CHAPTER TWO

SYSTEMS ENGINEERING

PURPOSE

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

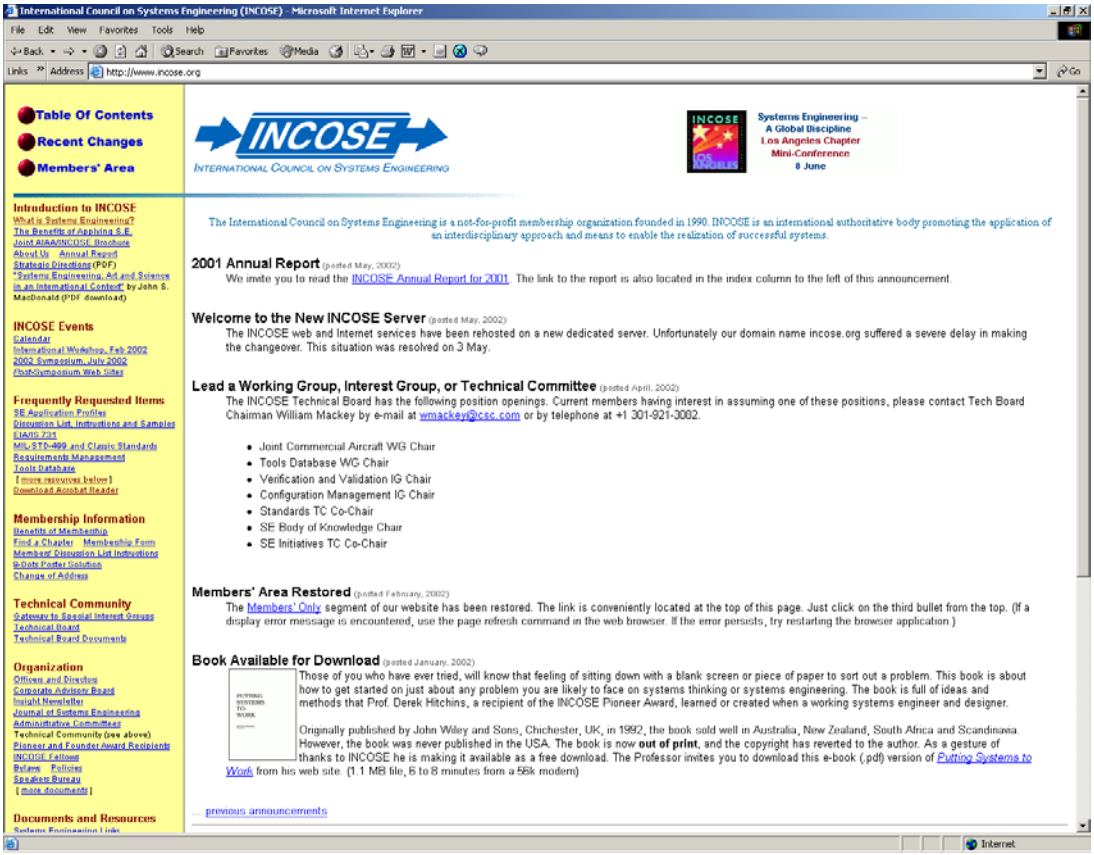
The following four methodologies that are commonly used in diverse systems engineering applications are reviewed:

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

DEFINITION

With the advent of large military and space systems in the 1960s engineers began to think of systems engineering in terms of the amalgamation of a number of engineering disciplines together with economics, human factors, goal setting, and evaluation techniques. A great deal had been written on the subject by the 1980s. Systems engineering has been described in many ways. Two definitions are provided here.

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



The International Council on Systems Engineering is a not-for-profit membership organization founded in 1990. INCOSE is an international authoritative body promoting the application of an interdisciplinary approach and means to enable the realization of successful systems.

2001 Annual Report (posted May, 2002)

We invite you to read the INCOSE Annual Report for 2001. The link to the report is also located in the index column to the left of this announcement.

Welcome to the New INCOSE Server (posted May, 2002)

The INCOSE web and Internet services have been rehosted on a new dedicated server. Unfortunately our domain name incose.org suffered a severe delay in making the changeover. This situation was resolved on 3 May.

Lead a Working Group, Interest Group, or Technical Committee (posted April, 2002)

The INCOSE Technical Board has the following position openings. Current members having interest in assuming one of these positions, please contact Tech Board Chairman William Mackey by e-mail at wmackey@csc.com or by telephone at +1 301-921-3082.

- Joint Commercial Aircraft WG Chair
- Tools Database WG Chair
- Verification and Validation IG Chair
- Configuration Management IG Chair
- Standards TC Co-Chair
- SE Body of Knowledge Chair
- SE Initiatives TC Co-Chair

Members' Area Restored (posted February, 2002)

The Members' Only segment of our website has been restored. The link is conveniently located at the top of this page. Just click on the third bullet from the top. (If a display error message is encountered, use the page refresh command in the web browser. If the error persists, try restarting the browser application.)

Book Available for Download (posted January, 2002)

Those of you who have ever tried, will know that feeling of sitting down with a blank screen or piece of paper to sort out a problem. This book is about how to get started on just about any problem you are likely to face on systems thinking or systems engineering. The book is full of ideas and methods that Prof. Derek Hitchins, a recipient of the INCOSE Pioneer Award, learned or created when a working systems engineer and designer.

Originally published by John Wiley and Sons, Chichester, UK, in 1992, the book sold well in Australia, New Zealand, South Africa and Scandinavia. However, the book was never published in the USA. The book is now **out of print**, and the copyright has reverted to the author. As a gesture of thanks to INCOSE he is making it available as a free download. The Professor invites you to download this e-book (.pdf) version of *Putting Systems to Work* from his web site. (1.1 MB file, 6 to 8 minutes from a 56k modem)

... previous announcements

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

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

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

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

RESOURCES

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

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

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

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

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

PROCESSES

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

Three examples of general process descriptions are provided here.

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

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

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

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

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

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

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

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

COMMONLY USED METHODOLOGIES

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

System Development Life Cycle

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

Structured Analysis

Structured analysis is a methodology that defines processes and data flows in a hierarchical sense. It is a commonly used alternative to flow chart methodology. Figure 4 illustrates the data flow diagrams for two analysis levels. The circles identify the processes (through process specifications) and the lines identify the data flows. Appendix C provides an example of the use of structured analysis for an application other than traffic control.

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

Quality Functional Deployment

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

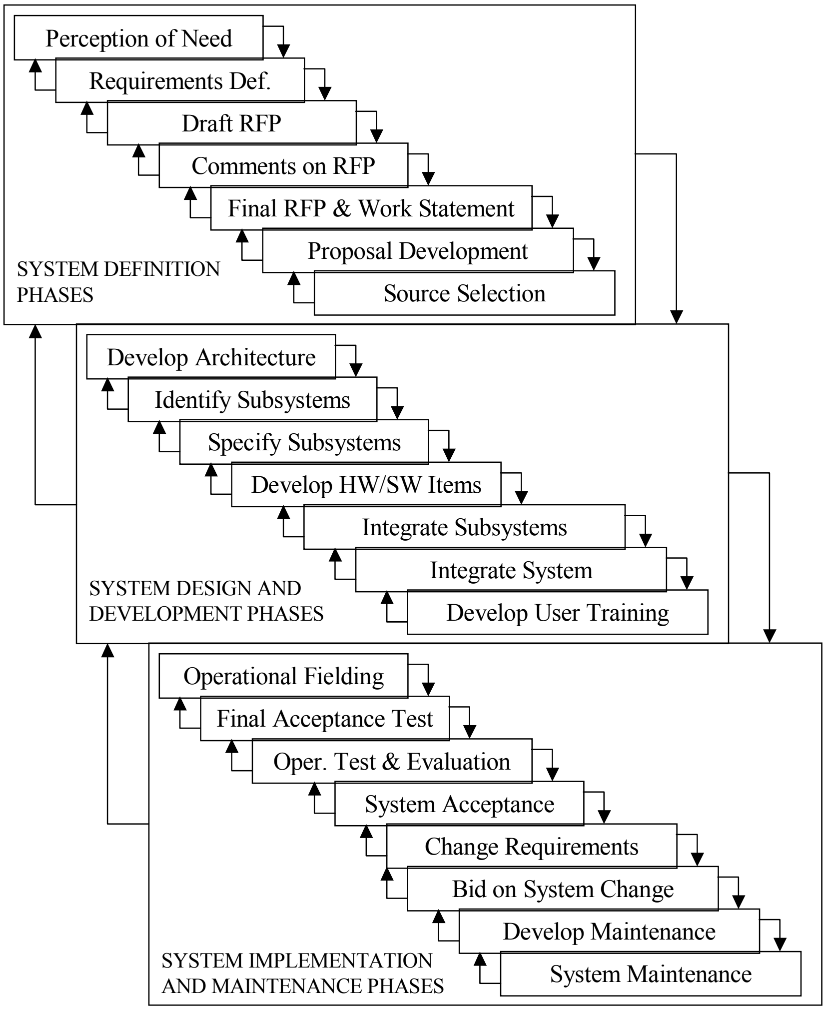


FIGURE 3 A 22-phase systems engineering life cycle (Sage 1992). (Reprinted by permission of John Wiley & Sons, Inc.)

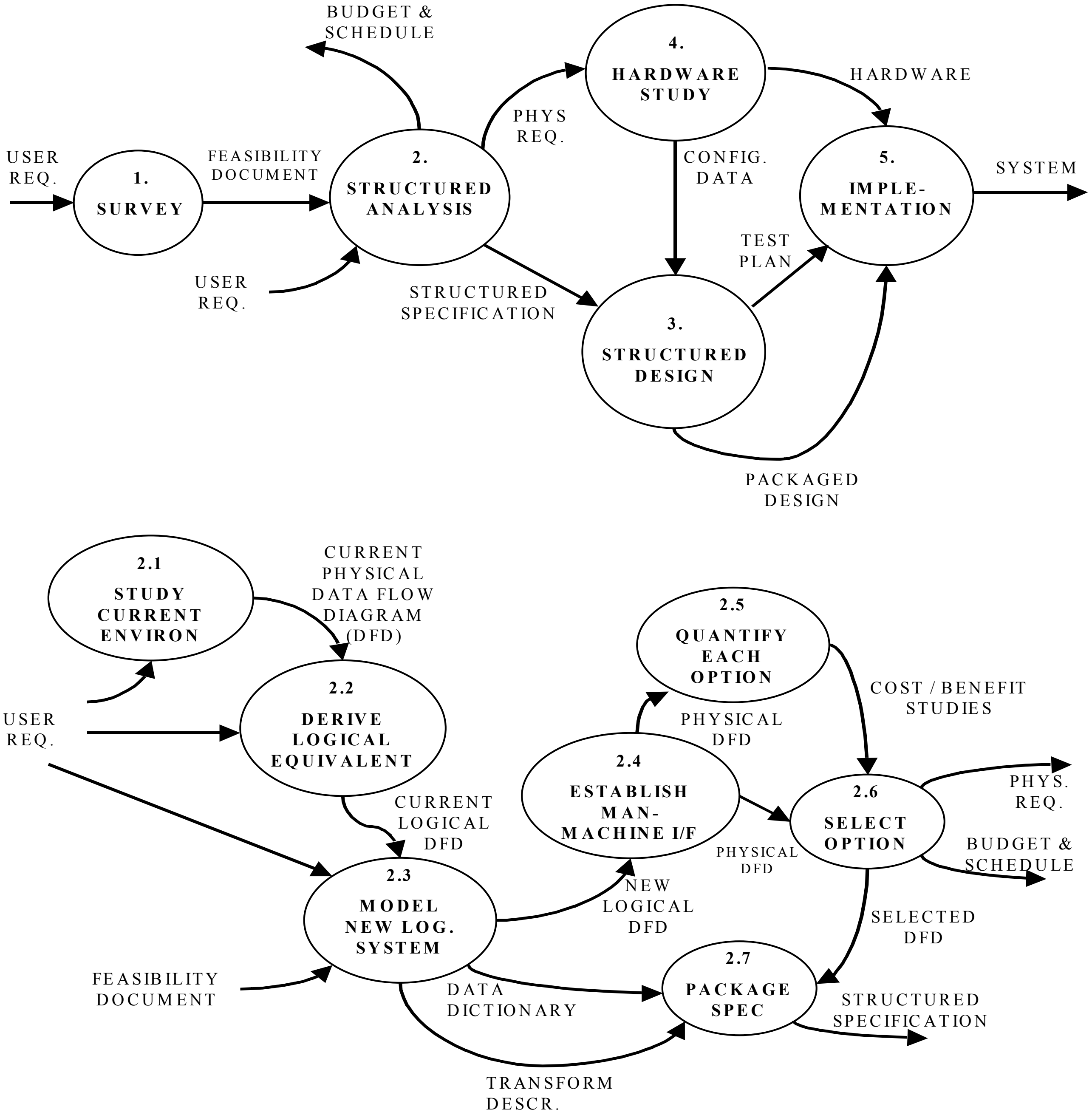


FIGURE 4 Presentation of two levels of structured analysis (DeMarco 1979). (Reprinted with permission of Pearson Education, Inc., Upper Saddle River, N.J.).

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

Industry-Specific Methodologies

Industries and sectors within industries (e.g., suppliers versus users) have developed specific methodologies to satisfy the systems engineering functions unique to the industry. Although these methodologies apply to the disciplines identified previously as well as to others, they are usually quite specific to the industry and are not often easily shared with other industries not closely related.

RELATIONSHIP TO TRAFFIC SIGNAL SYSTEMS

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

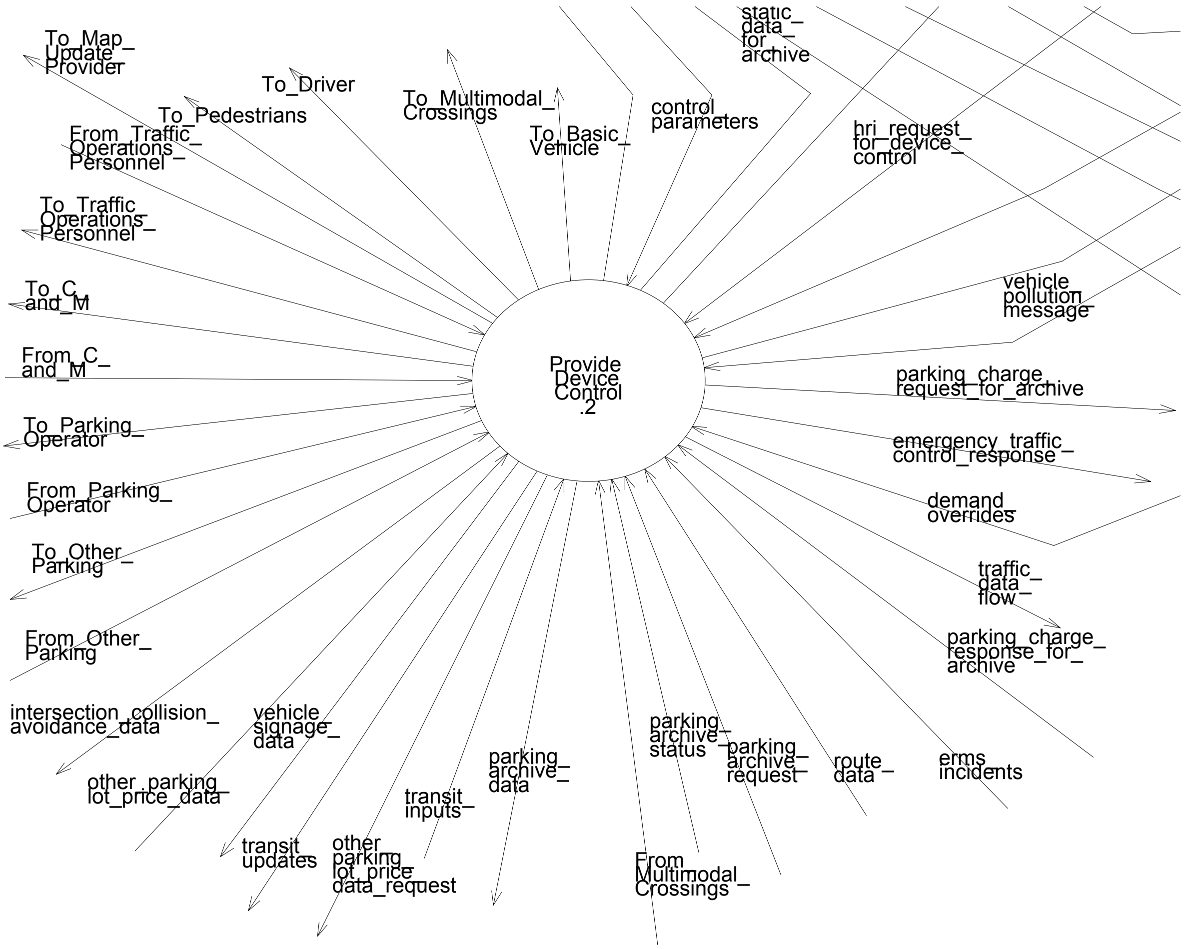


FIGURE 5 Portion of National ITS Architecture data flow diagram (*The National ITS Architecture* 1999).

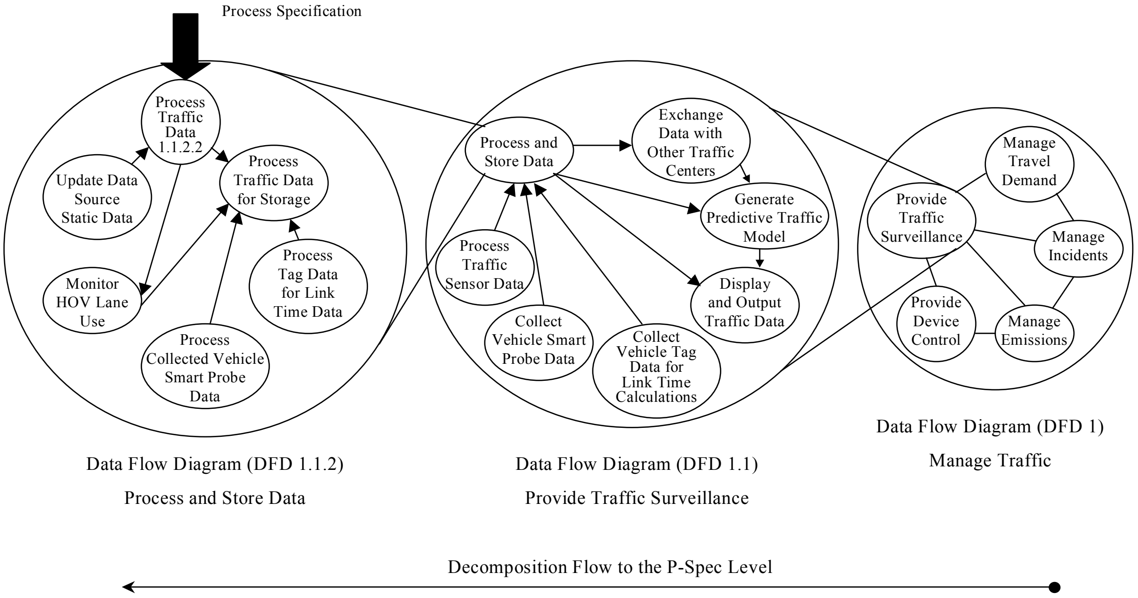


FIGURE 6 Example of logical architecture functional segmentation (*Developing Traffic Signal Control Systems . . .* 1998).

TABLE 1
EXAMPLE PROCESS SPECIFICATIONS (Overview Descriptions)

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

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

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

- Applications that are new or unique and that require development of new hardware and software technology. These applications may require the use of additional systems engineering techniques, such as charts and matrices, which couple physical principles to requirements. These systems often use new software techniques and algorithms. Military and space-related projects often fall into this category.
- Applications where the technology has basically been refined to practice and is commonly available. In this case, the systems engineering decisions center on the selection of appropriate technologies and procedures from the available set. Nonresearch-oriented traffic signal systems generally fall into this category.

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

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

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

Process	Application to Bridge Study
Situation definition	• Inventory transportation facilities • Measure travel patterns • Review prior studies
Problem definition	• Define objectives – Reduce travel time • Establish criteria – Average delay time • Define constraints • Establish design standards
Search for solutions	• Consider options – Locations and types – Tunnel or don't build – Toll charges
Analysis of performance	• For each option determine – Cost – Traffic flow – Impacts
Evaluation of alternatives	• For bridge project determine – Benefits vs. cost – Profitability – Cost-effectiveness
Choice of project	• Consider factors involved – Revenue cost forecast – Site location – Political judgment
Specification and construction	• Design of bridge – Superstructure – Piers, foundation • Construction plans – Contractor selection • Transfer of completed bridge to authority operation and maintenance

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

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

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