CHAPTER THREE

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.
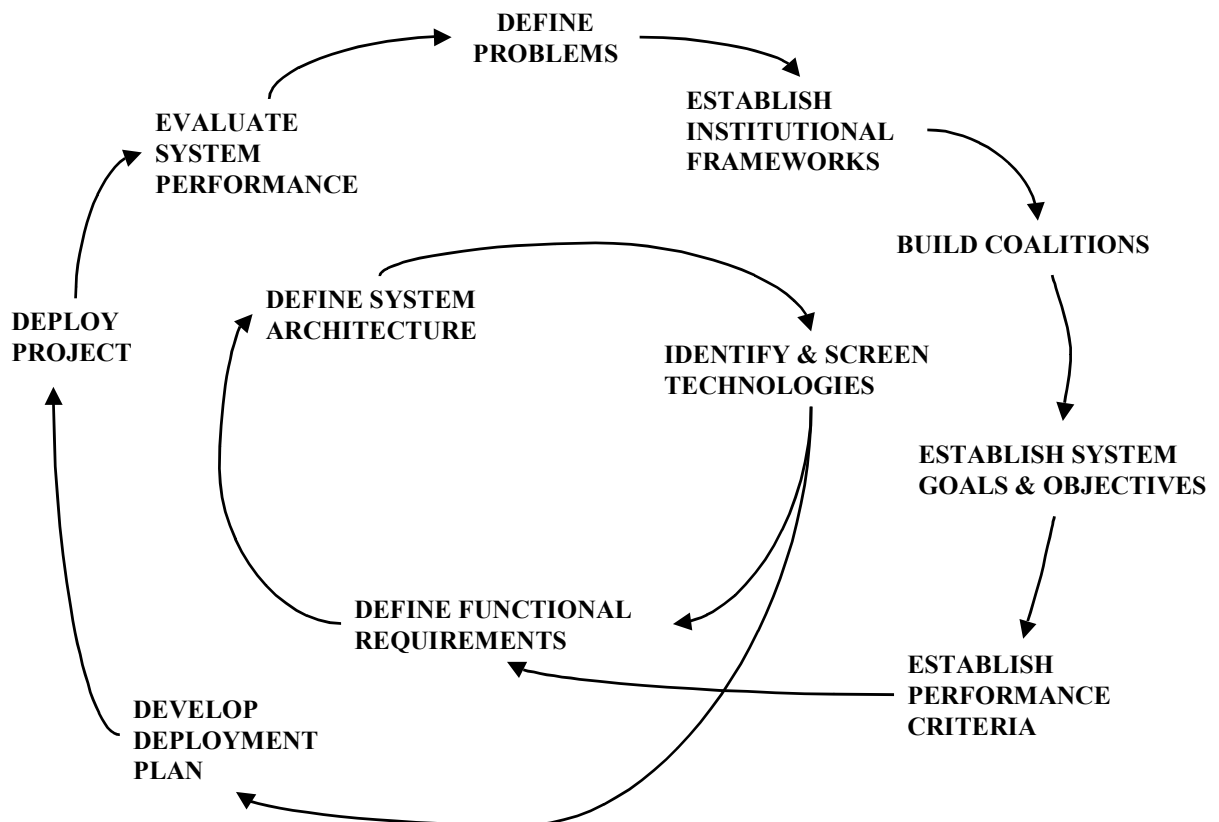

FIGURE 7 Steps performed in a typical systems engineering analysis (Carvell et al. 1997).

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.

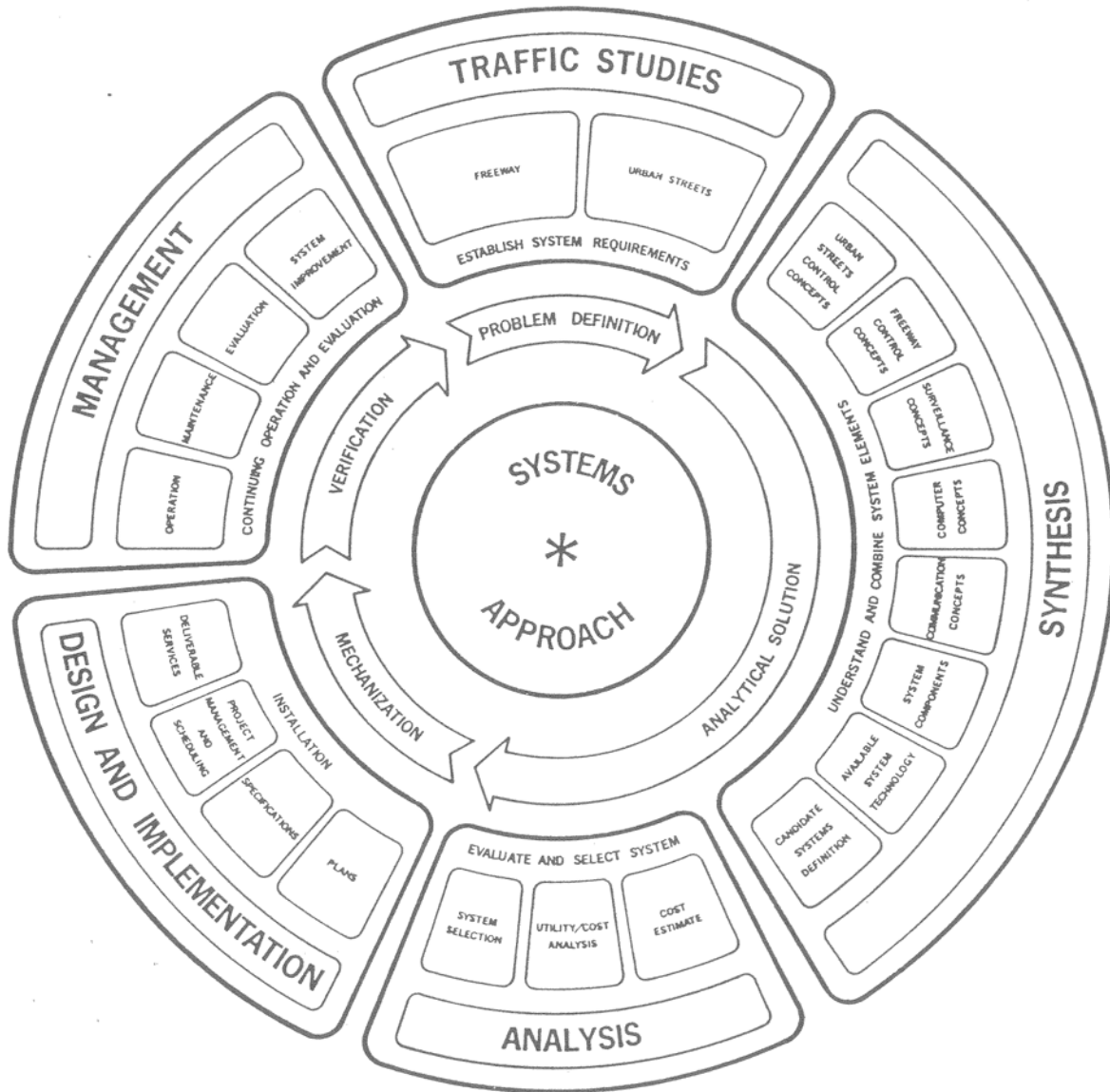The definition of systems engineering analysis is "A structured process for arriving at a final design of a system"

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	• Requirements originate from
	  – traffic growth or changes in traffic patterns
	  – equipment that is obsolete or requires excessive maintenance
	• Requirements development team includes
	  – management
	  – planning
	  – design
	  – operations
	  – maintenance

Identify alternative systems	• Information sources include
	  – manufacturers
	  – users
	  – system houses
	  – consultants
	  – researchers
	  – interested individuals

TABLE 5
ELEMENTS OF A TYPICAL IMPLEMENTATION PLAN

Element	Components
Needed Legislation	
System design	• System designer • System design life • System coverage • System design and operations/maintenance philosophies • System architecture • Integration of other functions • System components and functions • Communication subsystem design approach • Traffic operations center design features • Project phasing/scheduling • Design review
Procurement Methods	
Construction management procedures	• Division of responsibilities • Scheduling and establishing mileposts • Conflict mitigation • Coordination with other projects
System start-up plan	• Software and system acceptance tests • Partial acceptance • Documentation • Transition from old to new control • Operational support and warranty period • Training • Coordination with media
Operations and maintenance plan	• Evaluation – system evaluator – method of evaluation – cost of evaluation • Maintenance plan – maintenance policies for preventative maintenance, system malfunctions, etc. – formal maintenance management programs – initial inventory of spare parts and all necessary test equipment – training in providing limited maintenance to software and equipment
Institutional agreements	• 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
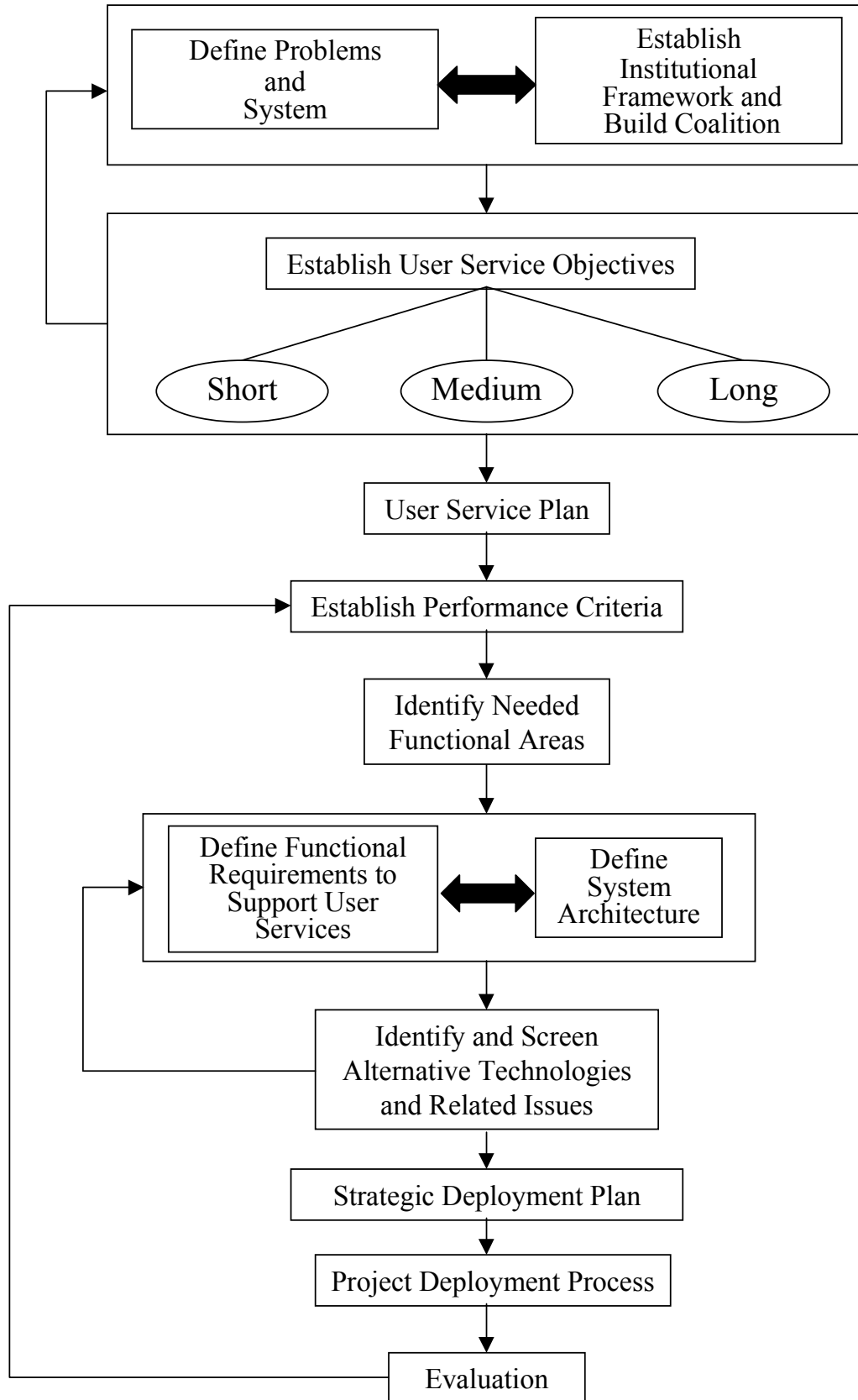
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┌─────────────────────────────────────────────────────────┐
│  ┌──────────────────┐         ┌──────────────────────┐   │
│  │ Define Problems  │◄───────►│     Establish        │   │
│  │      and         │         │   Institutional      │   │
│  │     System       │         │  Framework and       │   │
│  │                  │         │  Build Coalition     │   │
│  └──────────────────┘         └──────────────────────┘   │
└─────────────────────────────────────────────────────────┘

┌─────────────────────────────────────────────────────────┐
│        ┌──────────────────────────────────────┐          │
│        │  Establish User Service Objectives    │          │
│        └──────────────────────────────────────┘          │
│      ╱                  │                    ╲            │
│   ( Short )         ( Medium )            ( Long )        │
└─────────────────────────────────────────────────────────┘

                    ┌──────────────────┐
                    │ User Service Plan │
                    └──────────────────┘

                ┌──────────────────────────────┐
                │ Establish Performance Criteria │
                └──────────────────────────────┘

                    ┌──────────────────┐
                    │ Identify Needed  │
                    │ Functional Areas │
                    └──────────────────┘

┌─────────────────────────────────────────────────────────┐
│  ┌──────────────────┐         ┌──────────────────┐       │
│  │ Define Functional│◄───────►│     Define       │       │
│  │ Requirements to  │         │     System       │       │
│  │ Support User     │         │  Architecture    │       │
│  │ Services         │         │                  │       │
│  └──────────────────┘         └──────────────────┘       │
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                ┌──────────────────────────────┐
                │ Identify and Screen          │
                │ Alternative Technologies     │
                │ and Related Issues           │
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                ┌──────────────────────────────┐
                │ Strategic Deployment Plan    │
                └──────────────────────────────┘

                ┌──────────────────────────────┐
                │ Project Deployment Process   │
                └──────────────────────────────┘

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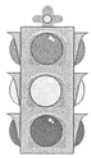
- Accident experience,
- Observations of signal timing performance and congestion patterns; formal measurements may result from these observations,
- Traffic count programs; growth factors may point to need for retiming, and
- Comments and complaints by the public.

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
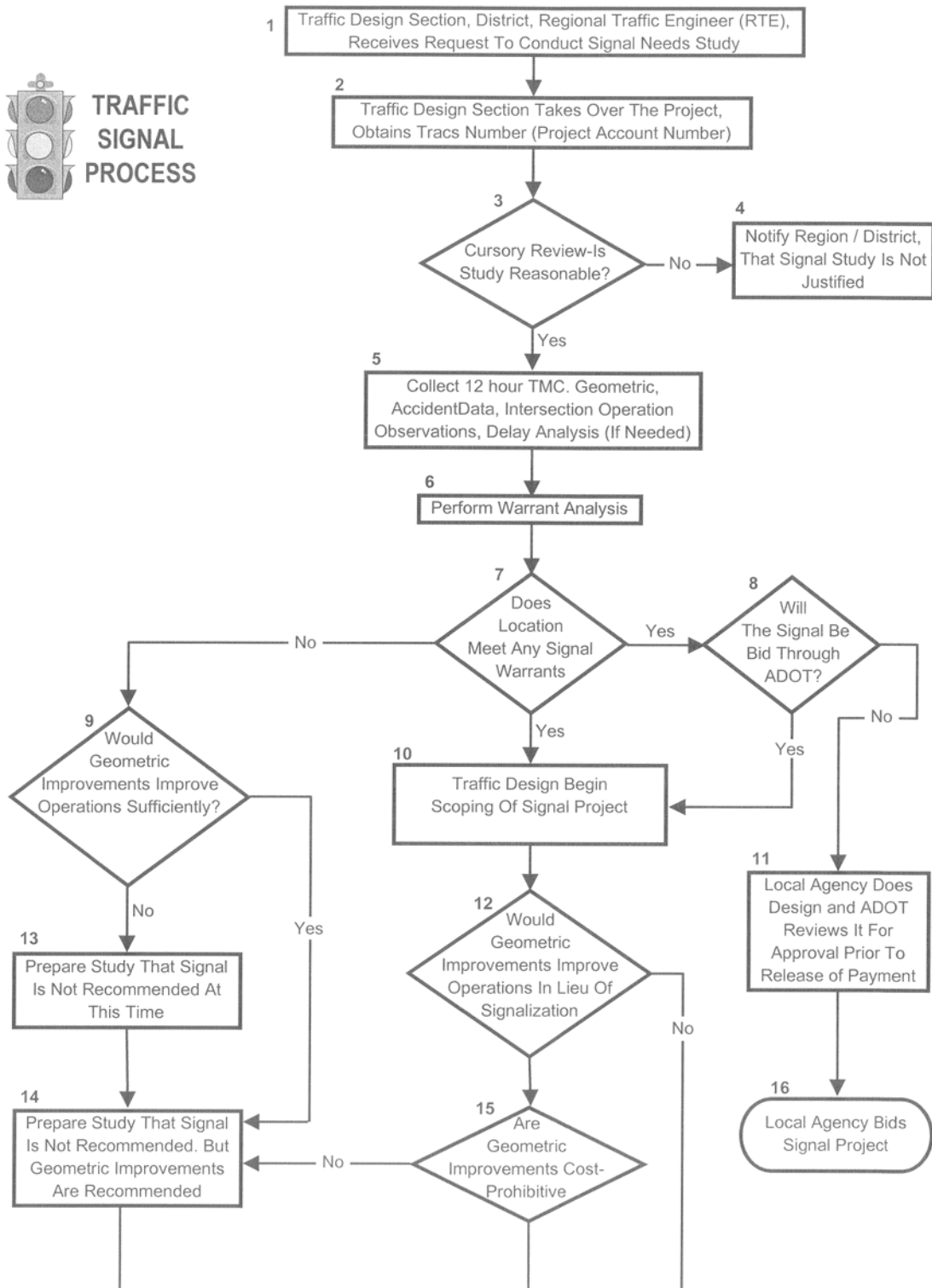
TRAFFIC SIGNAL PROCESS

1. Traffic Design Section, District, Regional Traffic Engineer (RTE), Receives Request To Conduct Signal Needs Study

2. Traffic Design Section Takes Over The Project, Obtains Tracs Number (Project Account Number)

3. Cursory Review-Is Study Reasonable? — No → 4. Notify Region / District, That Signal Study Is Not Justified

Yes

5. Collect 12 hour TMC. Geometric, AccidentData, Intersection Operation Observations, Delay Analysis (If Needed)

6. Perform Warrant Analysis

7. Does Location Meet Any Signal Warrants — No → ... — Yes → 8. Will The Signal Be Bid Through ADOT?

9. Would Geometric Improvements Improve Operations Sufficiently?

7. Yes → 10. Traffic Design Begin Scoping Of Signal Project

8. Yes → 10. Traffic Design Begin Scoping Of Signal Project
8. No → 11. Local Agency Does Design and ADOT Reviews It For Approval Prior To Release of Payment

9. No → 13. Prepare Study That Signal Is Not Recommended At This Time
9. Yes → 14.

12. Would Geometric Improvements Improve Operations In Lieu Of Signalization

11 → 16. Local Agency Bids Signal Project

13. → 14. Prepare Study That Signal Is Not Recommended. But Geometric Improvements Are Recommended

15. Are Geometric Improvements Cost-Prohibitive — No → 14.

12. No

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

17
Transmit Study To
Region / District

18
Prepare Final Scope With Or Without
Geometric Improvements Concludes
That A Signal May Be Installed ← No

19
Does The
Location Qualify
For Fedral Safty
Funding? — Yes →

20
Will FHWA
Approve Location
For *CLOSE*
Funding? — Yes →

21
Place Signal
Project
Into 5-Year
Program

No ↓

22
Transmit Study To Region / District
That Signal May Be Recommended

24
Prepare Scoping
Document Per
FHWA

23
Does
The Location
Involve A Local
Agency? — No

Yes ↓

25
Region (RTE) Contacts Local Agency For Their Concurrance

26
RTE Discuss % Participation With Local
Agency For Costs For Design, Installation,
Geometric Improvements, and Operations

27
Local Agency Sends Letter
Of Understanding To RTE

28
If Local Agency Concurs With
Recommendation, RTE Contacts
IGA Office And Traffic Design
Initiate IGA Process

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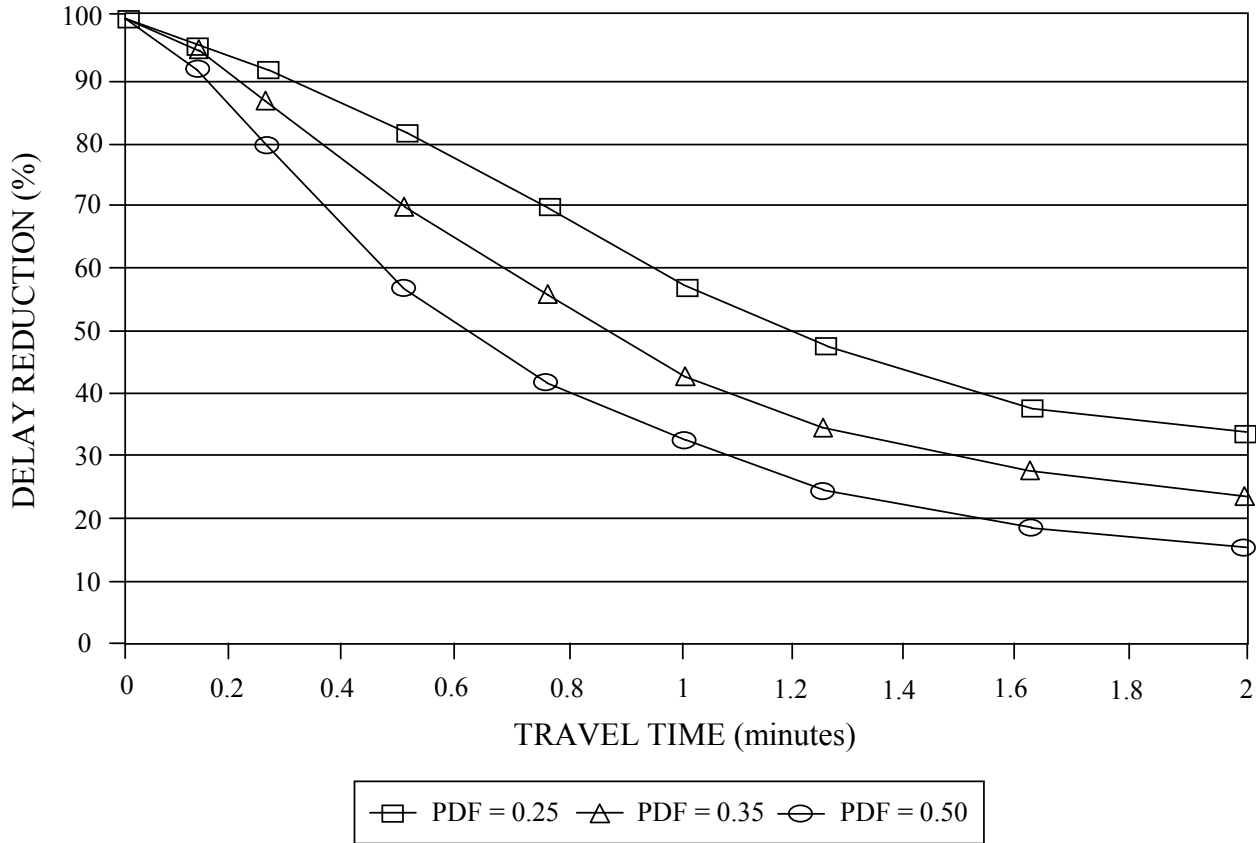
FIGURE 11 Benefits of signal coordination (Skabardonis et al. 1998).

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).

$$K = Q/(200(1 + t)) \qquad (1)$$

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 < 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).

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

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

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

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 nonproprietery 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.
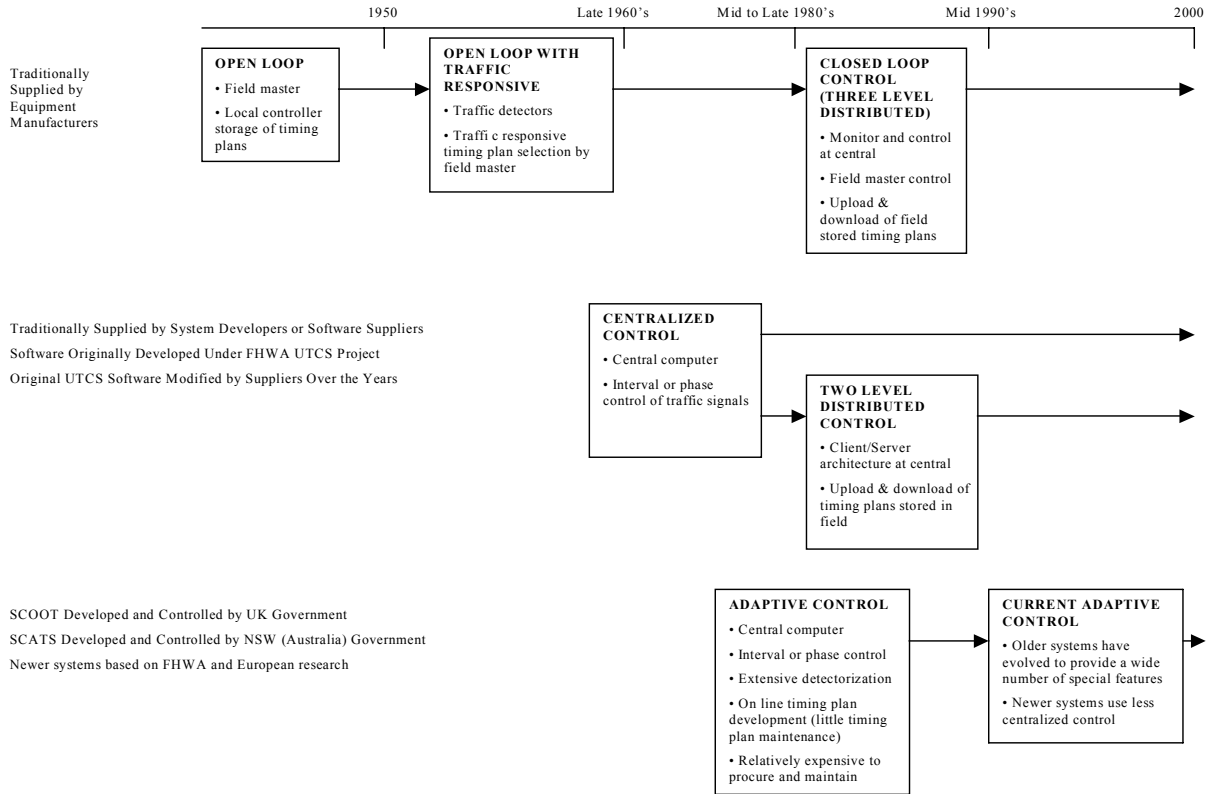
FIGURE 12 Interconnected traffic control system chronology.

TABLE 7
COMPLEXITY HIERARCHY OF TRAFFIC CONTROL SYSTEMS

Type of System	Features	Implementation Requirements
Level 1—Time base coordination • Time of day plans • Local intersection strategies	• Provides basic coordination	• Simple to implement. TBC provided by modern controllers • Requires timing plan maintenance
Level 2—Interconnected control • Time of day or operator-selected timing plans • Local intersection strategies	Level 1 + • Provides intersection and equipment status • Allows download of timing plans and changes • Provides record of system operation	Level 1 + • Wireline or wireless interconnect • Two or three level distributed control or central control • Few or no system detectors
Level 3—Conventional traffic-responsive control • Area traffic-responsive control • Critical intersection control (centralized architecture only) • Local intersection strategies	Level 2 + • 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 + • Modest level of system detectorization • Additional database development
Level 4—Adaptive control • Intracycle control or control by signal phase • Imbeds features of central control and local intersection control	Level 2 + • 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 + • 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
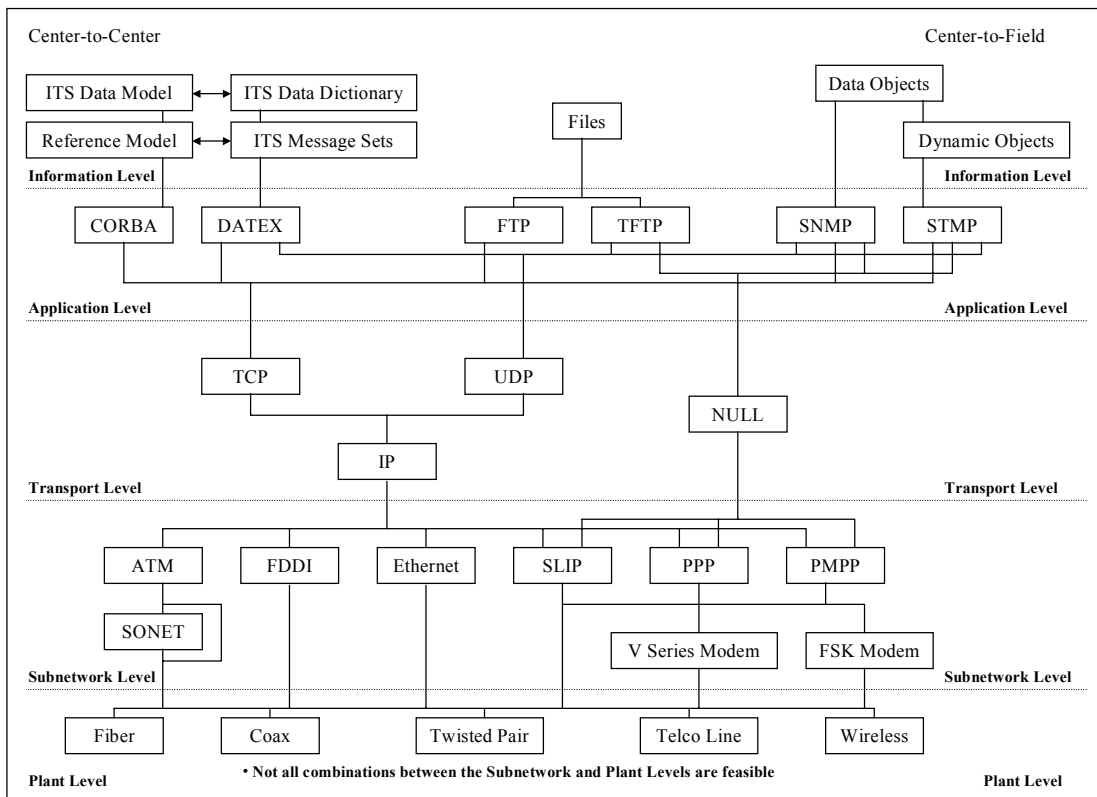

FIGURE 13 NTCIP standards framework (*The NTCIP Guide* 1999).

proprietary objects. The effect is to provide for a core set of functions to provide interchangeability and inter-operability, 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.
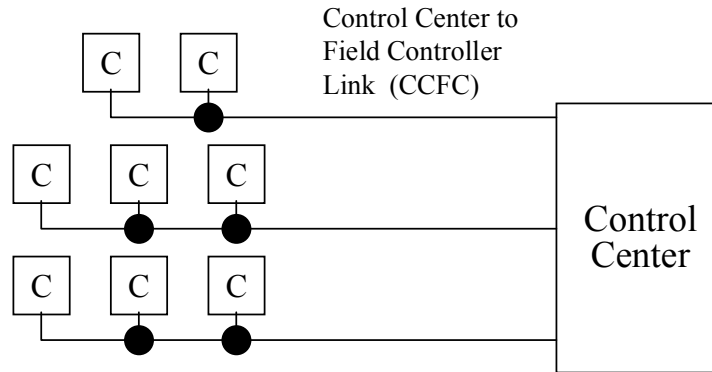
The FHWA report *Communications for Intelligent Transportation Systems, Successful Practices, A Cross-Cutting Study* (2000), describes the alternatives for selecting organizations to perform the communications system design. It also describes the relationships between communications design and the National ITS Architecture, particularly with regard to requirements for interoperability among agencies.

lthough 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).
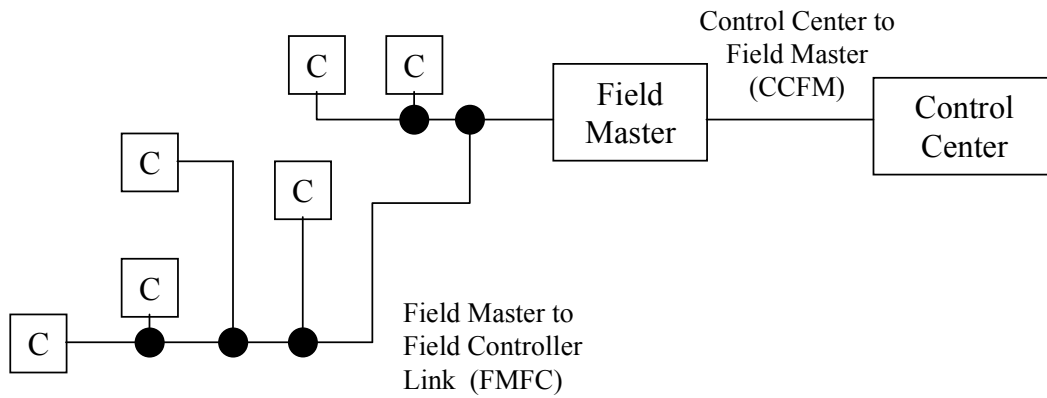
In larger traffic signal systems and in signal systems that share communications networks with other functions it may be difficult to perform a communications traffic loading model analytically. Commercial simulation packages may be used to perform this function. OPNET is an example of a simulation that 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.
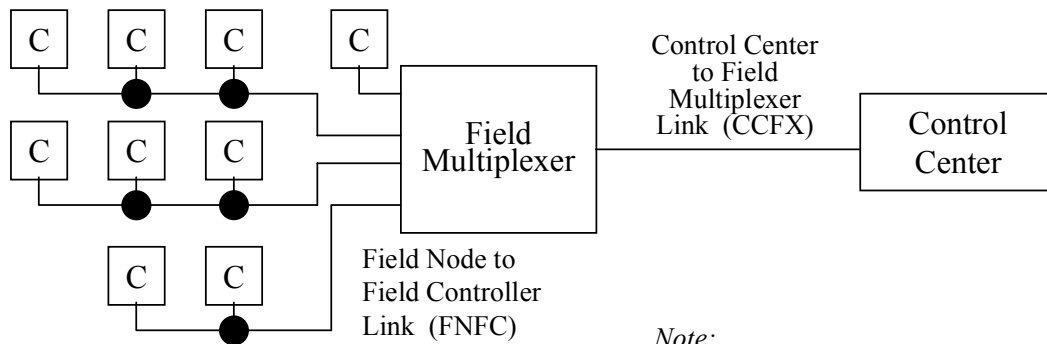
A. CENTRAL ARCHITECTURE

Control Center to
Field Controller
Link (CCFC)

C   C

C   C   C

C   C   C

Control
Center

B. DISTRIBUTED ARCHITECTURE

Control Center to
Field Master
(CCFM)

C   C

C

C

C

C

Field
Master

Control
Center

Field Master to
Field Controller
Link (FMFC)

C. COMMUNICATIONS TRUNKING ARCHITECTURE

C   C   C   C

C   C   C

C   C

Field
Multiplexer

Control Center
to Field
Multiplexer
Link (CCFX)

Control
Center

Field Node to
Field Controller
Link (FNFC)

Note:

All links that interface with field
controllers may be multiplexed

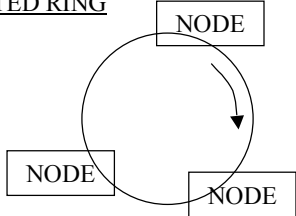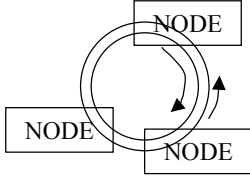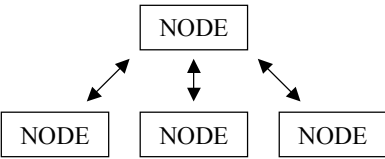FIGURE 14 Representative physical architectures (Gordon et al. 1993).

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

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 COMMERCIALLY AVAILABLE SENSOR TECHNOLOGIES

Technology	Strengths	Weaknesses
Inductive loop	• 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	• 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)	• Less susceptible than loops to stresses of traffic • Some models transmit data over wireless radio frequency link	• 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)	• 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	• Installation requires pavement cut or tunneling under roadway • Cannot detect stopped vehicles unless special sensor layouts and signal processing software are used
Microwave radar	• Typically insensitive to inclement weather at the relatively short ranges encountered in traffic management applications • Direct measurement of speed • Multiple-lane operation available	• Continuous wave Doppler sensors cannot detect stopped vehicles
Active infrared	• Transmits multiple beams for accurate measurement of vehicle position, speed, and class • Multiple-lane operation available	• Operation may be affected by fog when visibility is less than ≈20 ft or blowing snow is present
Passive infrared	• Multizone passive sensors measure speed	• 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	• Multiple-lane operation available • Capable of overheight vehicle detection • Large Japanese experience base	• 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	• Passive detection • Insensitive to precipitation • Multiple-lane operation available	• 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	• 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	• 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 COMMERCIALLY AVAILABLE SENSORS

| Technology | Output Data | | | | | Multiple-Lane, Multiple-Detection Zone Data | Communication Bandwidth | Sensor Purchase Cost[a] (each in 1999 U.S. $) |
	Count	Presence	Speed	Occu-pancy	Classifi-cation			
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)

[a]Installation, maintenance, and repair costs must also be included to arrive at the true cost of a sensor solution as discussed in the text.
[b]Speed can be measured by using two sensors a known distance apart or estimated from one sensor and the effective detection zone and vehicle lengths.
[c]With specialized electronics unit containing embedded firmware that classifies vehicles.
[d]Includes underground sensor and local detector or receiver electronics. Electronics options are available to receive multiple-sensor, multiple-lane data.
[e]With special sensor layouts and signal processing software.
[f]With microwave radar sensors that transmit the proper waveform and have appropriate signal processing.
[g]With multidetection zone passive or active mode infrared sensors.
[h]Models with appropriate beam forming and signal processing.
[i]Depends 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	• Cost for on-board equipment • Higher cost for intersection-based equipment	• 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:
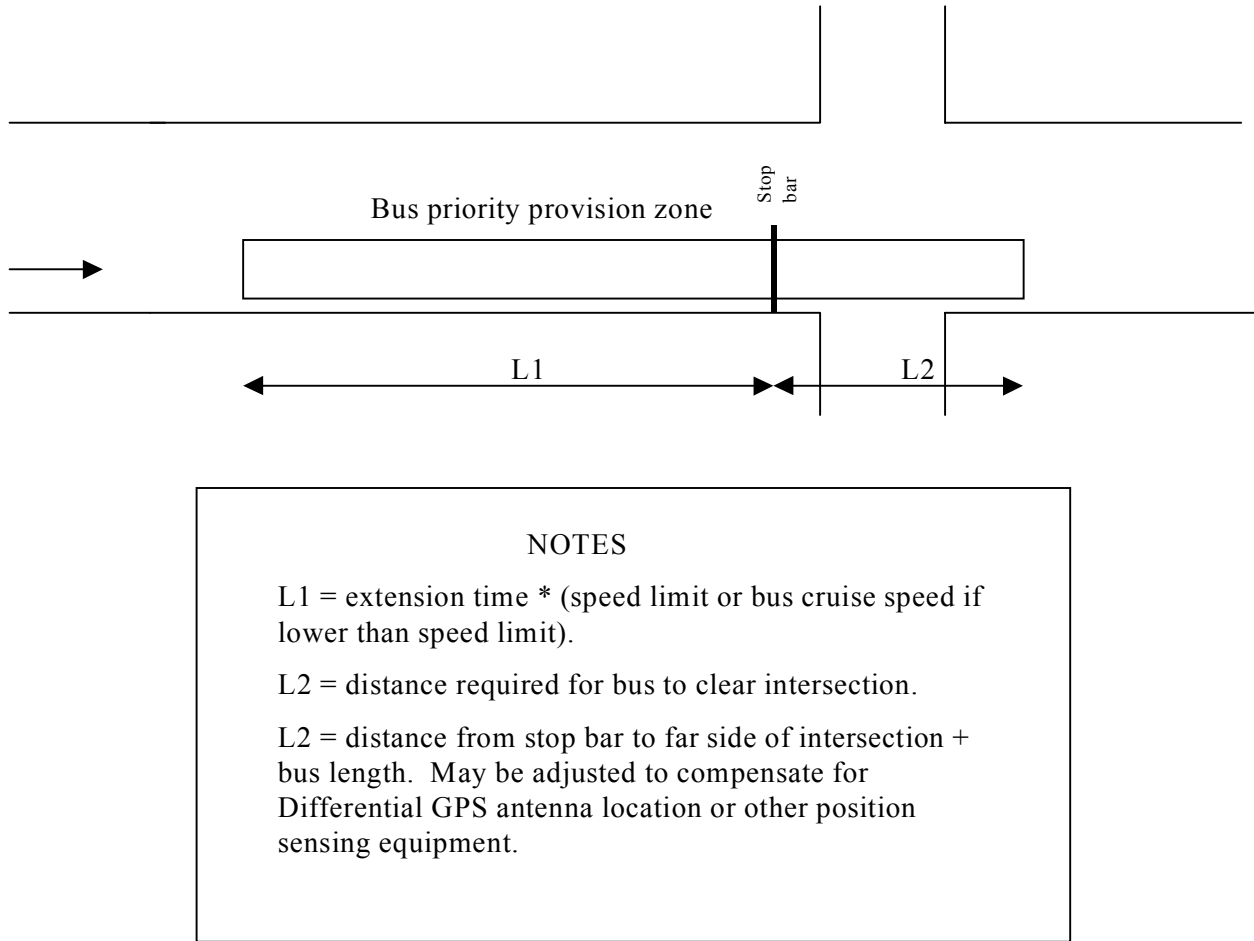
FIGURE 16 Bus priority provision zone.

– 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 nonproprietery 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				Curbside—A
and interface equipment	C	B	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.

Performance Ability
• Traffic operations requirements • Equipment reliability and adaptability • Ease of implementation • Ease of hardware and software maintenance • Parts availability

Personnel and Budget Implications

System Costs With Emphasis on Life Cycle Costs

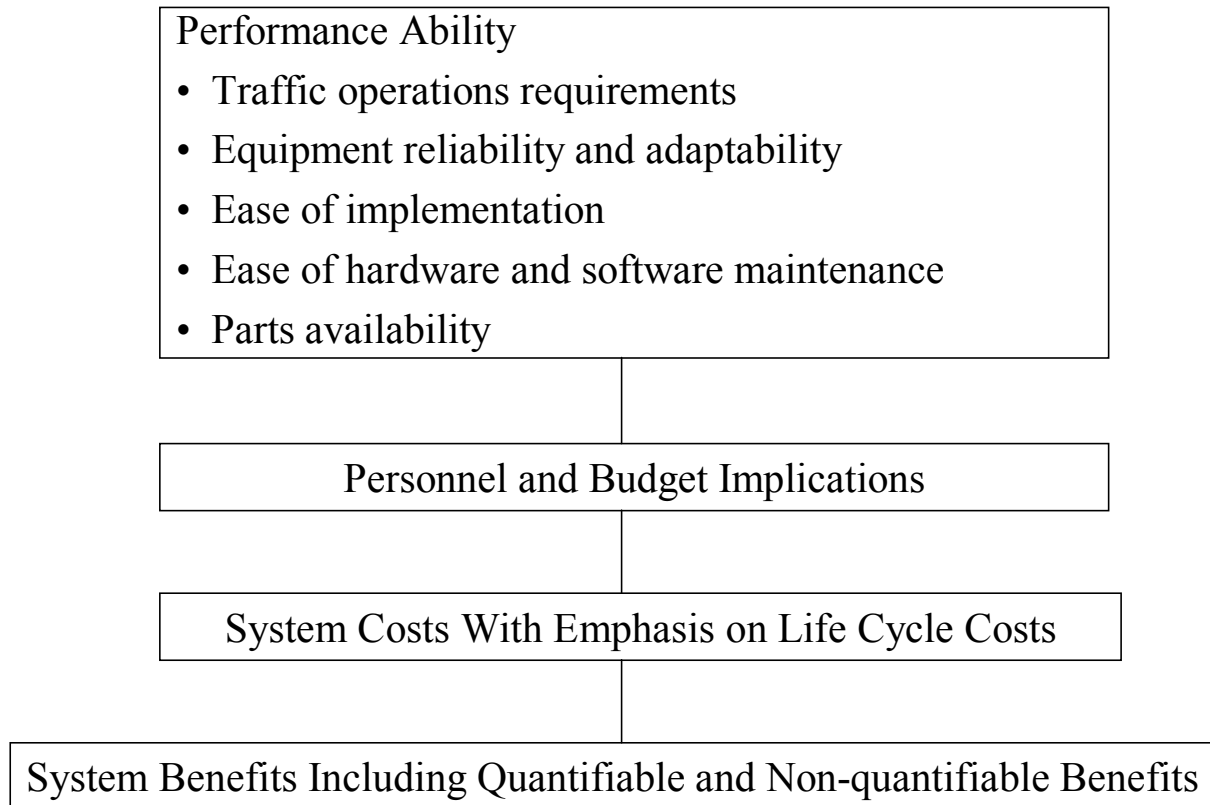| System Benefits Including Quantifiable and Non-quantifiable Benefits |
| --- |

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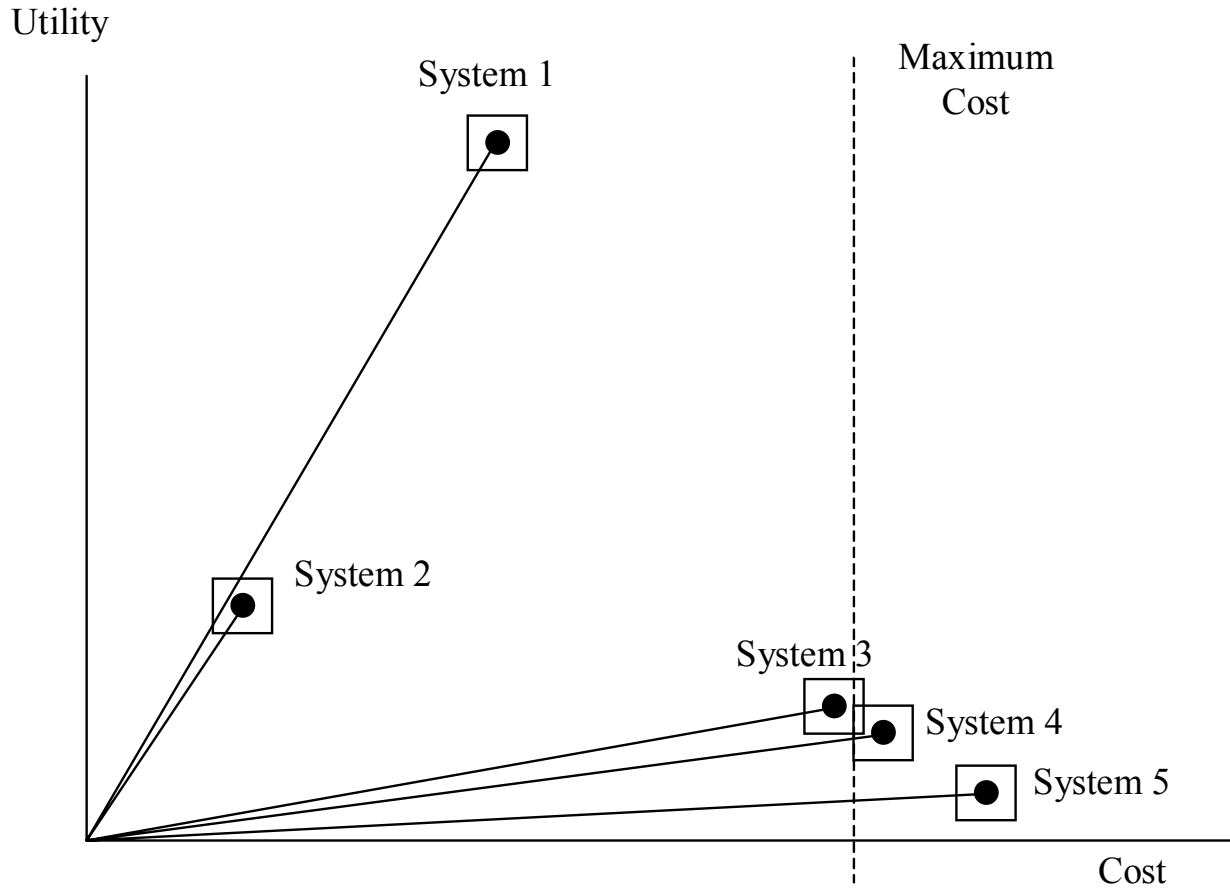
FIGURE 18 Utility–cost comparison of alternative systems (Gordon et al. 1996).

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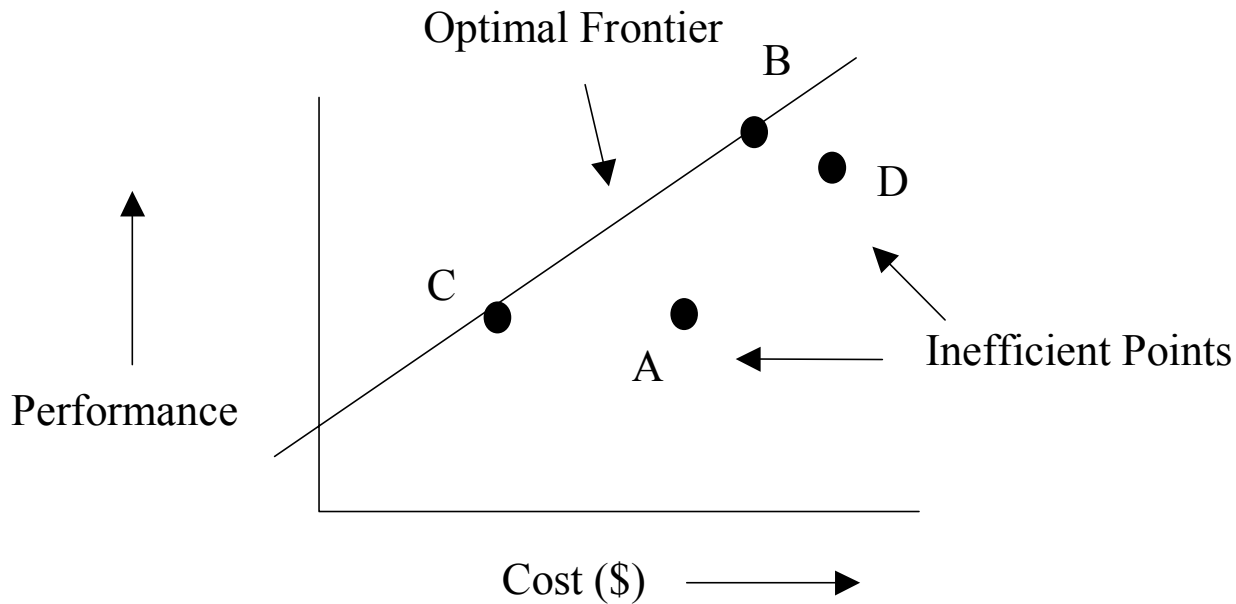
FIGURE 19 Optimal frontier (Clark et al. 2000).

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*):

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

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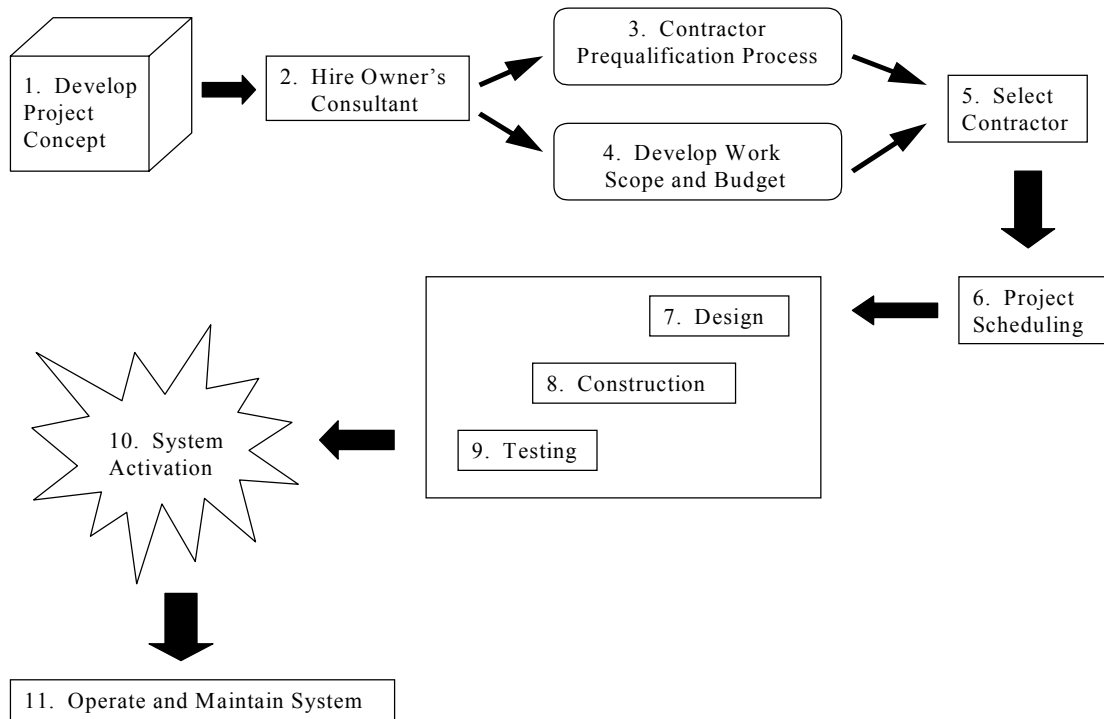
FIGURE 20 Model design/build process (Cronin 1996). (Used by permission of the Institute of Transportation Engineers).

• 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

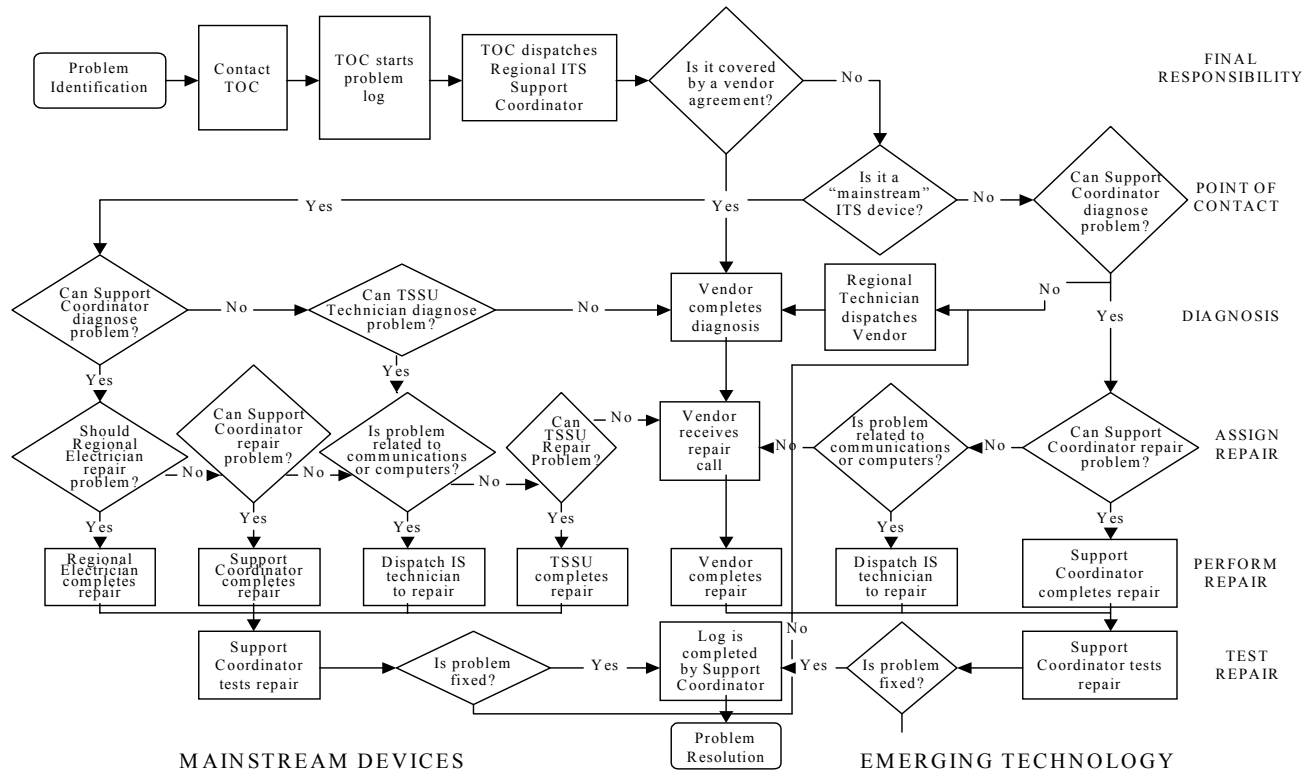(*Source*: Florida DOT, *Operations, Management . . .* 1999).

FIGURE 21 Two-tier maintenance model (Strong 2000).

Transportation Projects." In some cases the member universities offer the Fundamentals of ITS and Traffic Management course in whole or as part of an existing course. Additional information, including a listing of CITE member organizations is available on the CITE website (www.citeconsortium.org). Adler et al. (2000) discusses the current status of ITS professional level training theories and methodologies; an extensive set of references is provided. In addition, the National Highway Institute offers the course, "An Overview of Systems Engineering."

Technician Level Training Preparation for technician positions is typically accomplished through an associate degree in an appropriate engineering technology. Certification is provided through the following organizations:

- National Institute for Certification in Engineering Technologies (NICET) (www.nicet.org). NICET provides four levels of certification in traffic operations.
- International Municipal Signal Association (IMSA) (www.imsasafety.org). IMSA provides certification in the traffic signal area at three levels. It also provides certification in a number of related areas. Study guides are available.

PROJECT EVALUATION

Processes and Methodologies for Traffic Signal Systems Engineering

Requirements E1 and E2—Evaluation of the Project's Functionality

Evaluation is an ongoing process that occurs at all stages of system development and continues for the entire life of the system. Through the evaluation process the system designers and operators are able to determine how well individual projects meet the previously established system objectives. The evaluation process also allows system managers to identify possible enhancements to the system. These enhancements can include correcting operational or design problems, expanding the system either functionally or geographically, or incorporating additional systems into a regional architecture (Carvell et al. 1997). The evaluation process features three key components:

- Development of an evaluation plan,
- Selection of measures of effectiveness (MOEs), and
- Selection of evaluation methodologies.

Development of an Evaluation Plan Many agencies treat only the last two steps (measures of effectiveness and

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│              Transportation Management             │
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│                 The Tools of ATMS                  │
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│       Incident Management and Emergency Management │
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│                 Corridor Management                │
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│      Dynamic Route Guidance and In-vehicle Systems │
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│           Traffic Signal Systems Fundamentals      │
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│ Applied Systems Engineering for Advanced Transportation Projects │
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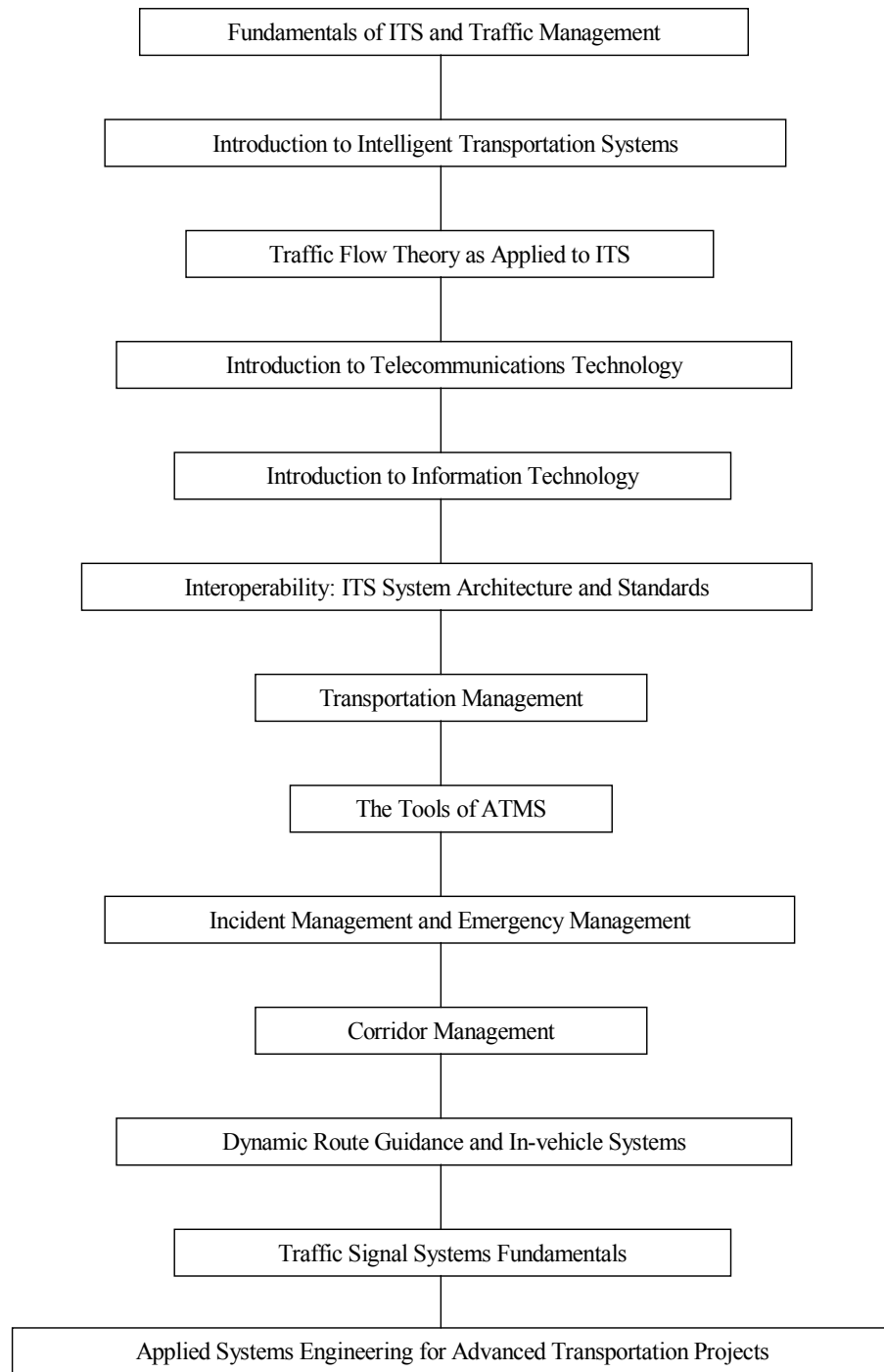
FIGURE 22 CITE on-line courses available as of November 2000 (CITE Consortium n.d.).

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 Direnzo 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 Direnzo (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).

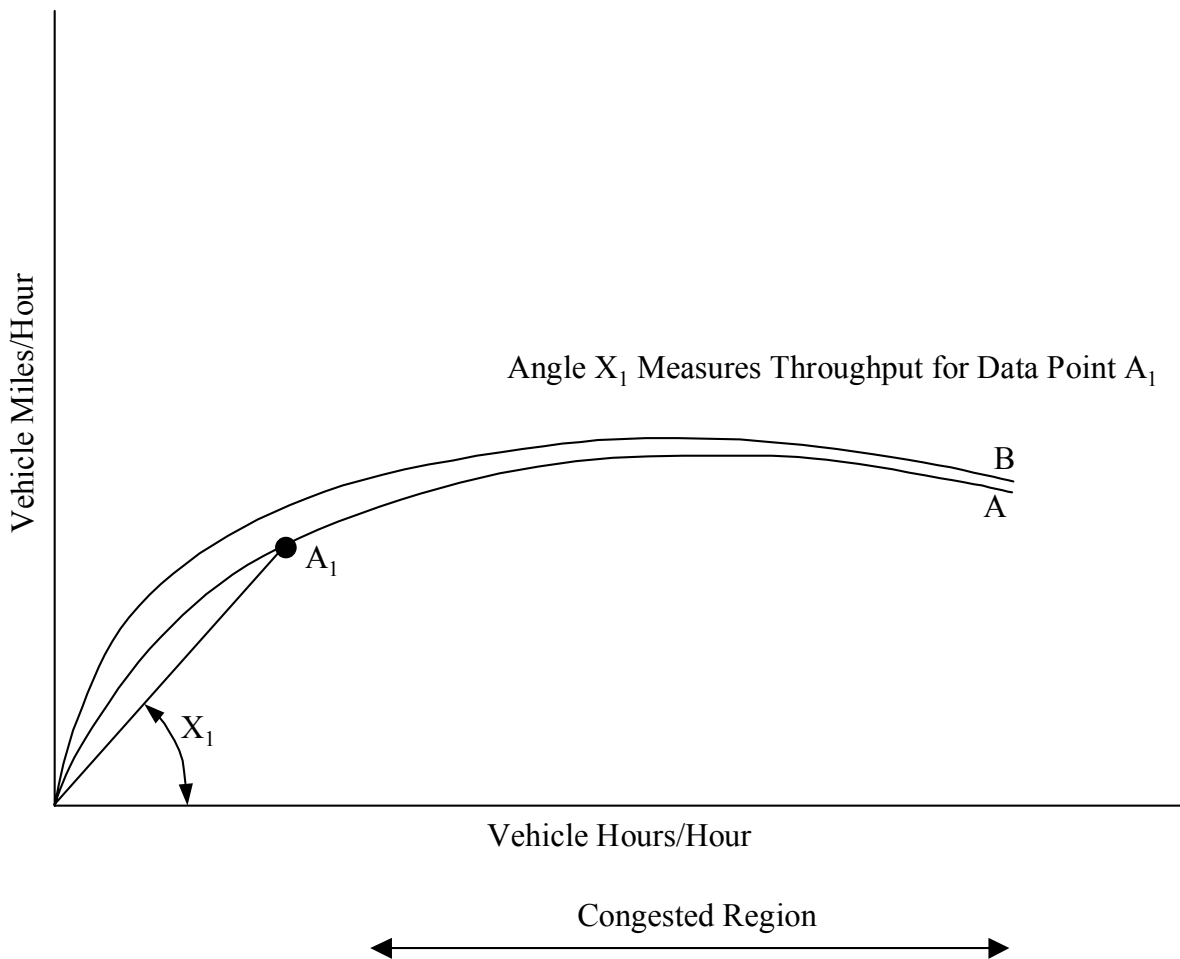Angle X_1 Measures Throughput for Data Point A_1

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).