate and maintain signal systems. The report discusses such issues as education, training, organization, legal issues, and costs. The report places more emphasis on freeway systems than on traffic systems.

A 1999 ITE report describes recommended practices for management and operation of ITS (*Management and Operation* . . . 1999).

Processes and Methodologies for Traffic Signal Systems Engineering

Requirements O 1 and O 2—Operations

TMC daily functions may include

- Monitoring of traffic conditions and signal system equipment operation.
- Collection of flow data.
- Generation of requests for coordinated operation with other agencies and response to requests.
- Communication with the public.

Other TMC functions performed on a periodic basis might include timing plan and database updates as well as the planning of modifications to the system. In many cases the TMC is operated by the same personnel as those engaged in other conventional traffic engineering activities.

Staff monitoring of system operations varies from periodic monitoring to continuous monitoring. The size of the jurisdiction, the number of signals involved, the signal control strategies employed, and the use of CCTV all contribute to the staffing policy. Table 19 provides a sample of staffing requirements.

Monitoring for equipment failure may be performed at the TMC or by the maintenance facility.

Although a considerable amount of information has been developed for TMC operations (*Operations, Man-*

agement . . . 1999), for the most part this documentation emphasizes traffic management operations for freeways and regional TMCs.

Requirements L 1.1, L 1.2, L 1.3, and L 1.4—Maintenance

Maintenance activities include (Baxter 1984; Gordon et al. 1996)

- Remedial maintenance requirements resulting from malfunction and equipment failure;
- Preventative maintenance, including work done at scheduled intervals to minimize the probability of failure. A manual is available to provide guidance (*Preventative Maintenance* . . . n.d.); and
- Modifications to rectify design flaws and improve equipment characteristics.

Provisions for maintaining software must also be made.

Tables 20 and 21 summarize maintenance guidelines.

Strong and Haas (2000) identified a number of states having maintenance plans. The following four possible models were identified:

- District/regional maintenance model (ITS equipment not separated from other equipment),
- Coordinated ITS maintenance model (a separate organizational unit exists for ITS),
- Two-tier maintenance model (combination of first two models based on level of technology). Figure 21 depicts a two-tier maintenance model, and
- Contractor-based maintenance model.

Requirements L 2.1, L 2.2, and L 3—Training and Education

Professional Level Training A number of universities offer professional level training. The Consortium for ITS Training and Education (CITE) is comprised of university and industry partners. It offers a number of on-line courses (Figure 22) for continuing education unit credit including, "Applied Systems Engineering for Advanced

TABLE 19
TRAFFIC SIGNAL CONTROL SYSTEMS IN URBAN AREAS

City	Population	No. of Signals in System	Type of System*	Type of Intersection Controller	No. of Personnel**		Comments
					Operations	Maintenance	
College Station, TX (4)	54,000	37	Eagle Marc	NEMA	1	2	Installed in 1992
Richardson, TX (5)	76,800	86	2M***	NEMA	8	6	NA
Anaheim, CA (6)	265,000	180	UTCS Enhanced	NEMA	4 equivalent full-time and 3 student interns	Maintenance contract	Personnel shown provide for operations and for maintenance contract supervision.
St. Paul, MN (3)	270,000	108	Computran UTCS	170	3	10	108 of 347 under central control; others under commercial closed-loop control; central control system installed in 1992.
Oakland County, MI (7)	1,100,000	95	SCATS	NEMA	6	Number not designated for system	Coordinated with Michigan DOT freeway traffic management and Siemens Ali-Scout Route Guidance System.
Toronto, ON (8)	3,600,000 [†]	1,641	NA	NA	38	Maintenance contract	Total of 1,641 traffic signals of which 75 are in the SCOOT system and 1,585 are in the older UTC computer traffic system. Personnel shown provide for operation of maintenance contract.
Los Angeles, CA (9)	3,500,000 [†]	1,566	UTCS 1.5 Gen	170	15	75	Total of 4,000 traffic signals of which 1,566 are under the ATSAC system computer control.

*Traffic Responsive Capability, SCOOT, and SCATS are Real-Time Traffic Adaptive Control Systems.

**The basis for reporting these data varies among agencies.

***Minnesota Microtronics.

[†]Metropolitan area population.

Notes: NA = not available; UTCS = urban traffic control system; ATSAC = Automatic Traffic Surveillance and Control; NEMA = National Electrical Manufacturers Association.

(Source: Gordon et al. 1996).

TABLE 20
ITS TRAFFIC SIGNAL MAINTENANCE GUIDELINES

Subsystem	Minor Maintenance	Major Maintenance
Cabinets	26 weeks	2–5 years
Signal heads	26 weeks	2–5 years
Span wire and poles	1 year	NA
Detectors	13 weeks	NA
Controller	1 year	NA
Interconnect equipment	1 year	NA

Note: NA = not available.

(Source: Florida DOT, *Operations, Management* . . . 1999).

TABLE 21
COMMUNICATIONS MAINTENANCE GUIDELINES

Technology	Minor Maintenance	Major Maintenance	Major Rehabilitation	Life Expectancy
Fiber optic cable plant	1 year	5 years	25 years	25 years
Fiber optic plant video and data equipment	—	26 weeks	3 years	10 years
Twisted pair cable	2 years	8 years	30 years	40 years
Coaxial cable	1 year	6 years	20 years	30 years
Spread spectrum	26 weeks	4 years	10 years	20 years

(Source: Florida DOT, *Operations, Management* . . . 1999).

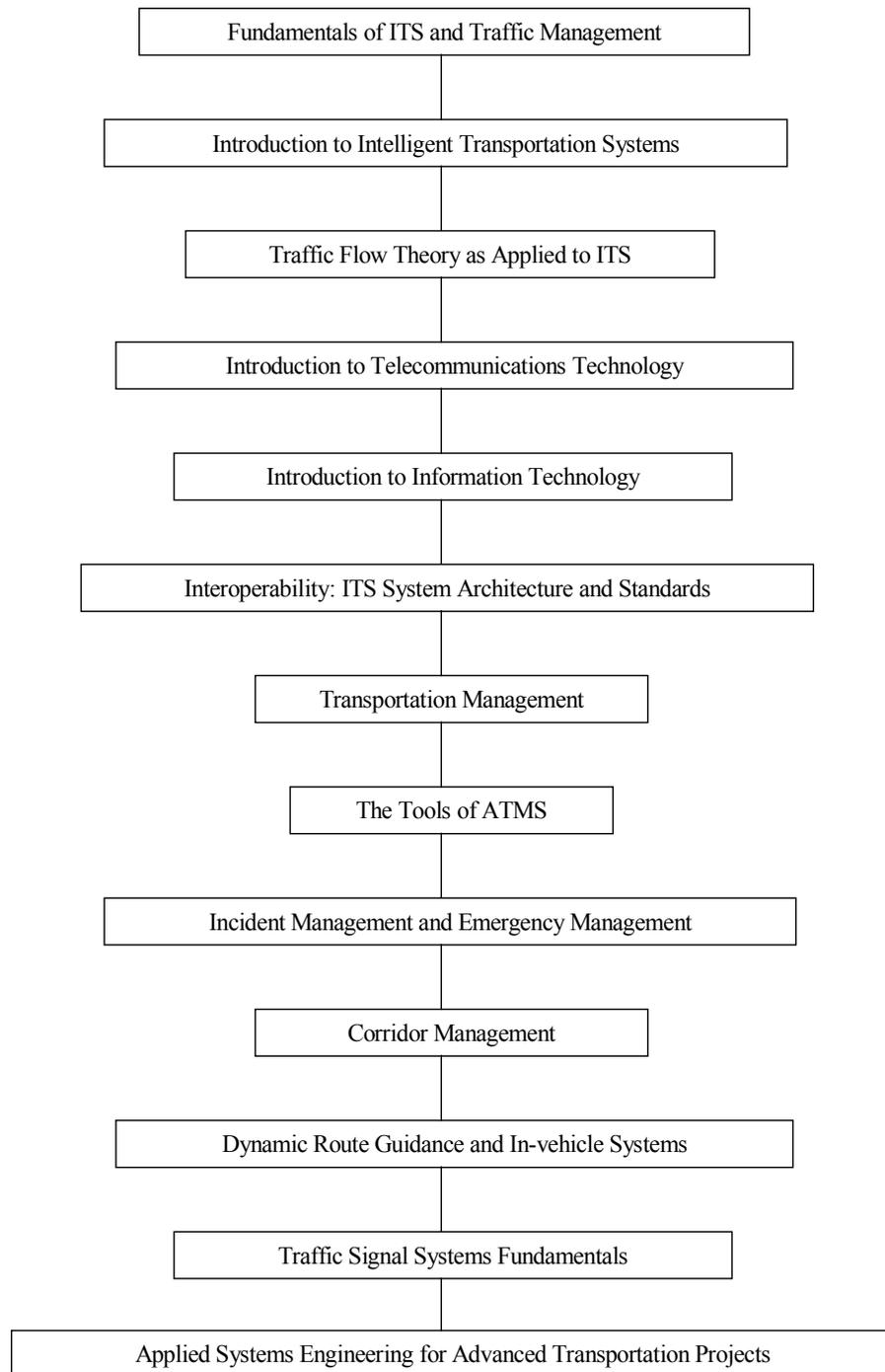


FIGURE 22 CITE on-line courses available as of November 2000 (CITE Consortium n.d.).

evaluation methodologies) in their evaluation plan. Some agencies have gone further and essentially incorporated the evaluation process into the transportation planning process. A comprehensive, performance-evaluation system methodology is described by Bloomberg et al. (1997). The approach relates

performance to travel patterns for particular sections of a municipality. Performance indicators include

- District accessibility,
- Origin destination characteristics,

TABLE 22
CRITERIA FOR DEVELOPING MEASURES OF EFFECTIVENESS (MOEs)

Criteria	Description
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.

(Source: Abrams and Drenzo 1979).

- Travel time,
- Travel flow, and
- Multi-modal service level.

The case study used GPS to collect data.

Selection of Measures of Effectiveness Abrams and Drenzo (1979) provided the criteria for developing MOEs shown in Table 22.

The National ITS Architecture identifies the “benefits metrics” shown in Table 23 in connection with traffic signal systems-related goals (*The National ITS Architecture* 1999).

Smith (1998) indicated that where good timing plans already exist, the incremental benefits of more sophisticated systems may primarily lie with the improved management capabilities provided. Recommended MOEs include

- Speed on a sample of arterial streets,
- Traffic volume (as a control variable),
- Number of stops,
- Average vehicle delay at signals,
- Number and severity of accidents, and
- Number of special events, construction/maintenance, and incident applications of the system.

The third *Traffic Control Systems Handbook* identifies the following MOEs and describes procedures for their estimation (Gordon et al. 1996):

- Total travel time,
- Total travel,
- Number and percentage of stops,
- Delay,

- Total minute-miles (minute-kilometers) of congestion,
- Average speed,
- Accident rate, and
- Throughput.

The *Handbook* also points out the need for considering changes in traffic demand during the evaluation process. The use of throughput in the manner shown in Figure 23 facilitates the comparison of systems A and B over a range of demand conditions.

Shbaklo and Reed (1996) provide a rating of MOEs to satisfy different objectives. Travel time and vehicle-miles traveled were rated highly for quantifying congestion.

MOEs for safety-related issues are underrepresented in the literature. Kaub (2000) summarizes and updates previous work and identifies safety levels of service.

Evaluation Methodologies Before and after studies are the most commonly used form of project evaluation and may be conducted as follows:

- Before and after studies using traditional techniques—Travel time and delay studies and intersection delay studies using methodologies described by Box and Oppenlander (1983) have traditionally been used for traffic signal systems evaluation. To minimize demand variation during the implementation of the project, the “before” study is often made using the new system with the project timing plans. The cost of data collection for travel time and delay studies may be reduced by using a GPS in connection with a recording device (Smith 1998).
- Evaluation using data obtained by traffic system—Central traffic system Levels 3 and 4 often have the

TABLE 23
BENEFITS METRICS

ITS GOAL	Related Metric
Increase transportation system efficiency and capacity	Traffic flows/volumes/number of vehicles Lane carrying capacity Volume-to-capacity ratio Vehicle-hours of delay Queue lengths Number of stops Incident-related capacity restrictions Average vehicle occupancy Use of transit and high-occupancy vehicle modes Intermodal transfer time Infrastructure operating costs Vehicle operating costs
Enhance mobility	Number of trips taken Individual travel time Individual travel time variability Congestion and incident-related delay Travel cost Vehicle-miles traveled Number of trip end opportunities Number of accidents Number of security incidents Exposure to accidents and incidents
Improve safety	Number of incidents Number of accidents Number of injuries Number of fatalities Time between incident and notification Time between notification and response Time between response and arrival at scene Time between arrival and clearance Medical costs Property damage Insurance costs
Reduce energy consumption and environmental costs	NO _x emissions SO _x emissions CO emissions VOC emissions Liters of fuel consumed Vehicle fuel efficiency
Increase economic productivity	Travel time savings Operating cost savings Administrative and regulatory cost savings Manpower savings Vehicle maintenance and depreciation Information gathering costs Integration of transportation systems
Create an environment for an ITS market	ITS sector jobs ITS sector output ITS sector exports

Notes: ITS = intelligent transportation systems; NO_x = nitrogen oxide; SO_x = sulfur oxide; CO = carbon monoxide; VOC = volatile organic compound.

(Source: FHWA, *The National ITS Architecture* 1999).

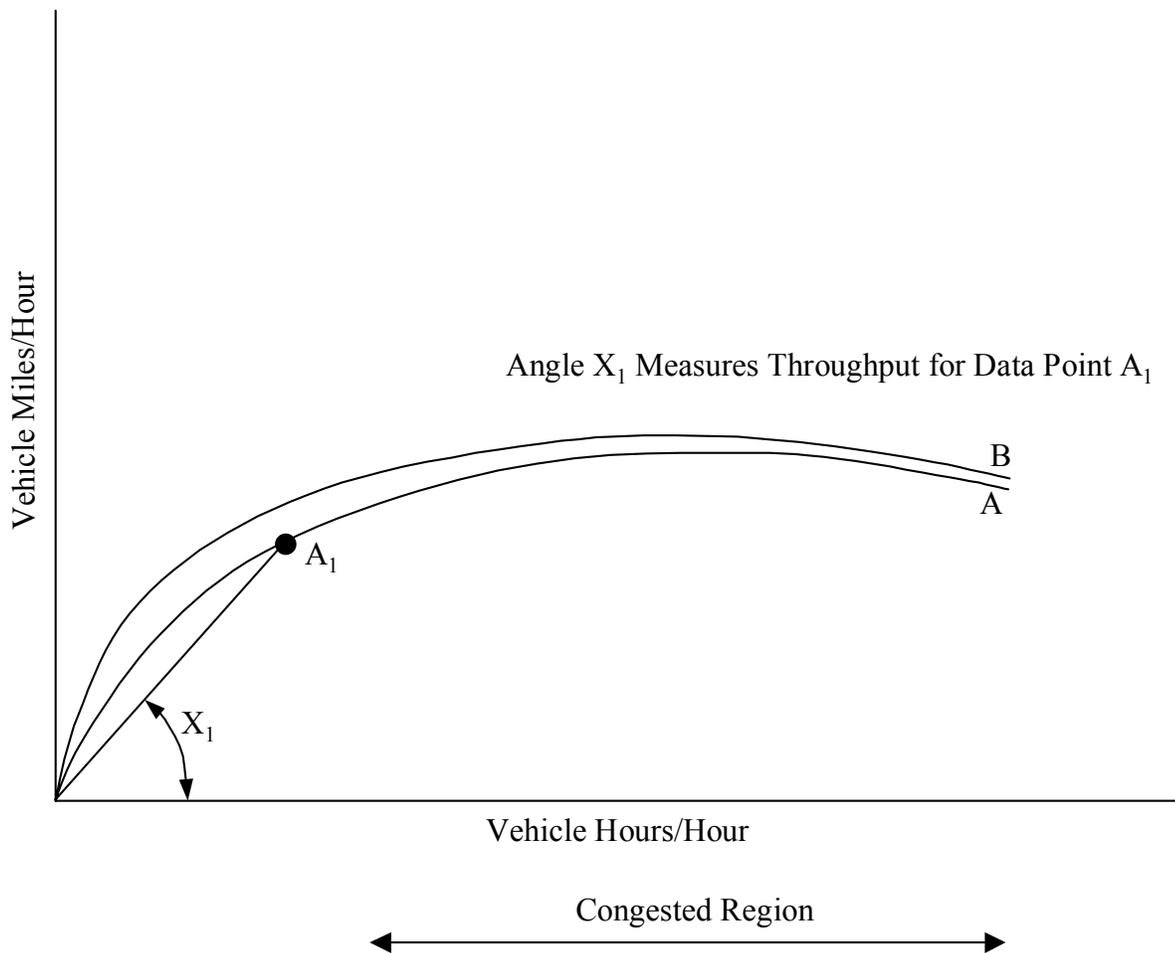


FIGURE 23 Throughput (Gordon et al. 1996).

surveillance capability to compute MOEs (such as delays and stops) that may be used to complement other evaluation techniques, such as travel time and delay studies, or to serve in their place. This system capability may be used to assess benefits in moving from a Level 1 or 2 system to a Level 3 or 4 system or for ongoing evaluation purposes.

Although the MOE trends as computed by traffic systems are usually fairly representative, the absolute MOE values may differ from independently measured values. Therefore, if this technique is to be used, it should first be calibrated to independently measured values.

Requirement E3—Evaluation of the Project Implementation Approach

The intent of this systems engineering requirement is to identify processes that might be improved in the future. In commercial ventures the cost and profit auditing process

often serves as a trigger to identify processes requiring improvement.

Agencies responsible for managing traffic signal systems often perform comparative reviews of certain processes or process components. These frequently include purchased equipment and services such as

- Traffic signal equipment,
- Contract maintenance services, and
- Intersection design services.

Monitoring of the agency's internally provided engineering, operations, and maintenance services, when performed, is usually done by management on an informal basis.

An example of a formal evaluation of the implementation approach for a traffic signal systems project conducted under the FHWA Field Operational Test program is provided by McNally et al. (1999A, B).

CHAPTER FOUR

CURRENT STATE OF THE PRACTICE

PURPOSE

This chapter presents the extent to which operational agencies use systems engineering processes and the processes most frequently used. This current state of the practice reviews the processes, deficiencies in available guidance, and issues of importance in the development of traffic signal systems. The processes examine four areas relating to (1) overall project processes and methodologies, (2) specifications, (3) local intersection control, and (4) operations and maintenance.

BACKGROUND

In the initial stages of this project, a questionnaire was distributed to states, counties, and cities. In retrospect, the

questions were not sufficiently detailed to provide a comprehensive picture of the state of the practice. Subsequently, a supplementary questionnaire was distributed to all of the states and 27 cities and counties. Responses were received from 26 states and 7 cities. The supplementary questionnaire, contained in Appendix A, sought to identify the extent to which agencies use methodologies and processes for traffic signal systems, and to identify the character of the processes used. For example, Figure 24 shows that the Minnesota DOT promotes technical courses for traffic professionals in systems engineering by means of its website. The questionnaire also sought to identify the areas for which additional material on processes or other tutorial material was needed. In addition, the questionnaire was structured to identify the perceived importance of various aspects of traffic system design. Because of the preponderance of state respondents, identification of the specific processes used reflects this particular group.

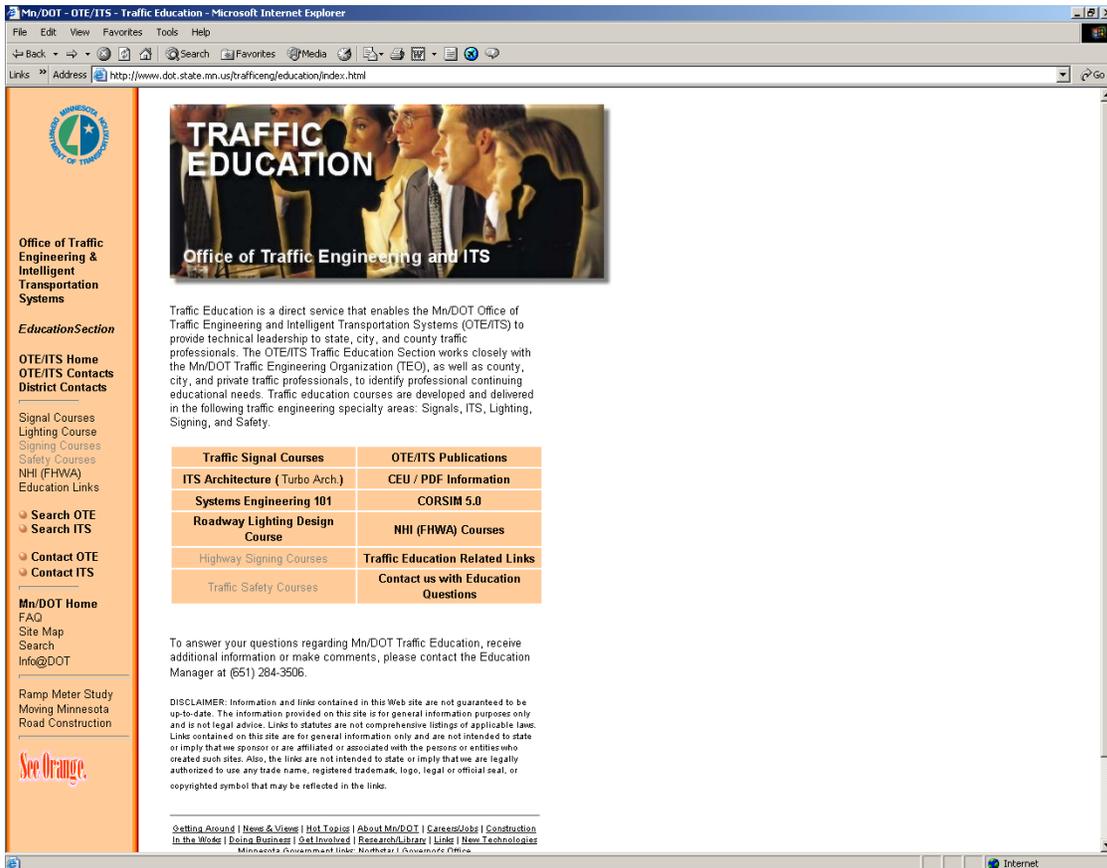


FIGURE 24 Minnesota DOT Office of Traffic Engineering and ITS website promoted a National Highway Institute course on systems engineering. (Courtesy: MnDOT.)

PROCESSES

The extent to which operational agencies use systems engineering processes and the processes most frequently used are described here.

Overall Project Processes and Methodologies

Goals and Objectives

Fifty percent of the respondents use a formal process for the development of goals and objectives for major upgrades. Processes mentioned included the following:

- Formal request for upgrade by traffic engineer;
- Reviews of volumes, artery characteristics, signal spacing, travel times, delay, and funding;
- Prioritization of intersection based on volume, accidents, and other characteristics;
- Project identification through concept meetings within the organization;
- Needs definition and requirements; and
- Goals based on traffic flow requirements and/or safety.

Project Management Approach

Eighteen percent of respondents prepare a formal document defining the management approach to be used in implementing major system improvements. Scoping studies are the most frequently used methodology. Justification studies performed by some states assess an agency's ability to operate and maintain the system. Studies also require the justification of additional cost for advanced systems. In some cases, the management approach is defined in a procedures manual.

Alternatives Evaluation Methodology for Major System Upgrades

Forty-three percent of the states and 50% of the cities use an alternatives evaluation methodology for major system upgrades. In addition, four of the respondents reported a benefit-to-cost ratio methodology, whereas two identified a utility methodology.

Systems Procurement Methodology

Seventy-seven percent of the respondents currently use a defined methodology to procure traffic systems. The overwhelming majority of these use some form of low bid process. In most cases, the process is determined by the ju-

isdiction's procedures. Some respondents expressed interest in moving to a design/build methodology. In addition, one respondent suggested that software should be a system integrator responsibility rather than a contractor responsibility.

Project Evaluation Methodology

Forty percent of the respondents perform evaluations in connection with major system improvements. Before and after studies using travel time, delay, and throughput are most commonly used. In some cases, these studies are only performed when required by funding sources. Thirty-six percent of the states and 43% of the cities conduct evaluations of traffic signal performance at periodic intervals.

Traffic Systems Engineering and Specification

Specifications

The percentage of organizations using standard specifications for traffic system procurement is shown in Table 24. Approximately 55% of the agencies responding perform major specification revisions every 5 years or less and 45% from 5 to 10 years. Reasons mentioned for specification revisions were (in order of decreasing frequency)

- New technology (including new standards),
- Needs and problems,
- Statute requirements, and
- Coordination with Caltrans standards.

TABLE 24
PERCENTAGE OF ORGANIZATIONS USING STANDARD SPECIFICATIONS

Component	States (%)	Cities (%)
Central control systems and field masters	89	86
Communications to the field	64	83
Field equipment (controllers and detectors)	100	100

Engineering Processes for Design of Central Traffic Controls

Thirty-nine percent of the states and 43% of the cities use a formal engineering process in the development of specifications for the type of traffic control system used. The processes mentioned include the following by states:

- Standard specifications (all systems implemented by the agency are of the same type).
- Traffic needs analysis.

and by cities:

- Evaluation of existing system, technology analysis, and best-fit review;
- Problem identification, functional analysis, and resource constraints; and
- Concept study.

Satisfaction with Processes Used

Respondents were generally satisfied with the processes used. Suggestions for improvement included

- Provide greater emphasis on the design/build approach,
- Improve material acceptance procedures,
- Use only proven technology,
- Shorten the planning cycle, and
- Use functional traffic system specifications and pre-qualify bidders.

Traffic System Communications

Twenty-four percent of the states and 33% of the cities used a formal planning design or engineering process for specifying traffic system communications. The processes used include

- Technology reviews,
- Communications master plan development and evaluation of equipment types,
- Review by signal standards committee concept meetings, and
- State design manual.

Field Equipment

Forty-three percent of the states and 29% of the cities follow a formal process in the development of designs and specifications for field equipment. Approaches mentioned include

- Use of NEMA and Caltrans specifications,
- Use of signal design manual,
- Use of qualified products lists,
- New product evaluation committee,
- Concept meetings,
- Review and test equipment using trial installations, and
- Reviews with stakeholders based on field experience.

National ITS Architecture

Only 11% of the respondents reported that the National ITS Architecture has significantly changed their systems

engineering approach to date for the design of traffic signal systems, even though many states have developed or are developing statewide and regional architectures. Changes included the following:

- Greater emphasis on needs definition,
- Use of new technology for monitoring traffic flow, and
- Emphasis on inclusion of National ITS Architecture structure in major upgrade.

Local Intersection Control

Establishment and Removal of Signals

All but two respondents use the MUTCD warrants as the principal basis for establishing new signals or removing existing signals.

Actuation of Isolated Intersections

Twenty-one percent of the states and 29% of the cities use a formal process for determining whether to actuate an isolated intersection. Many agencies provide actuation for all isolated intersections as a formal or informal policy. In addition, a small number of agencies perform an engineering study to determine whether actuation is required.

Coordination of Intersections

Forty-two percent of responding agencies follow a formal process in deciding whether coordination should be employed at an intersection. The processes used by these agencies include

- Coordination of signals with less than 1,000 ft of separation,
- Coordination of signals with less than 1 mile of separation,
- Coordination of signals if they are within an existing or proposed system,
- Study based on use of software programs,
- Preferences and expertise of program manager,
- Cost-benefit analysis, and
- Statewide study to identify prime arterial candidates for coordination.

Side Street Actuation in Coordinated Systems

Thirty percent of the states and none of the cities responding use a formal process in deciding whether side street

actuation should be employed in coordinated systems. The majority of the agencies always actuate the side streets except in the central business district. Processes used include analysis of intersection requirements and judgment of the project manager.

Operations and Maintenance

Operations

Thirty-two percent of the cities and states use a formal process for determining such operational parameters as hours of attended operation and operating mode. The predominant approach was the use of traffic studies. Other techniques included consensus reviews. In some cases, a formal operations staffing plan with budget constraints is proposed.

Maintenance

Sixty-two percent of the states and 17% of the cities responding employed processes or standards for planning and specifying maintenance and training. Traffic signal maintenance standards and preventive maintenance checklists were most commonly employed. A number of agencies specify maintenance response times and have standards for periodic or preventive maintenance.

PERCEIVED NEEDS IN AVAILABLE GUIDANCE

A survey question addressed the need for a report or manual describing a formal engineering process in a number of areas. The percentage of respondents perceiving needs in each area is provided in Table 25. The percentage of respondents addressing the need for additional tutorial material is shown in Table 26.

As perceived by the respondents, the greatest needs for additional information or guidance lie in areas relating to

- Central traffic control systems and field masters if they are required by the system architecture,
- Communications to the field, and
- Traffic signal deployment and maintenance.

TABLE 25
RESPONDENTS PERCEIVING NEED FOR REPORT OR MANUAL DESCRIBING A FORMAL ENGINEERING PROCESS

Area for Need	States (%)	Cities (%)
Specification of central control equipment and field masters	58	83
Design of communications to the field	58	83
Specification of field equipment	58	33
Design of traffic signal installations at intersections	56	50
Traffic signal system deployment and maintenance	54	83

TABLE 26
RESPONDENTS PERCEIVING NEED FOR INCREASED QUANTITY AND/OR QUALITY OF TUTORIAL MATERIAL

Area For Need	States (%)	Cities (%)
Specification of central control equipment and field masters	67	86
Design of communications to the field	60	86
Specification of field equipment	43	71
Design of traffic signal installations at intersections	58	57
Traffic signal system deployment and maintenance	63	71

IMPORTANT ISSUES

The questionnaire requested information on the respondents' perceptions of the importance of various issues in the development of traffic control systems. Tables 27 and

TABLE 27
IMPORTANCE OF VARIOUS ISSUES IN THE DEVELOPMENT OF TRAFFIC CONTROL SYSTEMS BY STATES

Issue	Importance Score
Legacy issues (compatibility with existing systems, equipment)	8.1
Ease, cost, and availability of maintenance and support	7.7
Availability of new national specifications (NEMA, NTCIP, ATC, etc.)	7.6
Familiarity with technology	7.6
Performance (real-time traffic flow optimization)	7.1
Compatibility with other ITS in your jurisdiction	7.0
System cost	6.9
Plan for introducing the NTCIP protocol for communication to intersection signal controllers	6.5
National Architecture conformance	6.5
Perceived future needs	6.1
Compatibility with ITS in other jurisdictions	5.3
Availability of new system coordination technology (e.g., SCOOT, SCATS, RTTRACS, OPAC, RHODES)	4.5

Notes: NEMA = National Electrical Manufacturers Association; NTCIP = National Transportation Communications of ITS Protocol; ATC = Advanced Transportation Controller; ITS = intelligent transportation system.

TABLE 28
IMPORTANCE OF VARIOUS ISSUES IN THE DEVELOPMENT OF TRAFFIC CONTROL SYSTEMS BY CITIES

Issue	Importance Score
Legacy issues (compatibility with existing systems, equipment)	9.0
Performance (real-time traffic flow optimization)	8.9
Compatibility with other ITS in your jurisdiction	7.8
Ease, cost, and availability of maintenance and support	7.6
Perceived future needs	7.4
Plan for introducing the NTCIP protocol for communication to intersection signal controllers	7.0
National Architecture conformance	6.9
Availability of new national specifications (NEMA, NTCIP, ATC, etc.)	6.7
System cost	6.4
Familiarity with technology	6.3
Availability of new system coordination technology (e.g., SCOOT, SCATS, RTTRACS, OPAC, RHODES)	6.3
Compatibility with ITS in other jurisdictions	5.4

Notes: For abbreviations see Table 27.

28 provide summaries of the responses. Importance is rated on a scale of 0 to 10, with 10 being the most important.

The relative importance of many issues for states and cities is generally similar, with legacy issues, traffic control performance, and maintainability key issues for both. States

place more emphasis on the availability of national standard specifications and familiarity with technology, whereas cities place greater emphasis on equipment compatibility within the jurisdiction. Compatibility with ITS in other jurisdictions and the availability of adaptive system technology were rated relatively low by both sets of agencies.

SUMMARIES OF EXISTING PRACTICES

PURPOSE

This chapter summarizes the results of current, formal engineering practices used by surveyed organizations in planning and evaluating traffic signal systems. The chapter concludes by identifying those traffic signal systems engineering topic areas lacking information on systems engineering processes. In addition, areas requiring future research and/or improved documentation are highlighted.

SUMMARY OF EXISTING METHODOLOGIES

Table 29 compares the use of engineering practices employed by cities and states with available systems engineer-

ing techniques. Items in the table denoted by asterisks indicate areas where methodologies are not documented in a way that can be easily located or used by practitioners.

The use of existing formal methodologies by practitioners is affected by the following:

- Lack of knowledge by practitioners of the existence of the methodologies.
- Lack of a user-friendly format.
- Strong design requirement needed to be compatible with existing systems or equipment.
- Organizational practices that discourage the use of system design methodologies such as (1) use of standard specifications or engineering practices in the

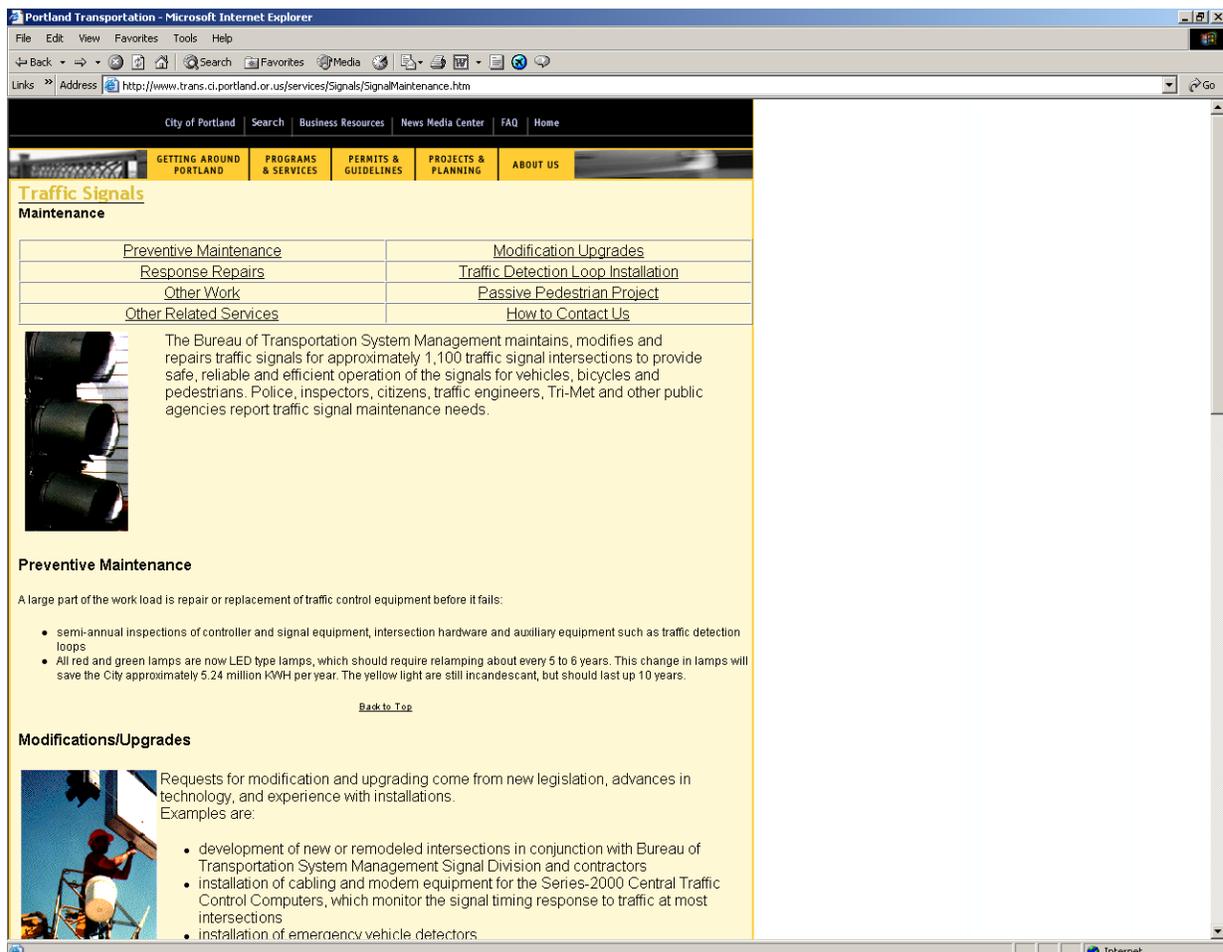


FIGURE 25 City of Portland (Oregon) Office of Transportation website describes current traffic signal maintenance practices. (Courtesy: City of Portland Office of Transportation.)

TABLE 29
SUMMARIES OF ENGINEERING PRACTICES EMPLOYED BY STATES AND CITIES WITH AVAILABLE TECHNIQUES

Topic	Currently Available Formal Methodologies	Use of Formal Techniques in Practice	Comments
Checklist of Traffic Signal Systems Engineering Requirements	Yes (e.g., structured analysis)	No	This document contains an initial checklist. The checklist may require additions or modifications.
Goal and Problem Definition	Yes	≈50%	Some agencies use a formal scoping process.
Project Management Approach	Yes	Infrequently	
Alternatives Evaluation	Yes	≈47%	
Project Evaluation	Yes	≈32% of states and 60% of cities	
Traffic Signal System Engineering			
Need for traffic signals	Yes	Nearly 100%	References MUTCD warrants and recommendations.
Signal timing	Yes	Mostly	Computer programs are widely used to develop timing plans.
Need for coordination of signals	Yes	≈42%	Computer simulation is sometimes used as a design tool. Utility or Delphi approaches are sometimes incorporated in system planning. There exists a significant absence of available information.* Research is required to develop methodology.* Recommend upgrading the presentation documentation and distribution of information.*
Coordinated traffic control systems	No methodology description available for selection of system capability level.	Sometimes	
	Some information on system detector placement available but not widely distributed.	Sometimes	
	Some information on Level 3-traffic responsive implementation available, but not widely distributed	Level 3 traffic-responsive operation is relatively infrequently employed, although Level 3 capable systems are widely used. Systematic techniques for establishing parameters are rarely used	
Communication System Engineering			
Selection of communication systems type	Yes, but requires update	≈28%	Often use methodologies other than formal methodologies. The integration of protocols such as NTCIP is a key issue. Recommend updating existing methodology to incorporate new technologies.*
Communication system design	Yes	Usually performed by design specialists	Detailed design guidance is often in other than traffic system literature.
Field Equipment Selection	Yes	≈35%	Generally used methodologies consist of evaluation of standard national specifications. Most agencies use these specifications and selection is made formally or informally.
Local Intersection Control			
Selection of local actuation strategy	Yes	Infrequently	Most agencies surveyed provide full or semi-actuation as design policy. Therefore, guidance is required as to when to employ the appropriate mode. Available guidance should be upgraded and represented in this way.*

TABLE 29 (Continued)

Topic	Currently Available Formal Methodologies	Use of Formal Techniques in Practice	Comments
Location and configuration of vehicle detectors for local actuation	Yes	Frequently	
Railroad and emergency vehicle preemption	Yes	Frequently	
Transit signal priority	Some information available	Information not available until recently	Effective design of transit signal priority is a technically complex issue. Insufficient information exists on when priority should be used, strategy selection, and design implementation.*
System Procurement	Yes	≈70%	Approach is often determined by agency policy and regulations.
Operations and Logistics			
Operations	In specific areas (e.g., signal timing)	Sometimes	Level of staffing and hours of staffed operation usually determined by experience and budget availability.
Maintenance	Yes	Most states and some cities	Many organizations have formal procedures for preventive maintenance and standards for field response requirements.
Training	Yes	Frequently used	Many organizations require and/or support maintenance training. Training for operations and operations support is often obtained from industry or by means of professional level courses.

Notes: MUTCD = *Manual on Uniform Traffic Control Devices*; NTCIP = National Transportation Communications for ITS Protocol.

* Indicates deficiencies in existing methodologies or their documentation.

selection of systems and equipment, (2) selection of signals for coordination, or (3) employment of local actuation.

- Lack of resources for operation and maintenance that may dictate the use of relatively simple and easy to maintain traffic systems and equipment. Figure 25 shows the city of Portland (Oregon) Office of Transportation “preventive maintenance” strategy.
- Designs constrained by specifications and practices developed for statewide use by the main office; although most state DOTs develop traffic system designs within the administrative region or division offices. Thus, the system designer is not fully free to establish the system design.

The traffic systems engineering processes discussed in chapter three focus on system design for a particular project in a particular location with goals established for that specific project. On the other hand, city and county traffic departments and state DOTs have, over time, developed specifications and design, operational, and maintenance practices that are perceived to best suit their needs as an organization, and to best satisfy their constituencies and stakeholders on an overall basis. Thus, it may not always be feasible or desirable to employ project-oriented systems engineering processes. It is, however, useful to close the gaps in providing information on systems engineering processes for these practitioners who are able to make use of it.

The following section summarizes those areas identified in Table 29 that require additional research or improved documentation.

- Checklist of traffic signal system engineering requirements—An example of a requirement set is provided in this document. It is subject to expansion or modification.
- Selection of system level (type of control strategy)—Current research does not provide the basis for a systematic selection. Research is needed.
- Placement of system detectors for Level 3 systems (centralized control, two-level distributed, closed loop)—The presentation of existing information should be made more accessible and user friendly to practitioners.
- Establishment of system parameters for traffic responsive operation for Level 3 systems (conventional strategies)—The documentation of methodologies for providing the database for traffic-responsive operation should be upgraded and made more widely available. The development of the database for Level 2 systems (time of day) is well understood by most traffic engineers. Most of the systems in use today are capable of operating at Level 3. For traffic-responsive operations, these systems generally employ either the First Generation Urban Traffic Control System control algorithm or a cycle, split, and offset selection algorithm based on detector threshold values. Most Level 3 capable systems currently operate

at Level 2. Although guidance exists for the development of Level 3 databases, it is not widely available and may not be easily used by traffic engineers. Documentation and its distribution should be improved.

- Communication systems—Existing methodologies for architecture and technology selection should be updated to reflect current technology and National Transportation Communications for ITS Protocol requirements.
- Selection of fully actuated and semi-actuated control strategies for field controllers—The existing documentation on the conditions for implementation and periods of use should be upgraded and made more widely available.
- Transit signal priority engineering—Additional guidance for selection of priority strategy, algorithm, priority locations, zones for priority request, and design implementation alternatives should be provided.

CONCLUSIONS

This chapter presents a summary of findings on system engineering processes, the use of systems engineering by practitioners, the availability of existing methodologies, and the need for additional guidance. Recommendations are offered to resolve current deficiencies and to prepare a user-friendly document for practitioners.

Systems Engineering Processes—Workers in the general field of systems engineering generally consider systems engineering to start with the problem definition process and extend to design, implementation, operations, and support functions. Although some of the general systems engineering methodologies are useful for traffic signal systems, the methodologies and processes that are focused for application to other fields are generally not transferable to traffic signal systems engineering.

Key processes have been identified in the following traffic signal systems engineering areas:

- Goals and problem definition,
- Identification of constraints,
- Planning structure for identification of requirements,
- Traffic signal systems design engineering
 - Need for traffic signals,
 - Signal timing,
 - Requirements for signal coordination,
 - Selection of type of traffic signal systems control,
 - Communication systems,
 - Intersection field equipment,
 - Local intersection control strategies,
 - Preemption,
 - Transit priority,
 - Alternatives evaluation,
 - System procurement,
 - Operations and logistics,
 - Project evaluation.

Use of Systems Engineering Processes by Practitioners—Systems engineering is often viewed by practitioners as including not only the technical and project-oriented issues discussed in systems engineering literature, but also the administrative practices and policies characteristic of their agency. The extent to which systems engineering processes are used varies widely depending on the specific engineering topic involved. As determined from survey responses, agencies are generally satisfied with the processes and practices that they employ.

Availability of Existing Methodologies for Traffic Signal Systems Engineering—Methodologies currently exist in the literature for many areas that comprise traffic signal systems engineering. This synthesis has identified and summarized these existing methodologies. The following areas require additional methodologies, the updating of existing methodologies, or the upgrading of existing documentation:

- Structured inventory of traffic signal systems engineering requirements.
- Development of methodology for selection of the capability level of the traffic control system.
- Improved documentation for developing a database for conventional traffic response signal systems.
- Improved documentation for the placement of system detectors.
- Updated documentation for the selection of type of communications systems.
- Improved documentation for operational use of fully actuated and semi-actuated control strategies.
- Guidance for engineering transit signal priority functions.
- Improved documentation for development and maintenance of signal systems.

Need for Additional Guidance—As identified by survey respondents the areas that most often require additional guidance include

- Central traffic control systems, including equipment at the traffic management center and field master controllers that may be required by these systems.
- Communications to the field.
- Traffic signal systems deployment and maintenance.

The following is suggested

- That a project be implemented to resolve the current shortcomings in existing traffic signal systems processes and their documentation as outlined at the conclusion of chapter five.
- That a high-visibility document be prepared to identify the most appropriate existing methodologies and incorporate the resolution of the shortcomings cited in chapter five. That the document provide the methodologies to practitioners in a user-friendly manner or direct them to appropriate references and emphasize

- Selection of central traffic control systems and communications to the field.
- Central traffic control systems, including required equipment at the traffic management center and field master controllers.
- Processes for the development of traffic-respon-

- sive databases for systems using First Generation Urban Traffic Control System and closed-loop control strategies.
- Processes for deployment and maintenance of these systems.

8

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ABBREVIATIONS

ANSI	American National Standards Institute
ATC	Advanced Transportation Controller
ATSAC	Automatic Traffic Surveillance and Control
BER	bit rate error
CBD	central business district
CCTV	closed-circuit television
CIC	critical intersection control
CITE	Consortium for ITS Training and Education
CW	continuous wave
GPS	Global Positioning System
HRI	Highway Research Institute
IMSA	International Municipal Signal Association
INCOSE	International Council on Systems Engineering
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MOE	measure of effectiveness
MUTCD	<i>Manual on Uniform Traffic Control Devices</i>
NEMA	National Electrical Manufacturers Association
NICET	National Institute for Certification in Engineering Technologies
NTCIP	National Transportation Communications for ITS Protocol
PDF	platoon dispersion factor
RF	radio frequency
TBC	time base coordination
TMC	traffic management center
TOD	time of day
TR	traffic responsive
UTCS	Urban Traffic Control System

APPENDIX A

Survey Questionnaire

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
Project 20-5, Synthesis Topic 30-01

**SYSTEMS ENGINEERING PROCESSES
FOR DEVELOPING TRAFFIC SIGNAL SYSTEMS**

SUPPLEMENTAL QUESTIONNAIRE

Name of primary respondent: _____
Title: _____
Agency: _____
Address: _____
Phone No.: _____
Fax No.: _____
E-mail: _____

Thank you for your response to the 1999 survey regarding NCHRP Project 20-5, Topic 30-01, *Systems Engineering Processes for Developing Traffic Signal Systems*. The survey results will be incorporated into a report providing a detailed nationwide summary of current practices concerning the processes, specifications, and equipment involved in the development, deployment, and maintenance of traffic signal systems.

The attached eight part questionnaire represents a supplement to the cited 1999 survey and seeks in-depth information and professional opinion regarding topics surrounding the engineering processes involved in the development, deployment, and maintenance of traffic signal systems. Part 1 of the questionnaire addresses current systems engineering processes employed in connection with major traffic signal systems. The next four questionnaire parts concern the planning, design, and/or engineering processes used in the specification of key traffic signal system components. Part 6 of the questionnaire pertains to system deployment and maintenance procedures. The final two survey parts ask respondents to evaluate various traffic control system concepts and identify improvements in the overall traffic signal system engineering process including the incorporation of a systems engineering approach.

Please return the completed questionnaire and any supporting documents via fax or mail to:

Steven P. Latoski
Dunn Engineering Associates
66 Main Street
Westhampton Beach, New York 11978 Tel (631) 288-2480 Fax (631) 288-2544

We would appreciate your response by **March 1, 2001**.

THANK YOU FOR YOUR TIME AND EFFORT!!

PART 1 GENERAL

Name of respondent: _____

Title: _____

Phone No.: _____

Objective: Part 1 pertains to the overall systems engineering process.

1. Does your organization use a formal process for the development of goals and objectives for major traffic signal system upgrades? **Yes** ___ **No** ___

1a. Describe the process used.

1b. Please enclose any available documentation or provide a contact below for obtaining documentation.

2. Prior to implementing system design, does your organization prepare a document defining the management approach to be used in implementing major system improvements? **Yes** ___ **No** ___

2a. Describe the document's scope.

2b. Please enclose any available documentation or provide a contact below for obtaining documentation.

3. Does your organization use alternative evaluation methodologies (e.g., benefit vs. cost, utility vs. cost) in selecting approaches for major signal system upgrade projects? **Yes** ___ **No** ___

3a. Describe the methodology(s) used.

4. Does your organization use a methodology to select a systems procurement approach (low bid, two step process, design/build, system manager, etc.)? **Yes** ___ **No** ___

4a. Describe the methodology(s) used.

- 4b. Is your procurement approach determined by your organization’s procedures? **Yes** ___ **No** ___
- 5. Does your organization conduct a formal evaluation (e.g., before and after studies) in connection with major improvements? **Yes** ___ **No** ___

5a. Describe the evaluation methodology(s) used.

PART 2 CENTRAL TRAFFIC CONTROL EQUIPMENT AND FIELD MASTERS

Name of respondent: _____

Title: _____

Phone No.: _____

Objective: Part 2 pertains to the planning, design, and/or engineering processes used in the specification of central traffic control equipment and field masters.

- 6. Does your organization use standard specifications to which central traffic control systems and field masters (if applicable) **must** conform? **Yes** ___ **No** ___
- 7. Does your organization use standard specifications to which central traffic control systems and field masters (if applicable) **may optionally** conform? **Yes** ___ **No** ___
- 8. If the answer to Question 6 or Question 7 is “yes,” how often are major revisions made to the specifications?

8a. What drives the specification revision cycle?

- 9. Does your organization adhere to a formal planning, design, or engineering process in the development of designs and specifications for the type of traffic system to be used (e.g., centrally controlled, closed loop, adaptive) for a particular application? **Yes** ___ **No** ___

9a. Describe the process used.

9b. Please enclose any available documentation or provide a contact below for obtaining documentation.

10. If the answer to Question 9 is “yes,” how successful has the formal process been?

10a. What changes would you recommend to the formal process?

11. Does your organization follow a formal process to determine how the system should be operated (e.g., hours of attended operation, operating mode, acceptable maintenance response time)? **Yes** ___ **No** ___

11a. If “yes,” describe the process used.

11b. Please enclose any available documentation or provide a contact below for obtaining documentation.

12. With the exception of standards related issues, has the National ITS Architecture significantly changed your organization’s systems engineering approach? **Yes** ___ **No** ___

12a. If “yes,” describe the changes attributed to the National ITS Architecture.

PART 3 COMMUNICATIONS TO THE FIELD

Name of respondent: _____

Title: _____

Phone No.: _____

Objective: Part 3 concerns the planning, design, and/or engineering processes used in the specification of a communications system to the field electronics equipment.

13. Does your organization use standard specifications to which communications to the field electronics equipment (e.g., media selection, modems, communication standards, and protocols) **must** conform? **Yes** ___ **No** ___

14. Does your organization use standard specifications to which communications to the field electronics equipment (e.g., media selection, modems, communication standards, and protocols) **may optionally** conform? **Yes** ___ **No** ___

15. If the answer to Question 13 or Question 14 is “yes,” how often are major revisions made to the specifications?

15a. What drives the specification revision cycle?

16. Does your organization adhere to a formal planning, design, or engineering process in the development of designs and specifications for the type of communication system to be used? **Yes** ___ **No** ___

16a. If "yes," describe the process used.

16b. Please enclose any available documentation or provide a contact below for obtaining documentation.

17. If the answer to Question 16 is "yes," how successful has the formal process been?

17a. What changes would you recommend to the formal process?

PART 4 FIELD EQUIPMENT

Name of respondent: _____

Title: _____

Phone No.: _____

Objective: Part 4 concerns the planning, design, and/or engineering processes used in the specification of field equipment.

18. Does your organization use standard specifications to which the field equipment (e.g., controllers, detectors, etc.) **must** conform? **Yes** ___ **No** ___

19. Does your organization use standard specifications to which the field equipment (e.g., controllers, detectors, etc.) **may optionally** conform? **Yes** ___ **No** ___

20. If the answer to Question 18 or Question 19 is "yes," how often are major revisions made to the specifications?

20a. What drives the specification revision cycle?

21. Does your organization follow a formal planning, design, or engineering process in the development of designs and specifications for the type of field equipment to be used? **Yes** ___ **No** ___

21a. If "yes," describe the process used.

21b. Please enclose any available documentation or provide a contact below for obtaining documentation.

22. If the answer to Question 21 is "yes," how successful has the formal process been?

22a. What changes would you recommend to the formal process?

PART 5 ENGINEERING AND DESIGN OF INTERSECTION INSTALLATIONS

Name of respondent: _____

Title: _____

Phone No.: _____

Objective: Part 5 concerns the planning, design, and/or engineering processes used in the specification of traffic signal installations at intersections.

23. Does your organization follow a formal planning, design, or engineering process in the determination of an engineering decision regarding whether an intersection requires a signal or if a signal should be removed?

Yes ___ **No** ___

23a. If "yes," describe the process used.

23b. Please enclose any available documentation or provide a contact below for obtaining documentation.

24. Does your organization follow a formal planning, design, or engineering process in the determination of an engineering decision regarding whether an isolated intersection should be actuated? **Yes** ___ **No** ___

24a. If “yes,” describe the process used.

24b. Please enclose any available documentation or provide a contact below for obtaining documentation.

25. Does your organization follow a formal planning, design, or engineering process in the determination of an engineering decision regarding whether coordination should be employed at an intersection? **Yes** ___ **No** ___

25a. If “yes,” describe the process used.

25b. Please enclose any available documentation or provide a contact below for obtaining documentation.

26. Does your organization follow a formal planning, design, or engineering process in the determination of an engineering decision regarding whether side street or turning phase actuation should be employed in coordinated systems? **Yes** ___ **No** ___

26a. If “yes,” describe the process used.

26b. Please enclose any available documentation or provide a contact below for obtaining documentation.

PART 6 OPERATIONS AND LOGISTICS

Name of respondent: _____

Title: _____

Phone No.: _____

Objective: Part 6 pertains to traffic signal system deployment and maintenance procedures.

27. Does your organization have procedures or standards for planning and specifying maintenance and/or training?
Yes ___ **No** ___

27a. If "yes," please enclose any available documentation or provide a contact below for obtaining documentation.

28. Does your organization conduct an evaluation of traffic signal system performance when performing an upgrade?
Yes ___ **No** ___

29. Does your organization conduct an evaluation of traffic signal system performance at periodic intervals?
Yes ___ **No** ___

30. If the answer to Question 28 or Question 29 is "yes," how is the evaluation performed?

30a. Please enclose any available documentation or provide a contact below for obtaining documentation.

PART 7 IMPROVEMENT OF TRAFFIC SIGNAL SYSTEM ENGINEERING PROCESS

Name of respondent: _____

Title: _____

Phone No.: _____

Objective: Part 7 seeks to identify improvements in the overall traffic signal system engineering process.

31. Does your organization perceive a need for a report or manual describing a formal system engineering process to address:

- a. Specification of central control equipment and field masters? **Yes** ___ **No** ___
- b. Specification of a communications systems to the field electronics equipment? **Yes** ___ **No** ___
- c. Specification of field equipment? **Yes** ___ **No** ___
- d. Specification of traffic signal installations at intersections? **Yes** ___ **No** ___
- e. Traffic signal system deployment and maintenance? **Yes** ___ **No** ___

32. Does your organization perceive a need for increased quality and/or quantity of tutorial material to facilitate the selection process for:

- a. Central control equipment and field masters? **Yes** ___ **No** ___
- b. Communications systems to the field electronics equipment? **Yes** ___ **No** ___
- c. Field equipment? **Yes** ___ **No** ___

- d. Traffic signal installations at intersections? Yes ___ No ___
- e. Traffic signal system deployment and maintenance? Yes ___ No ___

PART 8 IMPORTANCE FACTORS

Name of respondent: _____
 Title: _____
 Phone No.: _____

Objective: Part 8 concerns the evaluation of various traffic control system development and deployment issues.

33. On a scale of 1 (least important) to 10 (most important), rank the importance of the following in the development of traffic control system concepts, system specifications, equipment specifications, and intersection engineering designs:

Issues	Central System and Field Masters	Communications	Field Equipment
a. Legacy issues (compatibility with existing systems, equipment).			
b. Ease, cost, and availability of maintenance and support.			
c. Performance (real-time traffic flow optimization).			
d. Familiarity with technology.			
e. System cost.			
f. National Architecture conformance.			
g. Compatibility with other ITS in your organization's jurisdiction.			
h. Compatibility with ITS in other jurisdictions.			
i. Availability of new national specifications (NEMA, NTCIP, ATC, etc.).			
j. Availability of new system coordination technology (e.g., SCOOT, SCATS, RTRACS, OPAC, RHODES).			
k. Plan for introducing the NTCIP protocol for communication to intersection signal controllers.			
l. Perceived future needs.			
m. Other _____ _____			
n. Other _____ _____			

33a. If one or more traffic control components are checked under issue "I," please identify the specifications important to your organization.

34. Please list a contact person for obtaining additional information.

Contact person:	Name
	<hr/>
Title	<hr/>
Agency	<hr/>
Address	<hr/>
Phone	<hr/>
Fax	<hr/>
E-mail	<hr/>

Please send any documents detailing processes for developing, deploying, and maintaining traffic signal systems along with the completed questionnaire to:

Steven P. Latoski
Dunn Engineering Associates
66 Main Street
Westhampton Beach, New York 11978
Fax (631) 288-2544

End of Survey. **THANK YOU!**

APPENDIX B

Survey Respondents

STATES	CITIES AND COUNTIES
Alabama	El Paso, TX
Arizona	Los Angeles, CA
Colorado	Portland, OR
Connecticut	San Diego, CA
Illinois	
Iowa	
Maryland	
Mississippi	
Missouri	
Nevada	
New Jersey	
New York	
Ohio	
Oklahoma	
Oregon	
Rhode Island	
South Carolina	
Washington	

APPENDIX C

Example of Structured Analysis Process

Figures C1 and C2 provide an example of the first two levels of data flow diagrams for processes required by the bakery industry. The diagrams include symbols for the organizations and processes external to the baking process as well as symbols for information storages.

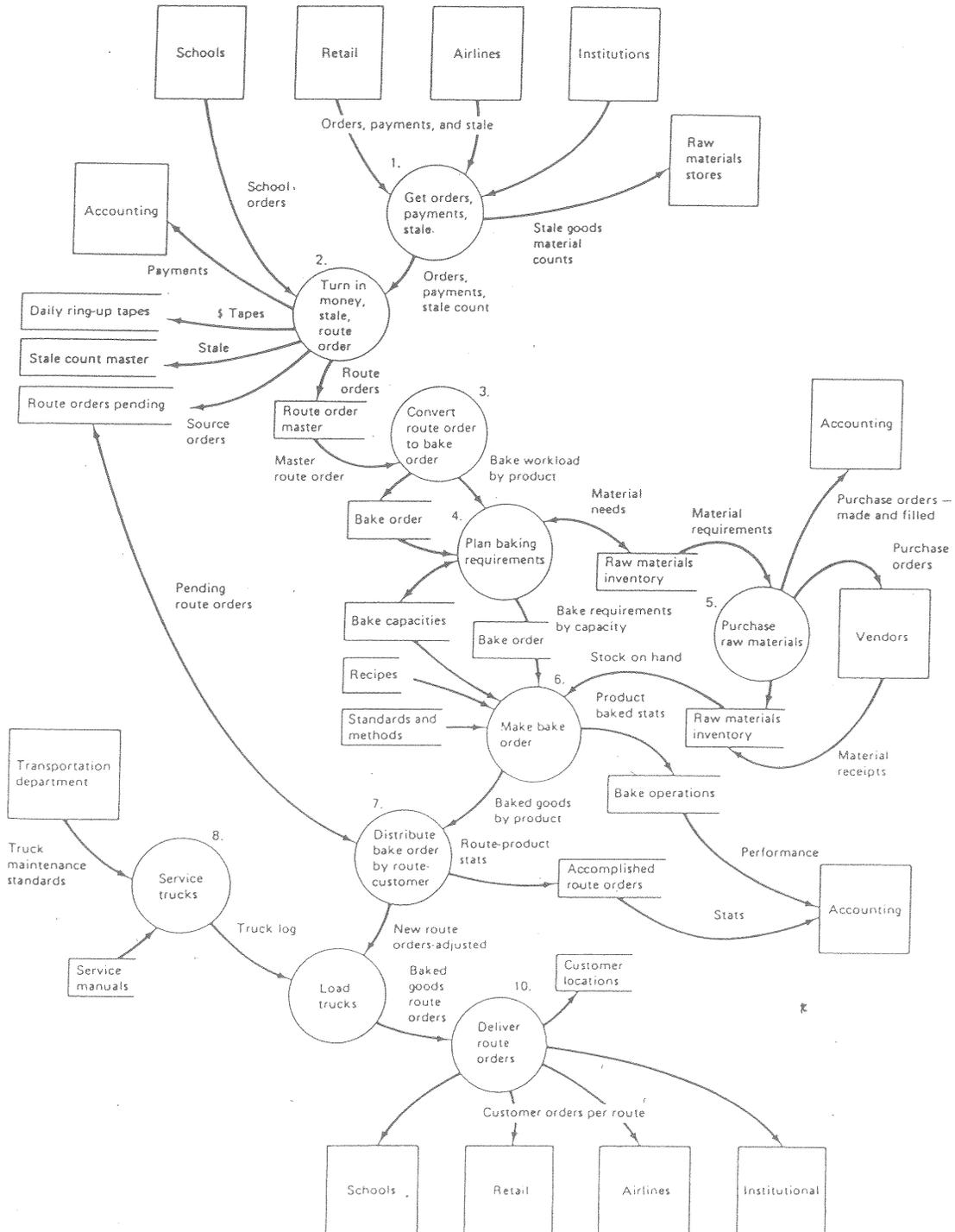


FIGURE C1 Bakery data flow diagram (Level 1) (Leslie 1986). (Reprinted by permission of Pearson Education, Inc., Upper Saddle River, N.J.).

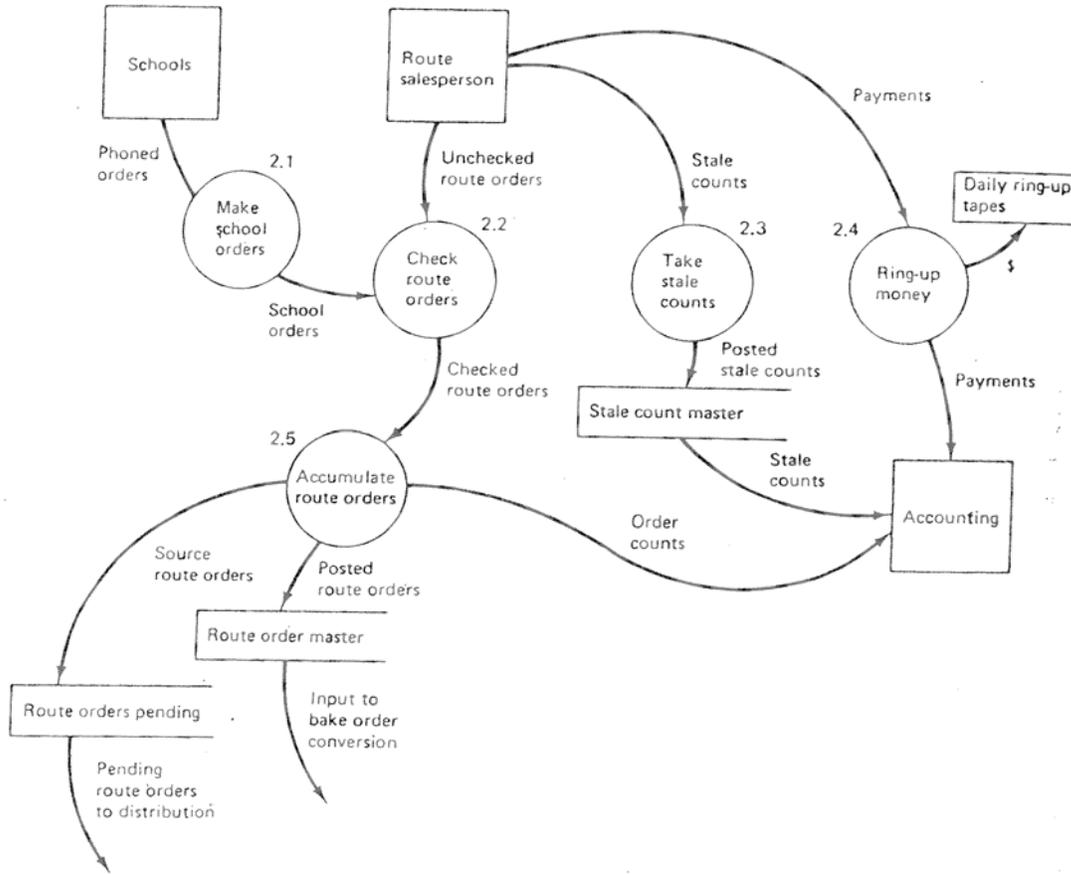


FIGURE C2 Turn in money, stale, route order process (Level 2) (Leslie 1986). (Reprinted by permission of Pearson Education, Inc., Upper Saddle River, N.J.).

APPENDIX D

Quality Functional Deployment Methodology

The following discussion is abstracted from the TRB report, “Improved Traffic Signal Priority for Transit” (1998).

To establish the relationships between system objectives, performance measures, and different strategy characteristics the Quality Functional Deployment (QFD) methodology was followed. QFD is a technique that was created primarily to improve the quality of manufacturing processes and was introduced by American automobile manufacturing companies in the early 1980s. The main idea of the QFD is to use matrix representation of available data or characteristics to identify interrelationships. The QFD method can be applied to any area or to any aspect where interrelationships between different system characteristics, objectives, or measures of effectiveness are to be discovered.

The QFD representation is based on a waterfall chart where *hows* of an upper level become *whats*, of the lower level of the chart (see Figure D1). After defining all *hows* and *whats*, the next step in QFD analysis is to determine the strength of relationships (or degree of correlation) between the *whats* and the *hows*. For our application, a checkmark is used to indicate that a relationship exists, but no attempt was made to establish the strength of this relationship. If any row of a matrix is blank, it should be removed or another characteristic (*how*) should be added.

For the purposes of this investigation, the initial *whats* are the stakeholder objectives. The stakeholders are the

owners/operators/users of the system(s) that will ultimately be affected by transit priority strategies. Each of the stakeholder objectives is addressed by one or more of the system characteristics. These characteristics determine how the ultimate system will attempt to meet the objectives. For example, one way that the transit operators’ objective to reduce operating costs can be satisfied is through route selection and scheduling.

The system characteristics then “waterfall” to become the *whats* in the next level of the QFD methodology. The *hows* in this case address how well the ultimate system performs these characteristics by defining measures of effectiveness that reflect the level of performance. For example, the schedule of a transit system is effected by the running times between time points, which is directly effected by the delay incurred at traffic signals and the level of traffic congestion along the transit route.

Continuing with the QFD methodology, these performance measures then “waterfall” to become the next level of *whats*. The *hows* then identify the important transit priority characteristics that should be addressed in the development of strategies to satisfy the original stakeholder objectives. It should be noted that the QFD process is being applied as a tool to establish the relationship between stakeholder objectives and transit priority strategy characteristics, but there may be additional considerations that could be addressed in the strategy development and evaluation.

The report provides a process for identifying transit priority strategy characteristics based on this methodology.

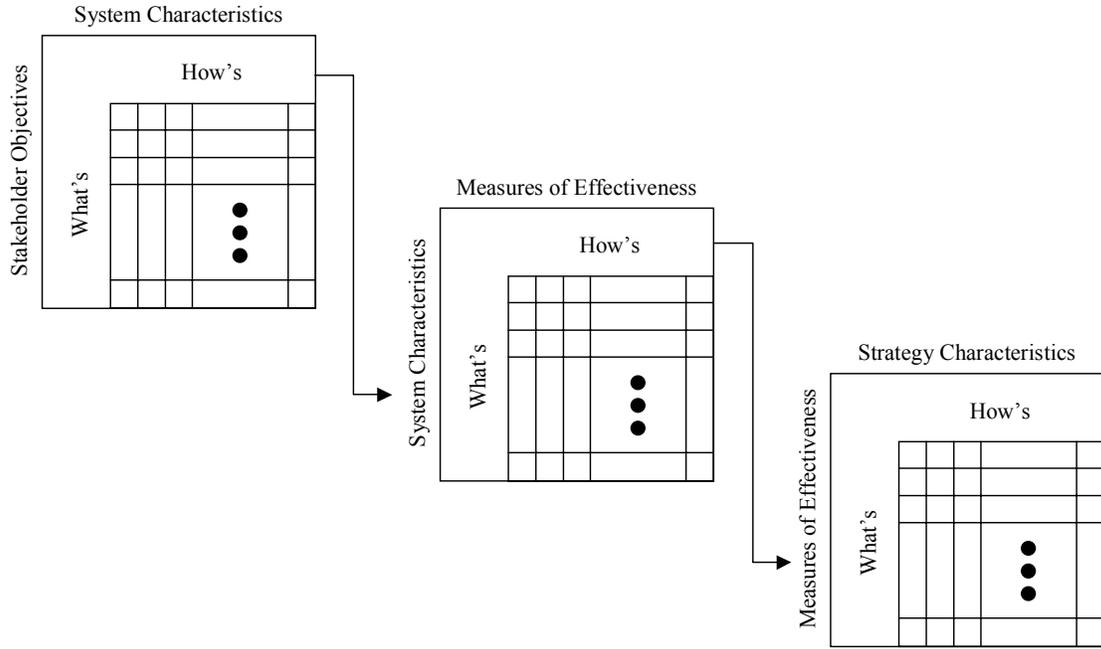


FIGURE D1 QFD “waterfall” relationships (*Improved Traffic Signal Priority for Transit* 1998).

APPENDIX E

Interface Alternatives for Communicating with Controllers

The Communications Handbook for Traffic Control Systems (Gordon 1993) identifies common interface approaches for communicating with controllers. Figures E1 and E2 are examples of such interfaces. Since its publication, the use of fiber optic modems in place of copper-based systems has become common. These modems may be provided as units in the controller chassis or they may be external to the chassis. Spread spectrum radio modems are also more commonly used than in the past.

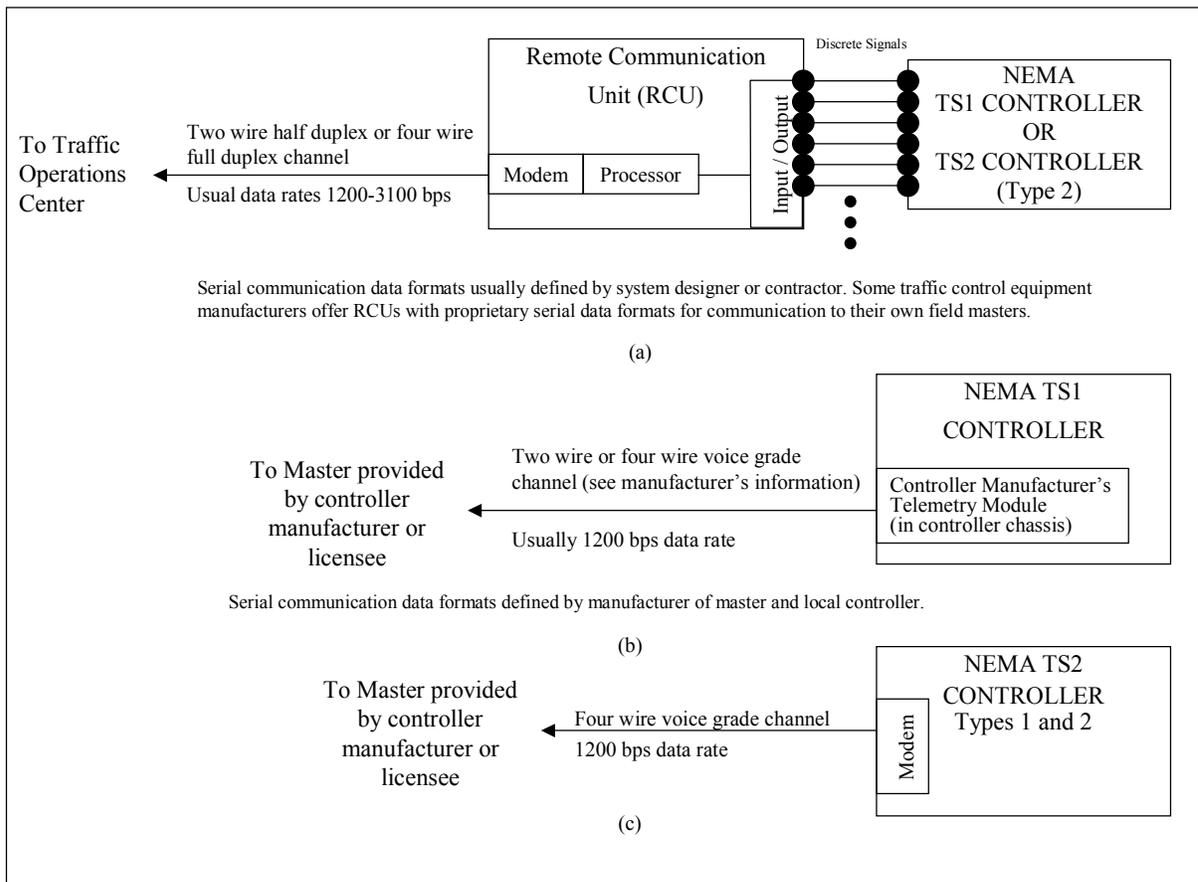


FIGURE E1 Communication interface alternatives for National Electrical Manufacturer's Association controllers (Gordon et al. 1993).

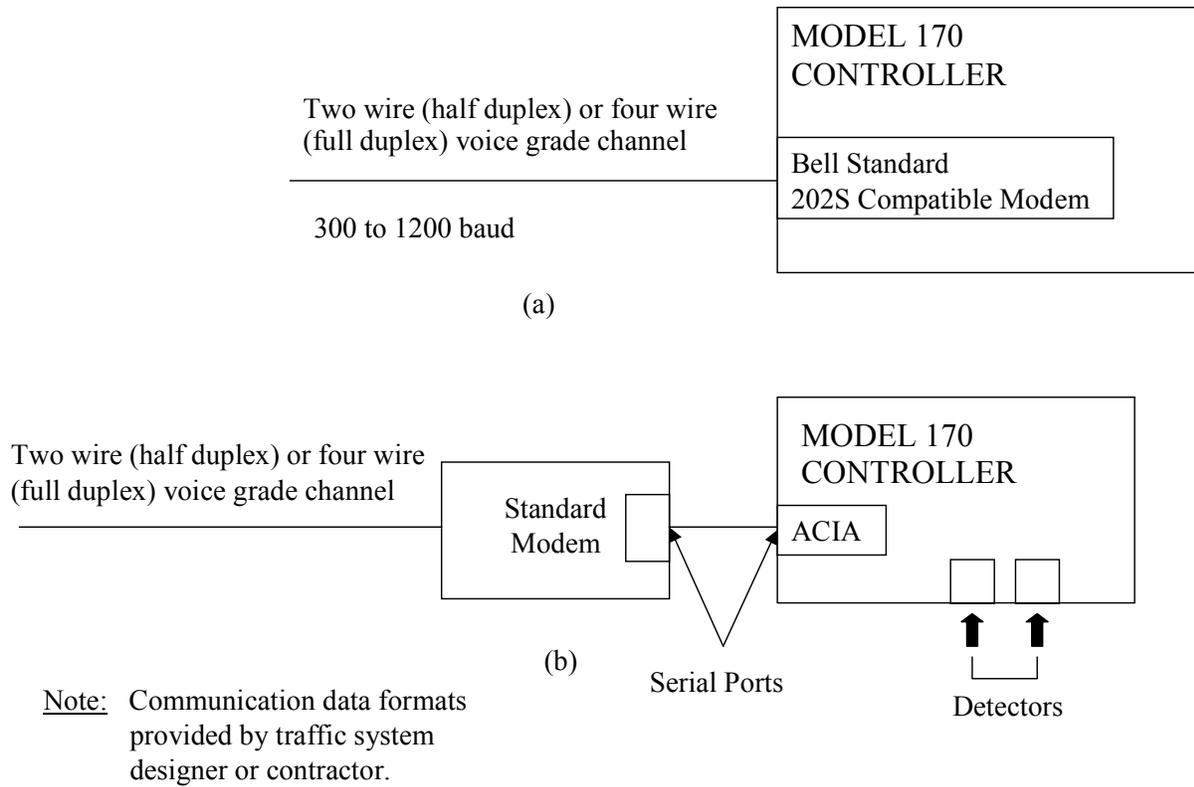


FIGURE E2 Communication interface alternatives for Model 170 Controller (Gordon et al. 1993).

APPENDIX F

Methodology for Communication System Selection

The *Communications Handbook for Traffic Control Systems* (Gordon et al. 1996) provides a formal methodology for selection of communications media and architectures for traffic signal systems and freeway systems. The *Handbook* discussed the procedural steps shown in Figure F1. Two examples of communication system design for signal systems are provided.

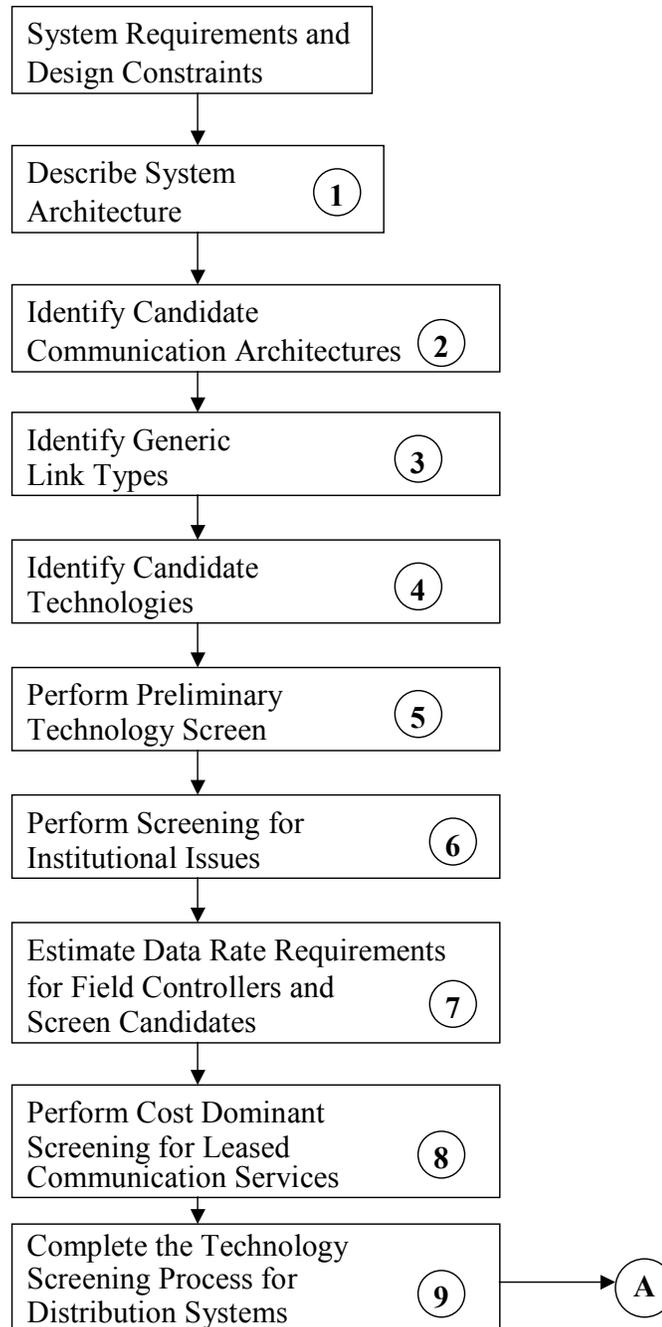


FIGURE F1 Procedure for selection communications architecture and technology (Gordon et al. 1993).

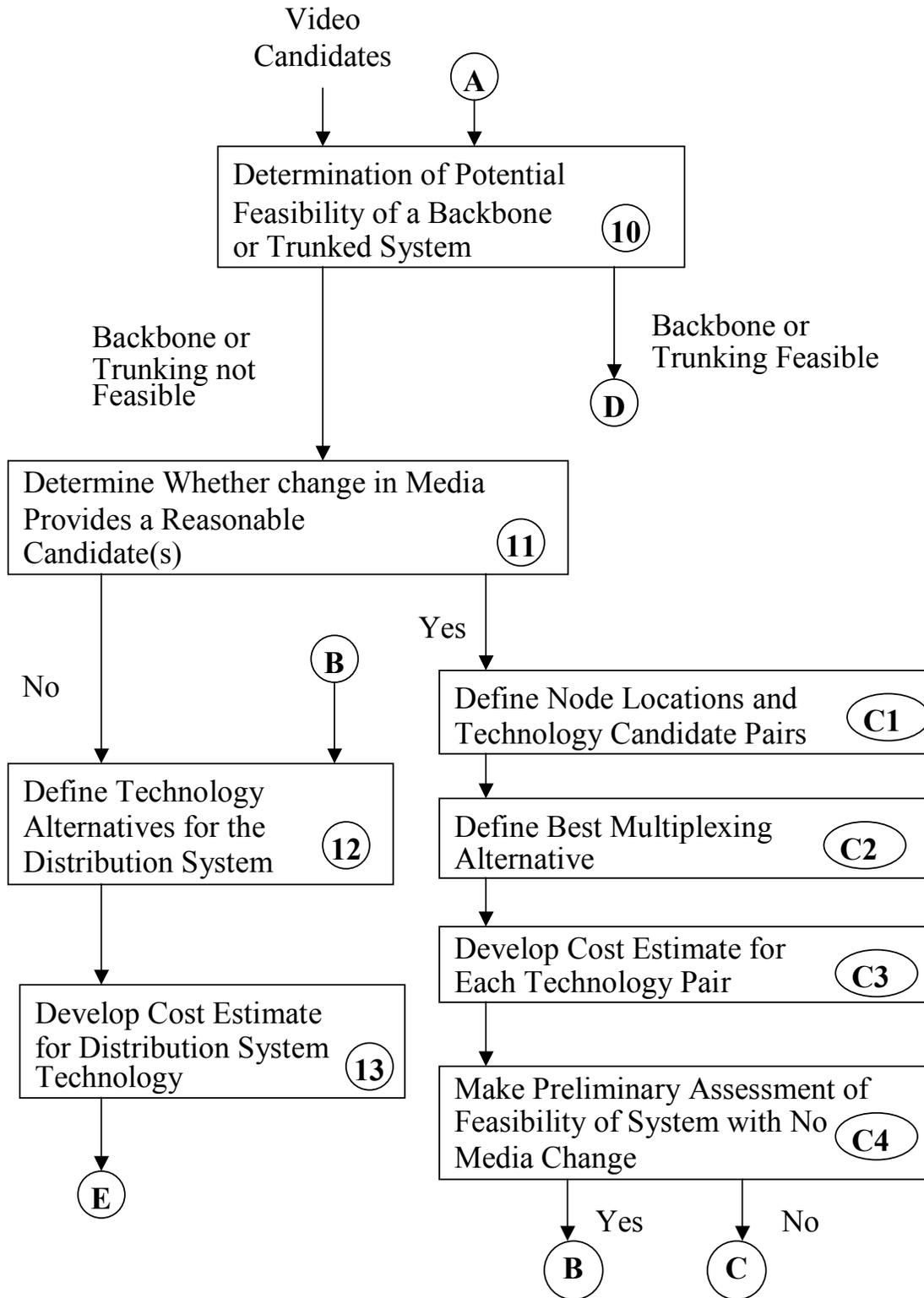


FIGURE F1 (Continued)

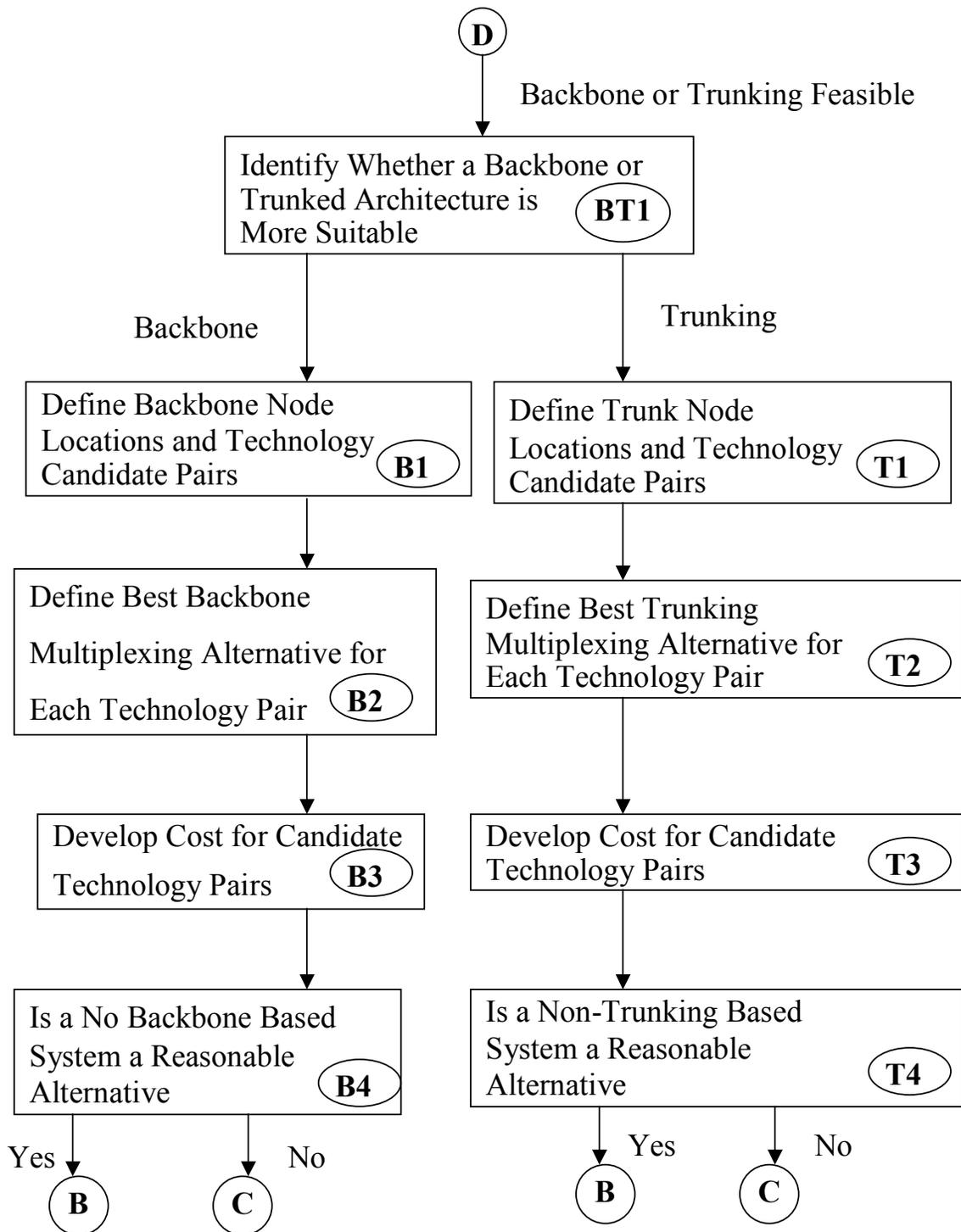


FIGURE F1 (Continued).

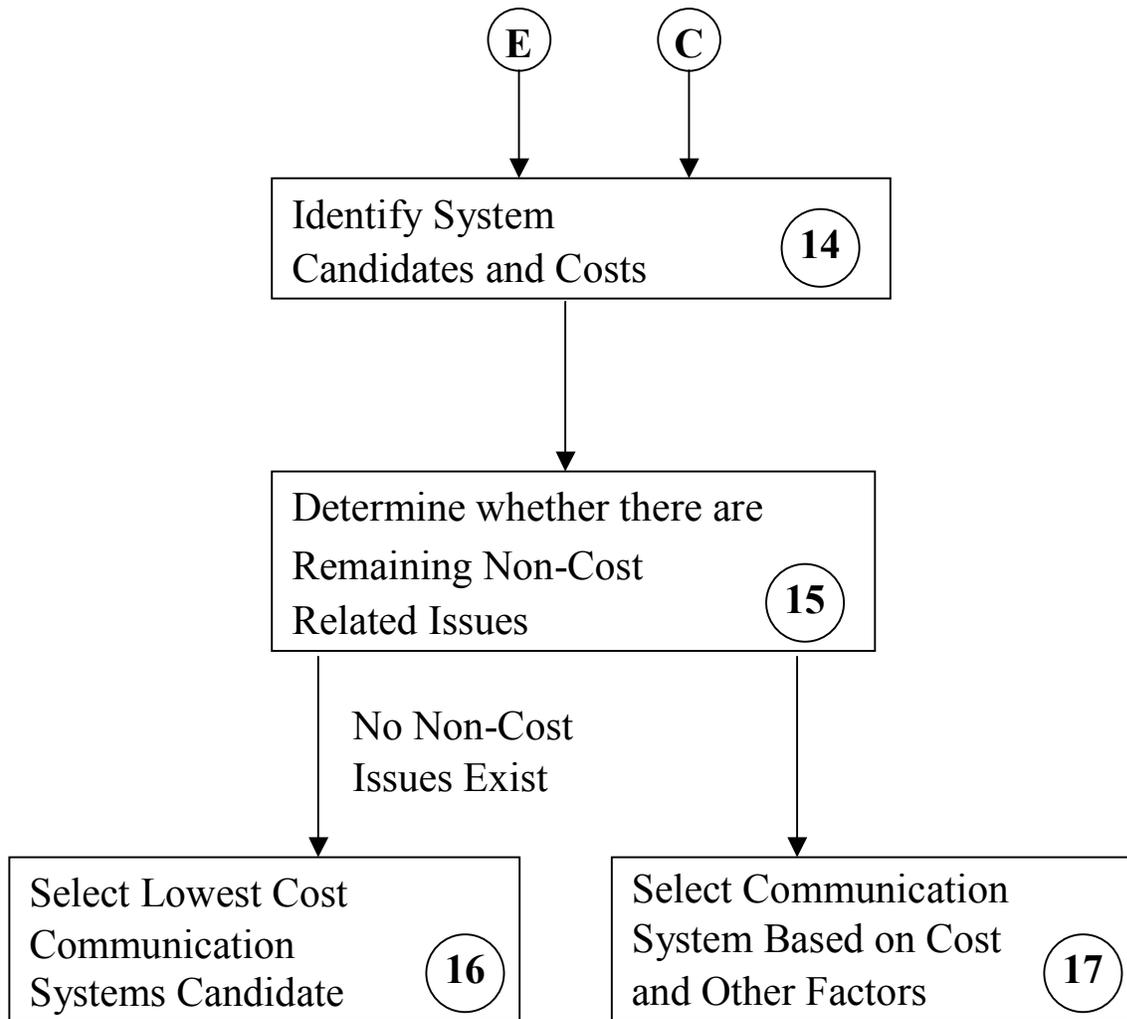


FIGURE F1 (Continued).

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Advisers to the Nation on Science, Engineering, and Medicine

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