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Development of System and Application Architectures for Geographic Information Systems in Transportation

This NCHRP digest describes the findings of the second phase of NCHRP Project 20-27(2), Systems and Applications Architecture for GIS-T, conducted by Alan Vonderohe, Teresa Adams, Chih-Lin Chou, Myron Bacon, Forest Sun, and Robert L. Smith, Jr., Department of Civil and Environmental Engineering, The University of Wisconsin-Madison. The digest was prepared by Kenneth S. Opiela, Ph.D., P.E., NCHRP SeniorProgram Officer, from the contractor's final report.

INTRODUCTION

This digest describes generic, spatially oriented models of DOT data and activities developed under NCHRP 20-27(2), *Development of System and Application Architectures for Geographic Information Systems in Transportation*. The need for development of enterprise information architectures to facilitate integrated transportation information systems was addressed using information engineering methods. The generic models can serve as templates for transportation agencies embarking upon information strategy planning to reduce high initial costs. DOT decision makers, information managers, and consultants working for transportation agencies should find the generic models useful and the explanation of Utah DOT's experience informative.

Analysis of the interactions between data and activities in the generic models revealed a series of generic business systems, each encompassing a closely coupled group of activities and data. Some of the business systems, especially those that support policy development and location referencing, were determined to be foundational in nature. That is, all other business systems depend upon data created, collected, or managed by the foundational systems. All business systems involved with infrastructure management are highly spatial in nature, as are many of those involved with agency management. This suggests that GIS has high priority among the appropriate technologies for information system implementation.

The experience of the Utah DOT in using a template-based approach to information strategy planning is described in some detail. Utah realized a savings of around 67% in comparison to the average cost of information strategy planning at other DOTs. The generic data and activity models produced by this research are at a higher level of detail than the template models that were available to UDOT. This means that more effort will need to be devoted to adding detail to these products to meet the specific circumstances of any one agency. However, the potential for significant savings remains.

The Need for a Better Way of Doing Business

Ironically, in the midst of the frenzy of the information age brought on by the Internet, Web pages, e-mail, television terminals, and

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other new technologies, the information systems community is in disarray and being downsized, outsourced, package-replaced, and decentralized (Zachman, 1997). Corporate management perceives databases built in the past 50 years as the "legacy" and current systems as hopelessly inadequate. On a scale of one to ten, chief executive officers (CEOs) rate the quality and timeliness of information they get at six and its appropriateness between three and four. In addition, CEOs declare that the greatest challenge facing the modern enterprise is "change." The requirements for quality, timeliness, and ability to manage change are forcing organizations to consider implementing enterprise information architectures.

Transportation agencies are no exception. In a typical transportation agency, numerous information systems have been developed over the years to support various activities of the agency. Usually, these existing systems cannot be linked electronically. Application-driven system development has resulted in isolated systems. Data are often unshareable, redundant, and fragmented. When new information is needed, it is often easier, quicker, and less expensive to develop a new system rather than modify an existing one. (For example, one agency determined that 60 different software packages, 17 different databases, and seven different hardware platforms are used to accomplish pre-construction engineering tasks [NCHRP, 1994]). System interfacing consists of hardcopy output from one system and manual key entry into the next.

Three changes in the working environments of transportation agencies are affecting the need for development of integrated transportation information systems (NCHRP, 1994). These changes are as follows:

- The interstate construction era has passed. Transportation agencies need to become experts at infrastructure management—maintaining and improving what exists. In doing so, planning decisions must minimize adverse environmental and economic impacts on surrounding communities.
- Transportation agencies now collaborate with external agencies (e.g., MPOs) in planning and decision making. As this continues, the need for consistent, accurate information will increase—regardless of which agency collects the data. The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) stimulated transportation agencies to plan and allocate resources according to network-level approaches rather than project-by-project or district-oriented approaches. The success of network-level optimization strategies depends on the availability of integrated network data and changes in how expenditures are prioritized.

Lack of integrated transportation information systems leads to the following three results (NCHRP, 1994):

- There are greater costs for gathering and analyzing information than if data were collected in a more consistent manner, managed on a more integrated basis, and used more widely within the organization. In the United States, 20 to 50 percent of all labor costs are dedicated to gathering, storing, retrieving, reconciling, and reporting the information used to run enterprises (Zachman, 1997).
- Many organizational units regard information as theirs. They collect it to meet their needs. In some cases, they are reluctant, because of tradition or technological limitations, to make information available to others in the agency. Without integrated transportation information systems, an organizational unit has two options for acquiring the data necessary to accomplish its mission: a unit can continuously request and then verify the accuracy and meaning of data maintained by another unit or the unit can expend the resources to collect and maintain its own data.
- More time is required to complete workflow processes. Transitions between applications interrupt what could be a smooth flow of data between interdependent processes.

Most transportation agencies have formal plans for managing technology, but few have plans for managing data. Technology investment plans focus on timing and the cost of enhancing existing hardware systems or of acquiring new ones. Technology investment plans are not enough. Application system development problems at transportation agencies usually derive from lack of a centralized plan that provides a systematic approach for guiding systems design. In addition, a lack of understanding of the lifecycle of business activities creates obstacles to implementation of systems and passing of information from management to planning, design, construction, maintenance, and operation activities.

Information strategy tools, methods, and the analytical process have been understood for decades and improved substantially since the late 1960s; however, agencies experience difficulties in getting from strategy to implementation. It is the architecture that bridges the gap between the strategy (and its associated expectations) and implementation. Agencies were trying to produce the enterprise's information systems, complex engineering products, to be relevant to a dynamic enterprise without having an architecture to follow or, in some cases, knowing what one was.

Without an architecture, enterprise systems are built according to a strategy that responds to isolated needs, piece by piece, program by program, and application by application. By the time they are finished, the pieces often do not fit together or are no longer relevant to the enterprise. Even if a system is produced that is relevant, its relevance cannot be maintained for long periods. The system tends to become obsolete quickly, and attempts to maintain its relevance are time-consuming and expensive. Staff are constantly busy building and maintaining it as organizational priorities change. Unable to have needs met by systems staff, many organizational units buy their own hardware, then move their applications from the centralized host computer or build their own applications. Data fragmentation, redundancy, and inconsistency worsen as application builders proliferate (Delaware, 1992; Missouri, 1993). Furthermore, maintenance costs and time increase exponentially with the addition of more systems. In 1967, 40 to 50 percent of the cost of a product was direct labor cost. Today, the direct labor cost ratio is as low as 15 percent (Zachman, 1997), partially because of the enormous cost of architectural discontinuities and redundancies.

Data management problems at transportation agencies are not new (Briggs and Chatfield, 1987). For years, transportation agencies have been developing systems that combine hardware, software, and data files to solve particular information problems. When the need emerged for management of pavement and bridges, pavement and bridge management systems were built with separate pavement and bridge files to store relevant data. The systems were isolated and the data files were unique to the system in which they were created. Over time, the systems and data files grew, causing integration and maintenance problems. The result is that data are fragmented, redundant, and incomplete. Users of the data within DOTs receive inaccurate, untimely information. Without centralized planning strategies, transportation agencies will continue to struggle to reorganize their structure and work procedures to achieve the strategic effects and increased productivity promises of automation.

Today's intense worldwide preoccupation with data warehousing is an attempt to find a way to compensate for the historical lack of enterprise data architectures (Zachman, 1997). Further, if enterprise architecture concerns are not included in a data warehouse implementation, the ultimate result will be increased frustration. Support will dissipate, as the enterprise perceives the warehouse as another redundant legacy file with a new name. The cost of a single, initial data warehouse implementation runs about $3 million with results often well below the goal of providing integrated views of the entire enterprise. The greatest effort in data warehousing projects lies in reverse engineering: digging through legacy and archived files element by element to discern their meaning. Subsequent warehouse efforts are focused on cleaning up error in the actual data. Cleansing, integration, and distribution are simply after-the-fact efforts to redeem a situation caused by lack of a data architecture in the first place.

The first phase of NCHRP 20-27 suggested that geographic information systems (GIS) can help facilitate data and systems integration by focusing on a generic aspect of most transportation data (i.e, location [Vonderohe et al., 1993]). One of the recommendations of that earlier work was that GIS be implemented in accordance with an overall strategic plan for information systems and technology. Failure to do so can lead to a new manifestation of the same problem: disparate, inconsistent, redundant, standalone spatial databases and GIS applications.

Enterprise Information Architecture

Definitions

An enterprise information architecture is "...a set of descriptive representations (models) that are relevant for describing an enterprise such that it (the enterprise) can be produced to management's requirements (quality) and maintained over the period of its useful life (change)" (Zachman, 1997). An enterprise information architecture can be conceptualized as including four distinct, but interrelated subarchitectures for (1) business activities, (2) data, (3) information technology, and (4) organizational structure (see Figure 1). This view arises from the notion of an information system consisting of a combination of technology, data, business procedures, and people applied to a business activity (FHWA, 1995).

Activity architecture refers to the work being done by the enterprise with an emphasis on how information is being used. The activity architecture characterizes all work as an interrelated collection of activities transforming input information into output information (FHWA, 1995).

Data architecture refers to the organization of all types of data used by an enterprise, where the emphasis is on what things are of interest. The data architecture includes an administrative component (i.e., management of the data models) and a management component (i.e., data collection, data access, data quality, and data security). The data architecture includes descriptions of the relationships among its elements (FHWA, 1995).

Technology architecture refers to hardware, software, systems, methods, and standards that the enterprise uses to develop and operate computer systems. It includes all computing and telecommunications equipment and software, all methods for developing and maintaining computer systems, and all enterprisewide technical standards. The emphasis of the technology architecture is on where the work is being done and where the data are (FHWA, 1995).

Organizational architecture refers to the people involved with an enterprise and to their organizational structure. The emphasis of the organizational architecture is on who is doing the work or who uses the information (FHWA, 1995).

The enterprise information architecture associates the four sub-architectures by characterizing relationships among their elements. Any given information system (e.g., pavement management system—PMS in Figure 1) will draw on some subset of the people, procedures, data, and information technology and their interrelationships. If the design of all information systems is based on this architectural concept, the information systems will be truly integrated. This full set of integrated information systems will be the most efficient combination of all people, procedures, data, and information technology that meets the total information needs of the enterprise.

Benefits of an Enterprise Information Architecture

Aside from the resolution of integration problems, other potential benefits of an enterprise information architecture are as follows:

- Development and implementation of integrated transportation information systems can lead to and facilitate re-engineering of a transportation agency's organizational structure and workflow.
- Use of rigorous methods for development of the architecture can facilitate implementation of a total quality management (TQM) program. Specifically, checks can be made for whether the data being collected satisfy all integrated uses and whether the data satisfy the assumptions associated with the analytical operations performed on the data.
- The enterprise information architecture can facilitate implementation of changes to business rules and strategies. Today, virtually all business strategies, rules, conditions, and triggers are expressed either in semantic (data) structure or procedural code. It is far easier to address changes if existing data and activity models are well defined and managed.
- The complexity and cost of installing, maintaining, operating, and changing networks are enormous, making architectural issues all the more important.

Enterprise architecture initiatives prove that doing it right is faster and cheaper. Every decision has either short-term or long-term implications. An initial investment in an enterprise architecture provides many large-scale, direct and indirect benefits over time.

Agency investment decisions are fueled by budget cycles. To experience the luxury of satisfying immediate need without an enormous sacrifice in downstream capabilities, state agencies must invest in an architecture infrastructure. Initial investments, although considerable, will deliver implementations faster and cheaper to satisfy current demand and will reduce the enormous costs and frustrations associated with systems resulting from the traditional application development process.

Rigorous Method for Development of the Architecture

Integrated information systems can be developed using a formal methodology called "information engineering (IE)" which is defined as "...the application of an interlocking set of formal techniques for the planning, analysis, design, and construction of information systems, applied on an enterprisewide basis or across a major sector of an enterprise" (Martin, 1989).

Martin defined the four stages of IE as follows:

1. Information Strategy Planning—where the goal is to describe the enterprise, its business activities, and its overall information requirements at a high conceptual level;
2. Business Area Analysis—where a more detailed study is performed on particular segments of the enterprise (business area analysis focuses on what the business area must do to accomplish its mission);
3. Design—where business systems that support a particular design area are described in detail; and
4. Construction—where all executable components of an information system are created (the goal is to create application systems that support an area defined during the design stage).

A high-level enterprise information architecture is developed during the first stage and described in a document referred to as an "information strategy plan" (ISP). This abstract view of the enterprise is then decomposed into increasingly finer levels of detail during subsequent stages until it is possible to generate program code from procedures and create database tables from low-level descriptions of data requirements.

Information Strategy Planning

Information strategy planning results in the following three models:

1. An activity model, usually expressed as a hierarchy of functions and processes. Functions are high-level, ongoing activities (e.g., "transportation planning") made up of lower level functions and processes. Processes are low-level activities that are executable (e.g., "draw cross-section")—they start and stop. Processes have data inputs and data outputs, referred to as "data dependencies." Figure 2 shows part of the activity hierarchy from the Missouri Highway and Transportation Department's ISP.
2. A data model, usually expressed as an entity relationship diagram (ERD). An ERD contains the following:

- Subject areas, which are major, high-level classifications of data that pertain directly to a major topic of interest. Subject areas are groups of entity types (TI, 1993).
- Entity types, which are fundamental things of relevance to the business about which facts can be kept. Each entity type is defined in terms of its attributes and relationships (TI, 1993).
- Relationships, which are named associations between entity types that embody information relevant to the organization (Martin, 1990). A relationship has (1) optionality, indicating whether it is required or optional, and (2) cardinality, indicating the number of instances of one entity type that can be associated with one instance of the other entity type in a relationship pair. Optionality and cardinality are critical in database design.

Figure 3 shows part of the entity relationship diagram from the ISP of the Missouri Highway and Transportation Department (HTD).
3. An interaction model, which characterizes the operations that activities perform on data. The interaction model is usually expressed as a matrix whose rows represent activities in the hierarchy and columns represent entity types in the ERD. The cells of the matrix contain values that indicate the operations. Valid operations are create (c), read (r), update (u), delete (d), and none (blank). For this reason, the interaction matrix is sometimes referred to as the "CRUD" matrix. Figure 4 shows part of the CRUD matrix from Missouri HTD's ISP.

The activity, data, and interaction models together are sometimes referred to as a "business model."

Information strategy planning includes analysis of the interaction model to identify business areas (collections of related activities and data) and potential business systems within the business areas. Business systems are more closely coupled logical groupings of activities and data that form the activity and data components of an information system. Business areas and business systems are identified by analysis of affinities among activities through their operations on data and analysis of affinities among entity types through the activities that operate on them. Through analysis of the activities and data that they contain, each business area and business system can be defined and characterized. Moreover, the relationships between business systems can also be inferred from the interaction model, once the business areas and systems have been identified. The reordered CRUD matrix will indicate which business systems create or manage data that other systems require. The characterization of business systems and identification of relationships between them reveals a "business systems architecture." The business systems architecture represents the integrated activity and data components of the overall enterprise information architecture.

The technical component of an ISP is integrated with the enterprise's business strategies to develop priorities for business area analysis and other subsequent stages of information engineering (see Figure 5).

Information strategy planning, and the subsequent stages of information engineering, must be supported by computer-aided systems engineering (CASE) software. CASE tools are necessary for guiding the methodology and for managing the models. The CASE tool used in this research was Texas Instrument's Information Engineering Facility (IEF).

Need for a Generic Architecture Template

Some transportation agencies have recognized the need for and benefits of formal information strategy planning. By 1994, at least seven state (i.e., Delaware, Florida, Kansas, Michigan, Missouri, New York, and Wisconsin) and one provincial (i.e., New Brunswick) DOTs had developed ISPs that included models of data and activities. By 1996, at least three more had undertaken or completed either information engineering or business process re-engineering projects (i.e., Minnesota, Texas, and Utah).

These enterprisewide efforts to perform the tasks in Figure 5 require considerable investment of time and money. A typical activity model at the ISP level might include 150 activities, while a typical data model might include 100 entity types and numerous relationships. Development of an ISP, for an agency of moderate size, might include interviews with 200 to 300 people, up to 10,000 person-hours of staff time on the part of a core project team, and consultant fees of $300,000 or more.

The need to commit such resources can cause agencies to postpone information strategy planning, limit the effort to priority areas resulting in something less than enterprisewide models, or forego development of formal ISPs altogether. If effective means can be found to reduce the level of necessary initial investment, thus facilitating development of enterprise information architectures, many more transportation agencies should be able to realize both short- and long-term benefits.

Research Objectives and Approach

The notion that state transportation agencies all have very similar missions, authorities, and responsibilities suggests that they should have similar business requirements and that they might carry out similar business activities and have similar data needs. If these similarities can be identified, using comprehensive, rigorous methods, it should be possible to develop generic data and activity architectures that could serve as templates for ISP development and provide potentially significant savings in time and money.

The primary objective, then, of this research was development of generic data and activity models leading to a systems and applications architecture which will provide a basis for innovative applications critical to the missions of state DOTs. Given the national-level effort of the GIS-T Pooled Fund Study (ATR, 1995) to develop a formal systems architecture for integrated transportation planning, the research team worked to ensure the compatibility of this material with the results of that work.

The first phase of NCHRP 20-27 provided a suggested model for information technology based on a server-net architecture (Vonderohe et al, 1993). An additional objective of the current research was to map the derived generic business systems onto the suggested server-net. In this way, the overall effort was intended to provide a top-level view of the common technology, data, and activities needed to support innovative applications. These, then, are three of the four sub-architectures constituting an enterprise information architecture and identified as necessary for development of integrated transportation information systems (FHWA, 1995).

The generic data and activity models were derived by synthesis of existing models developed by eight DOTs (i.e., Delaware, Florida, Kansas, Michigan, Missouri, New Brunswick, New York, and Wisconsin). All but one of these DOTs (i.e., Wisconsin) had developed enterprise models encompassing both infrastructure management and agency management. The scope of Wisconsin DOT's ISP was design and construction.

Synthesis of the DOTs' models required development of a methodology, similar to that of Elmasri et al (1987) as implemented by Nyerges (1989), but at a much higher level of abstraction. The methodology included a means for integration with the GIS-T Pooled Fund Study architecture to ensure compatibility and for adaptation of components of an additional architecture (Utah DOT) that was being developed concurrently with the research.

The initial result of synthesis was an incomplete collection of generic model components that often had non-exclusive definitions. The components had no relationships or sequences among themselves, resulting in a lack of structure, coherence, and underlying meaning. To overcome this problem, a deeper semantic, related to that of the GIS-T Pooled Fund Study (ATR, 1994), was formed to guide the modeling process.

Subsequent to synthesis and semantic development of the data and activity models, information engineering methods were used to derive an interaction model and, ultimately, to identify generic business systems and business areas.

DEVELOPING A GENERIC ARCHITECTURE TEMPLATE

Semantics of the Resulting Overall Model

The underlying semantics of any model are what give the model meaning and provide a basis for clear definition of model components and their interrelationships. The semantics of an information architecture drive the formation of structure in the activity hierarchy, assist in identifying and defining necessary data elements, and define and clarify the interactions among activities and data.

The semantic model applied in this research is one of resource allocation, driven by planning, with directives derived from departmental policy. It models the efficient and effective conduct of business through planning and management of programs of transportation improvement and business projects, developed in such a way as to optimize requests for resources and allocation of those resources to meet the goals and objectives of the agency.

Semantics in the Activity Model

Figure 6 depicts relationships among high-level functions in the synthesized model and places them in appropriate time frames. All activities are policy-driven. The overall direction for development of transportation systems and management of the agency is established during strategic planning (a 10- to 20-year horizon) in accordance with policies. Strategic planning affects transportation planning (a 5- to 20-year horizon), information resource planning, and research planning (both having 5-year horizons). These longer term planning activities converge to intermediate (a 2- to 5-year horizon) business planning. Business planning formulates what the agency intends to do for both transportation improvements and agency management. Business planning also drives a budgeting function. Given an approved budget, the development of transportation improvement projects and business projects (e.g., support services) begins (a 2-year horizon), ultimately leading to feedbacks to policy development and planning activities.

An innovative semantic aspect of the Utah DOT's activity model was adapted at a lower level. Design and construction were coupled through a single function termed "transportation component improvement development." This function consists of establishing a spatial reference base for a project, developing the improvement, evaluating the improvement, and accepting the improvement—all of which are common to both design and construction. That is, from an information standpoint, there is no difference between design and construction. Both of them develop improvements to transportation components. The improvement is virtual in the case of design. It is real in the case of construction. In terms of operations on data, updating the description of an improvement with a design plan is no different than updating that description with as-built information after construction.

Semantics in the Data Model

The synthesized activity model describes policy–based resource allocation driven by planning, and the data model must support these activities. The ERD characterizes the logical relationships among entity types. Entity type relationships in the synthesized model were merged and condensed to indicate associations between subject areas in Figure 7. Lines connecting subject areas in Figure 7 indicate the presence of at least one relationship between entity types in those subject areas. The data model is a policy-centered model that has strong ties with transportation system, treatments, plans and programs, regulations, and communications. Information on allocation of resources (e.g., money and equipment) for projects is contained in plans and programs. Information architecture and human resources define the business infrastructure for conducting projects.

At a lower level of the model, entity types in the subject area "geography" play a vital role as the spatial reference base for projects, for assembling transportation system components into transportation systems, and for providing the basis for location referencing in general. These entity types enable collection, maintenance, and analysis of the vast majority of information of interest to a transportation agency, from descriptions of the transportation infrastructure and its state to data on the buildings and grounds in which the agency houses its offices.

Semantics in the Interaction Model

Figure 8 is the clustered CRUD matrix. Indicated interactions were derived, in part, from ideas expressed in the following discussion.

Agency policy and vision are derived from legislation and societal values. Strategic planning develops strategies, goals, objectives, and criteria based upon the policy and vision of top management. These outputs from strategic planning form the basis for subsequent planning activities. They provide directions, targets, and performance measures for framing the agency's activities and gauging the effectiveness of plans. Each subsequent planning activity updates the outputs from strategic planning, providing feedback from evaluations of performance.

Information engineering methods are modeled as part of a larger information resource management function that draws upon the results of strategic planning to create and carry out a plan for the enterprise information architecture. This architecture, which describes the interrelationships among the agency's business activities, data, technology, and organizational structure, provides primary inputs for business planning.

Business planning assesses business needs and leads to development of one or more business programs, each of which includes one or more business projects. In parallel, the transportation planning function leads to development of one or more transportation improvement programs, each of which includes one or more transportation improvement projects. Resource needs of programs and projects drive a budgeting function that produces a budget and makes actual resources available. Programs and projects are adjusted in response to the availability of actual resources.

The intermodal transportation planning model from the GIS-T Pooled Fund Study is intact, wherein functional transportation systems are assembled from transportation system components, themselves being drawn from the general population of transportation components representing all modes. Levels of performance of functional transportation systems are compared to demand to determine transportation system needs. Needs are associated with underlying causes, and treatment strategies are developed on the basis of past treatments, costs, and benefits. Transportation improvement projects are conceptualized and evaluated, leading to development of transportation improvement programs. Initial selection of functional transportation systems is on the basis of the objectives and criteria established earlier through strategic planning (ATR, 1994).

The "transportation component improvement development" function (design and construction) creates and updates each transportation component for which the state DOT is responsible. Subfunctions of "transportation component improvement development" appear in rows of the CRUD matrix that correspond to boxes (business areas) 7 and 8. Other intermodal components (i.e., trails, terminals, transit facilities, fleets, and continuous flow facilities) are created in the database by an "external data sharing" function. This function also creates "geographic themes" that are additional spatial and spatially referenced data that DOTs must acquire from external custodians to support planning, design, and construction. Such geographic themes include wetlands data managed by natural resource agencies, cadastral data managed by county government, and archeological data managed by historical societies. The external data sharing function also provides DOT data to external parties.

Data collection and monitoring of the states of transportation components are modeled by the "transportation component performance development" function. Data on transportation components and their states are read and updated by transportation planning functions and by transportation operation functions (i.e., traffic management, weather operation, incident response, and route planning).

Interactions among remaining functions and data complete the generic description of a transportation agency's business. Examples include permits created by "permit issuing," contracts created by "contract management" and updated by "monitoring of work in progress," and accounts and invoices created by "financial services" and read by "auditing." Additional example interactions derive from management of capital equipment, management of buildings and grounds, and development of human resources.

Business Areas and Business Systems

Generic business areas are identified in Figure 8. Each business area contains one or more business systems. The 14 business areas, 33 business systems, and their definitions are as follows:

1. Policy—This business area contains a single business system as follows:

- Policy Integration—Distills public values, visions, and mandates for transportation into a set of specific, concrete policies, objectives, and goals related to availability, quality, and performance of transportation facilities and associated services (ATR, 1994).

2. Information Resource Management—Supports the agency's systems architecture, internal communication, and document processing systems. Business systems are as follows:

- Information Resource Management—Applies CASE and other tools for developing and managing the agency's information architectures.
- Electronic Communication Management—Provides hardware, software, and network support for e-mail, WWW access, and other telecommunication activities.
- Agency Document Management—Supports assembly, modification, and indexing of the agency's plans, standards, and library of reports.

3. Business Infrastructure—Supports day-to-day management of the agency's facilities and business operations. Business systems are as follows:

- Employee Benefits—Tracks information and provides data processing support for employee benefits and training programs.
- Facilities Management—Supports space allocation, design, construction, and maintenance of the agency's buildings and grounds facilities.
- Real Property Management—Supports inventory and management of title to real property and improvements controlled by the agency.
- Supplies and Equipment—Supports inventory, accounting, and management of capital equipment and supplies used by the agency. Provides data processing for requests, maintenance, and depreciation.
- Business Resource Allocation—Allocates positions, buildings and grounds, and equipment for business programs and projects.

4. Public Communication—Supports preparation and release of information to the public, including the agency's publications and notices to travelers. Business systems are as follows:

- Advanced Traveler Information—Provides information to travelers concerning travel conditions and the states of transportation facilities.
- Publications—Supports assembling, modifying, and typesetting of the agency's public literature.

5. Transportation Planning and Programming—Provides development of candidate improvement

projects, leading to development and management of improvement programs based on transportation system needs. Business systems are as follows:

- Program Development and Management—Evaluates the effectiveness of each project concept based on performance, environmental, social, and economic effects. Projects are then incorporated into regional and statewide plans and improvement programs (ATR, 1994).
- Treatment Development—Associates performance needs with underlying causes, thereby identifying appropriate system- and component-level treatments. Effective treatment strategies are developed based on an evaluation of past treatments plus life cycle costs and benefits. Treatment strategies are synthesized into project concepts that reconcile all treatment alternatives (ATR, 1994).
- Functionally Integrated Transportation System—Maintains the inventory of transportation components and the functional transportation systems set up to monitor policy objectives. Generates and allocates system- and component-level travel demands (ATR, 1994).

6. Transportation Operation—Includes advanced traffic management, incident management, transportation monitoring and performance assessment, and weather operation. Business systems are as follows:

- Advanced Traffic Management—Provides analysis of traffic conditions and operations of traffic control devices, including signalization, ramp metering, congestion management, and ITS. Traffic management uses real-time condition data for design of traffic controls.
- Incident Management—Plans for and responds to events that affect the state of transportation facilities.
- Transportation Monitoring and Performance Assessment—Determines the value for each transportation component state and compares actual performance to desired levels of performance.
- Weather Operation—Provides mitigation of road conditions made unsafe by meteorological changes.

7. Design and Construction—Supports preparation of plans, specifications, and construction of transportation improvement projects. Business systems are:

- Computer-Aided Design—Supports development of plans and specifications for transportation improvement projects.
- Estimating and Scheduling—Provides integrated cost estimation and scheduling of materials, equipment, and workforce for transportation improvement projects.
- Social/Environmental Evaluation—Provides GIS applications for evaluating socioeconomic and environmental effects of a transportation improvement project.

8. Location Control—This business area contains a single business system as follows:

- Location Control—Supports development and maintenance of location referencing systems, including linear, geodetic, and cadastral control. Includes support for photogrammetric engineering, and real property surveying and mapping.

9. Contract Administration—Supports preparation of bids, selection of contractors, and management of contracts. Business systems are as follows:

- Contractor Selection—Supports pre-qualification of vendors; preparation, issuance, and evaluation of bids; and preparation of contracts.
- Contract Management—Supports ongoing evaluation of work operations, management of contract change orders, authorization of final payment, and contract close-out.

10. Compliance—This business area contains a single business system as follows:

- Compliance—Tracks and provides data processing support for the agency's interpretation of, and compliance with, federal and state regulations, to ensure that agency activities are conducted legally.

11. Research and Development—This business area contains a single business system as follows:

- Research and Development—Supports research planning, prioritization of research needs, and allocation of funding to research projects. Monitors research progress, and supports development of research results into agency standards.

12. Vehicles and Drivers—Tracks information on driver licensing and motor vehicle registration and licensing. Business systems are as follows:

- Driver Licensing—Tracks licensing information, processes applications, and provides support for testing of persons seeking licenses for operation of motor vehicles.

- Motor Vehicles—Supports registration and licensing of motor vehicles, evaluation and approval of requests for oversize/overweight permits, and queries by law enforcement officials.

13. Financial Management—Supports financial aspects of the agency's business, including accounting, auditing, and budgeting. Business systems are as follows:

- Accounting—Supports management of funds within the agency.
- Audit—Supports internal and external audits.
- Budgeting—Supports preparation of a fiscal period financial plan and monitoring of expenses.

14. Interagency Cooperation—Supports regulatory functions of the agency, with regard to public and private transportation facilities, and sharing of data necessary for statewide intermodal transportation planning. Business systems are as follows:

- Data Sharing—Supports sharing of data with external parties through translation to and from standard formats and models, including metadata, editing functions, and quality assurance measures.
- Transportation Facility Regulation—Supports regulation of public and private transportation services and terminals.

Business System Relationships

Analysis of the interdependencies expressed in the clustered CRUD matrix suggests that the derived business systems are themselves interrelated by more than business areas in the overall integrated business systems architecture. These relationships are conceptualized in Figure 9. The business systems generally fall into three broad categories: (1) agency management, (2) infrastructure management, and (3) foundational systems. Agency management systems are identified with vertical text on the left-hand side of the figure. Infrastructure management systems are identified with vertical text on the right-hand side of the figure. Interrelationships among agency management and infrastructure management systems strengthen toward the center of the figure. Two systems, Contractor Selection and Real Property Management, fall on the boundary because they are equally significant to agency management and infrastructure management.

Foundational systems support all other systems and are identified in Figure 9 by horizontal text. Every activity of the agency depends upon policy, so Policy Integration supports all other systems. Some of the foundational systems support either agency management systems (e.g., Information Resource Management) or infrastructure management systems (e.g., Data Sharing), but not both. Location Control supports Facilities Management and Real Property Management (within agency management) and all infrastructure management systems through its support of Functionally Integrated Transportation System. The Functionally Integrated Transportation System and the Transportation Monitoring and Performance Assessment System support most of the infrastructure management systems because all those systems require information on the transportation system and its performance. Business Resource Allocation supports agency management systems because all activities require resources.

Dependencies of the systems upon spatial data and functions tend to increase from left to right in Figure 9. All infrastructure management systems and many agency management systems have spatial components. Four of the foundational systems are primarily spatial, and Location Control, a critical system in support of many others, exists because of the spatial nature of the others.

Links to Server-Net Architecture

NCHRP Report 359, "Adaptation of Geographic Information Systems for Transportation" (Vonderohe et al, 1993), recommended that transportation agencies begin planning for incremental adoption of a server-net technology architecture. Since publication of the report, the directions of technology development have been as expected and some transportation agencies are moving toward server-net environments. The report suggested 15 possible types of servers, summarized here. It should be re-emphasized that the particular division of labor among servers, suggested in *Report 359* and summarized here, is but a first-iteration design that will require refinement as further design proceeds and as implementation is initiated.

Servers of the first kind, *spatial data servers*, contain and provide their clients with access to spatial entities such as coordinates and shapes, and to topology (relations among spatial entities). In general, these data constitute digitized maps represented as vectors. More specifically, spatial data servers provide information about points, lines, areas, and networks plus topological relationships among entities of these types. Spatial data servers might also provide information (e.g., elevations, slopes, aspects, and volumes) about digital elevation models and other surface models.

Attribute data servers contain data in relational tables (or perhaps in non-relationally structured forms of the kinds used in older database models). In general, these servers are nodes using the standard database management systems of the present time, although the data schemas used must, in many cases, be extended to include location fields that enable linking of the attribute data to spatial-data references as will be required, for example, for the production of thematic maps or for various kinds of analytical modeling.

Spatial image data servers contain geographic data organized by raster (e.g., satellite images, scanned aerial photographs, and digital orthophotographs). These images will be indexed so that they can be spatially retrieved and processed, for example, as required to register them against a map for purposes of displaying or printing a map laid over an image.

Non-spatial image data servers contain scanned documents (e.g., accident reports and sketches, or construction sketches), scanned photographs (e.g., of bridges or of pavement segments), and eventually digital audio and video images. These images will be locationally indexed so that they can be retrieved and presented in terms of spatial data references.

Complex object data servers contain complex data structures such as those used within CAD systems to represent, for example, highway construction designs. Once again, these structures will be locationally indexed so that they can be retrieved and presented in terms of spatial data references.

Servers of the sixth kind, *overlay servers*, aggregate and integrate data from various kinds of data servers as required for construction of thematic maps, overlays of images and maps, spatially specified data retrieval, analytical modeling, and other GIS activities. Complex overlay operations can require combining of information from several sources, including one or more spatial databases and one or more data sets from other kinds of data servers.

Analytical computation servers vary widely in function and complexity. They realize the models that users need to run against geographic data (e.g., network analysis models or traffic demand assignment models). They also do the many other kinds of computation required for transportation applications (e.g., image processing, proximity analysis, cluster analysis, flow analysis, aggregation and other kinds of statistical processing, resource allocation, path finding, pattern finding and matching, best-fit computations, surface-area and volume computations, and engineering design computations).

User interaction and display servers are the workstations that support individual users. They support map-oriented query directed against spatial data and the other kinds of data servers, and they support displays of the results—results whose generation may require calls on overlay servers and analytical computation servers. The research team is not proposing construction of a server-net computing environment devoted exclusively to GIS applications. These user-station servers are exactly the same ones that support word processing, desktop publishing, electronic mail, electronic collaboration support and other kinds of "groupware," accessing databases for all kinds of non-GIS uses, computer-aided design, decision support, financial modeling, project scheduling, and the hundreds of other now common, as well as yet to be imagined, uses to which networked workstations and PCs will be put.

GIS application development servers provide source code databases (with capabilities required for version control), coordination support for programmer teams, documentation databases, linkers, optimizing compilers (most other language tools, in particular, macro interpreters, incremental compilers, and language-specific editors, will be assigned to user stations), and other CASE tools.

Servers of the 10th kind, *spatial data capture and transformation servers*, translate data from digitizers and scanners into the formats required for input into, and updating of, the spatial databases maintained by spatial data and image servers, and do various kinds of data interpreting (e.g., of photogrammetric measurements) and data converting (e.g., between raster and vector formats; between spatial data structured according to different reference systems; between different map projections; or between standardized exchange formats and internal storage formats).

Cartographic data servers construct and store symbolic structures (map surface symbols) that drive electronic map displays and hard copy map printing and publishing devices. The multi-user cartographic data server maintains symbol libraries, map templates, finished maps (in appropriately differing versions), and other cartographic tools and products of general use to map-making and map-applying user groups.

New technology servers act as place holders. They are meant to include any number of additional server types—different ones for different technologies. The point is that computing environments structured in terms of server nets can easily, without causing disruption, be extended to exploit new technologies simply by incorporating new kinds of servers. Examples of possible new technology servers are *expert system servers* and *animation generator servers*.

Any given server net will have several other kinds of *general purpose servers* (e.g., internet gateways, plotter drivers, printer drivers, film recorder drivers, and typesetter drivers). One such kind that will be available in every server net of the future is a *directory server* that will catalog and describe the resources in a net—from them, users will be able to discover what resources are available and how to access such resources.

Servers of the 14th kind, *history servers,* will be needed to store historical data no longer of current interest but possibly required for legal purposes, to perform historical analyses, and to create databases that contain event histories and temporal trajectories. These servers will be supported by mass storage devices (e.g., optical storage devices or tape devices) capable of economically storing massive amounts of data (i.e., many trillions of bytes).

Servers of the 15th kind, *specialized application servers*, such as ones dedicated to advanced traffic management or transportation system monitoring and performance assessment, will make use of many of the other kinds of servers in the net. This is standard operating procedure for client-server networks.

Report 359 was careful to emphasize that, although its focus was geographic information systems, many of the servers characterized above would appear in any general server net for transportation computing. That is, given the pervasive nature of locational aspects in data and functions, sharp distinctions should not be made between transportation computing and spatially based computing. This idea was explored in the analysis of transportation business systems relationships, above.

Business System/Server Mapping

Figure 10 illustrates an initial mapping among the business systems and servers described above. The servers most likely to be used by each business system are indicated. Any given business system might draw upon the resources of servers that are not indicated, but probably to lesser extents.

Attribute data servers, user interaction and display servers, and general purpose servers are required by most of the business systems. They support both agency management and infrastructure management, as well as foundational applications. Spatial data servers support infrastructure manage-ment systems, foundational systems, and those agency management systems near the center of Figure 9. Spatial image data servers support planning, engineering design, some operations, and facilities management. The location control system provides data to both spatial data servers and spatial image data servers.

Non-spatial image data servers are used by publications, agency document management, and driver licensing systems as well as some of the infrastructure management systems. Complex object data servers are used by those systems requiring access to, or providing, design information and other complex spatial representations.

Overlay servers are used by infrastructure management systems, some foundational systems, and the facilities management system. Analytical computation servers support the business systems that do network analysis, reference system analysis, broader spatial analysis, and predictive modeling. GIS application development servers are required by the information resource management system only. Spatial data capture and transformation servers are used by the location control and data sharing systems only. Cartographic data servers are required by those systems that use map-oriented displays.

New technology servers are indicated for the advanced traveler information, incident management, and advanced traffic management systems. These systems require servers that support real-time data acquisition from a wide variety of sensors, in addition to electronic control of devices and communications for dispatch. History servers are used by those systems that develop and analyze trends over time, evaluate past performance, or require a temporal chain of records. Specialized application servers are indicated for those systems that might have dedicated computing resources.

APPLICATION OF THE GENERIC TEMPLATE

Research Products and Their Use

The activity model contains 106 activities in a six-level hierarchy. Nearly all activities, including all those used in the CRUD matrix, are functions. In some cases, processes are included below low-level functions to provide clarity. The data model contains 94 entity types in 15 subject areas. The entity types do not include attributes. The interaction model, the business systems architecture, and interrelationships between business systems and servers, are described above.

The activity model and data model were synthesized from several state DOTs' ISP models. Therefore, the models are generic and agencywide and can serve as templates for other transportation agencies that want to develop their own models. The activity model consists of agencywide ongoing activities in infrastructure management and agency management. The subject areas and entity types of the data model indicate the essential information needs of transportation agencies. The models are based on synthesis of highway engineering or agencywide models from seven states and provinces, the transportation planning model of the GIS-T Pooled Fund Study, and Utah DOT's integrated design and construction models. Therefore, the models are generic.

The models are at a high level of abstraction because they are generic. Their utility is founded on the notion of "one framework fits all" rather than "one size fits all." The activity and data models will need to be decomposed and have detail added by DOTs using them as templates to initiate the information strategy planning process; however, their potential for providing significant savings is high. The interaction model can serve as a guideline, and the business systems architecture and server-net mapping can serve as references.

DOTs that have developed information architectures of limited scope should also be able to use the results of this research. Components of the synthesized activity and data models that are redundant with those of the agency can be discarded. Components that model parts of the enterprise not yet addressed by the agency can be used as templates in a manner similar to that described above.

The experience of one DOT in using templates for activity, data, and interaction modeling is described in the following section.

Utah DOT's Experience with Templates

The Utah DOT's experience in developing an engineering information strategic plan provides definitive examples of sound information engineering practice, use of existing models as templates, and subsequent benefits that can be realized.

Background

The Utah DOT recently faced the same dilemma and posed the same set of questions that many DOTs have struggled with. A rapidly changing technological environment creates demands that outstrip many DOTs' abilities to take best advantage of advances and innovations (Geographic Paradigm Computing, 1995). Not the least among these technological changes is the rapid advancement of GIS. Many GIS applications were being either developed or proposed at the Utah DOT without a comprehensive plan for their integration. Because of an earlier GIS needs survey, management was aware that many functional units maintained, were developing, or were in need of spatial data. Some kind of planning tool or planned approach for deciding how to proceed was necessary to maximize efficiency and prevent chaos.

An RFP for a comprehensive plan to integrate transportation and geographic data using GIS was issued in March, 1995. The RFP called for (1) synthesis of a spatial or engineering user needs document from the raw user needs survey data and (2) development of a GIS strategic plan that prioritized applications and established directions for adoption of the technology.

The accepted proposal suggested that what was really needed was an ISP for engineering. This was a shift from a technological point of view (GIS) to a functional point of view (engineering) and provided a context for examination of spatial data and GIS needs.

First Steps—Executive Briefing and Team Formation

During April, 1995, a briefing, by the selected consultant, was held for the executive team. This team consisted of the Secretary of the Department, the Deputy Director, and other members of the Department's executive staff. The briefing outlined what was needed from the Department, in time and resources to develop the ISP. The executive team made a commitment to proceed. The executive team was requested to identify, with the assistance of the consultant, departmental staff members who would serve on the project team. Eight Utah DOT managers representing planning, design, construction, safety and traffic operations, real estate, and information systems were selected. The project team, with the consultant serving as facilitator, was assembled in May, 1995. The team leader was the Director of the Bureau of Research and Development.

First Team Task—Development of Charter Statement

The project team began by developing its own charter statement. This initial work addressed a critical underlying issue—agreement, on the part of mid-level managers, to take an enterprisewide view rather than that of their own functional area. That is, it was much more instructive for them to realize the information flows among them as managers, and how much they were interdependent on one another, than it was to do the specific technical work of data and process modeling. Human interaction during development of the ISP was just as important as the technical work.

The mission that emerged in the charter statement was to develop a geographically referenced framework of Utah's transportation infrastructure to enhance access to information and group decision making. There were three objectives as follows:

1. Development of a comprehensive information framework, integrating process, data, and technology;
2. Development of a GIS implementation plan, based upon the framework, that is both understandable and realistic; and
3. Supporting Utah DOT's goals by providing the Department with a consensus direction that has management's support and commitment.

The third objective arose from a previous strategic planning exercise wherein high value was associated with consensus decision making in the organization. The project team included several relatively senior managers who were there to develop and present agencywide mid-level management consensus recommendations to top management.

The mission statement provided a scope of work: the activities, data, technology, and organizational structure involved with transportation systems (i.e., planning, programming, design, construction, maintenance, roadway inventory, transportation operations, and real property management). Departmental administrative activities (e.g., financial and human resource management, public information management), and regulatory activities (e.g., commercial vehicle operations) were designated as out-of-scope.

The mission statement identified the following deliverables:

- An Engineering ISP, including activity, data, and interaction models, a business systems architecture, a technology architecture, and an overview of the current technological environment (to be drawn from the existing GIS needs survey);
- A draft implementation and operational plan, essentially assigning timelines, budgets, priorities, and organizational support to the business systems architecture in the ISP; and
- A stakeholder briefing wherein the project team would present the work and recommendations to the executive team.

The mission statement reflected the following assumptions:

- The project team would be able to adopt an enterprise perspective and reduce its own parochial differences,
- The project team could adapt generic information frameworks more quickly than they could develop their own from scratch, and
- The framework and strategy produced by the study would be given serious consideration and would be implemented as appropriate.

Template Approach

The following models were available to serve as templates:

1. The GIS-T Pooled Fund Study (PFS) planning model (ATR, 1994),
2. The Wisconsin DOT Division of Highways model for design and construction (WisDOT, 1992), and
3. The NCHRP 20-27(2) linear referencing system model (Vonderohe et al, 1995).

The belief was that, at a strategic level, most DOTs are very similar. Although the language used in these models and at Utah DOT might differ, the underlying concepts are creations of national and statewide policy. DOTs have much the same mission. Given the same mission, it is likely that they have the same functional breakdown.

The scope of the Utah DOT ISP was infrastructure management. The three available models covered all of infrastructure management, except transportation operations. It was in the modeling of this functional area, that the most time was expected to be devoted.

Activity Modeling

The activity model was developed first because it is usually easier to understand data, in terms of information needs, after activities are understood. The facilitator developed a draft activity model template from the available models prior to the first working session. The draft model was examined, initially at a summary level of detail to determine the fit of high-level functions. As individual components of the model were addressed, the technical manager on the team closest to that functional area took the lead in the discussion. The objective was to validate or invalidate the draft model as presented. All team members were active participants, with each having the opportunity to demonstrate expertise.

Considerable time was devoted to definitions, so that everyone understood what the activities were. All team members had to become equally knowledgeable in the full scope of activities. Most team members had a fairly good understanding of upstream activities, that is, activities that produced or operated on data they required. On the other hand, many of the team members were not knowledgeable of downstream activities, that is, activities that required data they produced.

Consensus was achieved relatively quickly on the draft material. There were some minor changes in the transportation planning area, addressing facilities that were in the template that Utah DOT did not manage or facilities that Utah DOT did manage that were not in the template. Utah DOT had the advantage of having already identified Departmental and transportation system goals and objectives. The team members understood policy-driven resource allocation planning which was the underlying philosophy of the Pooled Fund Study model.

Modeling of design and construction based on the template went quickly. That part of the draft model had been developed by a DOT, so the words and concepts were familiar. Much of the design process follows AASHTO or federal design guidelines. At a functional level, all DOTs are designing and constructing projects in much the same way.

Because the template reflected the planning, design, and construction processes, the team was able to devote more time to development of a new part of the model for transportation operations. The activities included weather operations, vehicle dispatch, and tracking, many of which addressed ITS functionality, envisioned as necessary for the future. Transportation operations was Utah DOT's innovative contribution to the overall model.

Right-of-way management was the last functional area to be addressed. The team gained insight into right-of-way management as a separate line of business while dealing with issues of cadastre, the Public Land Survey System, and interrelationships with projects. Right-of-way management did not fit neatly into policy development, planning, design, construction, maintenance, or transportation operations.

The activity model was completed in one week of 8- to 10-hour days. It consisted of a fully adapted or adopted process model with 165 processes that had been analyzed, created, or validated. Extensive use of the template had been made during development of the activity model

Data Modeling

Prior to the first data modeling session, the facilitator developed a draft template entity relationship diagram from the available models. The objective was to validate or invalidate the template. Considerable team input was required for defining subject areas. Much time was devoted to agreeing on the names of data and then regrouping them—there seems to be much more latitude in naming data than in naming processes or in understanding process descriptions. Team members tended to prefer to use familiar names of data rather than adopting other names intended to have the same meaning.

The largest problem in working with abstract entity types (i.e., entity types without attributes) is that entity types are truly defined by their attribute characteristics; therefore, the modeling discussion often included "for example" attributes to provide reference. Optionality and cardinality are difficult to develop in working sessions. Because it is not reasonable to attempt to teach data modeling and then do it in a 1-week period, much of the working session time was devoted to understanding data concepts, with the technical data modeling being done off line by the facilitator and presented to the team for validation.

A complete data model was developed in 1 week. The model had 110 high-level entity types with a complete set of relationships, including optionality and cardinality, embedded among them. At the end of a second working week, the team had produced an activity hierarchy and an entity relationship diagram consistent with it. Good use had been made of the template in development of the data model, although its use was not as extensive as it had been in preparing the activity model.

Interaction Modeling and Business System Definition

Refining the activity model involved the concept of data pre-conditions and post-conditions (i.e., what data were necessary to trigger a process and, after execution of the process, how had the data been transformed or what new data had been created). Therefore, considerable knowledge on interactions had been developed and documented as a consequence of preparing the activity and data models.

The challenge was to address each possible interaction in a 165 x 110 matrix. Here, the existing interaction models served more as a reference than as a template. However, if there was a given cell intersection in the developing model that corresponded with one in any of the available models, the existing information was used either to validate the assertion of the team or as a point of departure in discussion.

Interaction clustering and subsequent refinements created 27 business systems in seven business areas. As in the current research, some business areas and systems were more foundational than others and formed a basis for prioritization. The foundational or core business areas were policy, location referencing, and inventory. Data created or managed by these systems were required by all others. This finding validates the results of the current research in that the same or similar business areas were found to play a central role in the architecture derived from the synthesized models.

Interaction modeling and development of the business systems architecture were completed in one week. At the end of the third working week, all technical tasks for the ISP had been completed.

Benefits Derived from the Approach

Table 1 compares cost, calendar time, level of effort, and method for development of ISPs at five DOTs. Out-of-pocket real-dollar costs to Utah for development of the Engineering ISP were about 33 percent of the average costs incurred by the DOTs whose models were synthesized in the NCHRP research. The effort required about half the normal calendar time, although in person-days it was less than half. All the technical work was done in 3 weeks spread over about 4 months. Typically, ISPs require 8 months to a year at DOTs. The Utah DOT project team began writing its charter in the middle of May, 1995, and the executive team had the final report during the first week of September.

Without a template, 165 processes would have been conceptualized and then very specifically defined. Considerable effort would have been devoted to writing new definitions versus the reduced effort required for deciding whether or not existing processes and definitions were appropriate.

The GIS-T Pooled Fund Study transportation planning models were developed in 6 working weeks by a team of 8 to 10 people. The Wisconsin DOT models for design and construction were developed by a team of 8 to 10 people that met for 2 days a week for 9 months. To the same level of detail, those direct investments were available to the Utah DOT.

The templates allowed the project team to understand the thinking that had gone on before and provided a convenient basis on which to accept, modify, or reject the elements. Having the perspectives of other DOTs increased their confidence in the viability of the model.

Finally, there was hidden utility in getting a team of people together who did not know what one another was doing, or worse, thought they knew when they did not. The project team realized they were interdependent in ways they had not perceived before. Previously, most major systems funding and definition had been the responsibility of data producers who were not well informed of the requirements of data users. As a consequence of the ISP effort, people downstream of the data collection process were making suggestions about how data could be improved in quality and timeliness.

The Engineering ISP has helped develop a high-level understanding of what is possible and important. It has provided a direction for technology adoption and adaptation that is efficient, effective, and integrative. The department is moving toward a working environment in which people can obtain the information they need without long searches.

The ISP has facilitated GIS adoption and diffusion to the regional level. While there has been an effort to enhance and integrate the ISP with current management systems for pavements, bridges, safety, and congestion systems, it is important to note that new applications have also been developed. New applications currently in place, under development, or under consideration include the following:

- Safety—analysis of accidents for deer fence planning and prioritization of winter weather operations,
- Construction—status reporting and analysis of proximity between projects and aggregate sources,
- Maintenance—monitoring of treatment effectiveness and coordination of scheduling routine maintenance such as pavement markings, and
- Commercial Vehicle Operations—fine-tuning of enforcement operations on the basis of geography, brake testing facility siting, and route selection (avoidance of grades too steep for trucks).

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This research developed generic data, activity, and interaction models leading to a business systems architecture that provides a basis for integrated applications critical to the missions of state DOTs. In order to do so, the ISP-level models of seven state and provincial DOTs were synthesized. This approach required development of a synthesis methodology. To ensure compatibility with the architecture developed by the GIS-T Pooled Fund Study, the activity and data models of that study were adapted as the transportation planning components of the current work. In addition, innovative aspects of the Utah DOT models, completed after the current work was initiated, were incorporated by importing or adapting them to the synthesized models.

Analysis of the interaction model yielded 33 generic business systems in 14 generic business areas. The business systems can be grouped into three broad categories: infrastructure management, agency management, and foundational systems.

The infrastructure management and agency management systems require data created and managed by the foundational systems. Dependencies among systems suggest priorities for emphasis within transportation agencies. The two systems, upon which the largest numbers of others depend, are one that supports development of agency policy and one that establishes the basis for location referencing. All infrastructure management systems and many agency management systems are highly spatial in nature and, therefore, conducive to development in GIS environments.

The generic activity and data models resulting from this research should be thought of as templates, providing a starting point for refinements that reflect the individual characteristics of each agency. The models are generic and at a high level. They will have to be tailored and developed in greater detail for individual agencies. But, they provide a starting point for those agencies beginning the development of enterprise models—and they might provide detail in untouched areas for some agencies that have completed an ISP of limited scope.

The activity model is expected to be of the greatest use, with its names, definitions, and structure being suitable for adaptation by many DOTs. The data model is expected to be useful as a starting point for scoping subject areas and defining entity types. The interaction model is expected to be useful as a guideline for modeling and as a source for validation. The business systems architecture is expected to be useful as a reference.

The experience of one DOT (Utah), indicates a potential savings of 50 to 75 percent with use of an ISP-level template. The generic models produced by this research are at a higher level than those used by the Utah DOT, so more decomposition will be required with their use, but the potential savings should nevertheless be significant.

An earlier phase of this research recommended that transportation agencies begin planning for incremental adoption of a server-net technology architecture. The current work included mapping of the 33 generic business systems to the conceptual server-net suggested in the earlier work. Consistent relationships were identified between the functions and data of the business systems and the divisions of labor assigned to the servers. Taken together, the NCHRP 20-27 Phase 1 and Phase 2 research products provide a generic basis for adaptation of technology, understanding of enterprisewide business activities and data needs, and development of integrated information systems and innovative applications by transportation agencies. When these are considered along with the results of the GIS-T Pooled Fund Study, they should facilitate development of comprehensive strategies for exploitation of technology and detailed plans for integrated transportation information systems.

Results of the work constitute high-level views of three of the four sub-architectures of a generic enterprise information architecture: (1) activity, (2) data, and (3) technology. The results include relationships among the elements of these three subarchitectures.

Seven recommendations resulted from the research, as follows:

1. Transportation agencies should adopt an information engineering approach, leading to an enterprise information architecture, for planning and design of integrated transportation information systems. A fully computerized enterprise cannot be built without information engineering techniques. Development of an enterprise information architecture is the only way to plan for coordination and evolution of different systems and at the same time allow the systems to be built independently.
2. Transportation agencies should not develop an enterprise information architecture without support and commitment from top management. The architecture must be regarded as a corporate resource for developing and maintaining integrated information systems, not as a special project.
3. Information engineering should not be regarded as a rigid methodology but rather as a structured guideline for information systems planning and design. The agency must resolve that the information engineering approach is iterative, results are evolutionary, and benefits grow in the long term.
4. A transportation agency must choose the right people for the enterprise information architecture development team. Individuals should be team-oriented, able to see the "big picture," knowledgeable about the details of individual systems, have the authority to make decisions, and supportive of the information engineering methodology.
5. Transportation agencies should acquire and use a CASE tool to manage the information engineering models and, ultimately, the architecture. Manual maintenance of the necessary models is nearly impossible. The most notable strength of CASE tools is in their ability to manage both structured models and the overall architecture.
6. Transportation agencies initially embarking upon ISP development should use the models produced by this research as templates, expecting to modify and fine-tune them to suit their specific circumstances. Significant savings can be realized using a template as a starting point.
7. Transportation agencies with existing ISPs of limited scope should use components of the generic enterprise models as templates for unmodeled areas.

FINAL REPORT AVAILABILITY

The full agency report for Project 20-27(2) will not be published in the regular NCHRP report series. However, loan copies of the agency report are available by contacting: Transportation Research Board, National Cooperative Highway Research Program, 2101 Constitution Avenue, N.W., Washington, DC 20418.

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GLOSSARY

The following definitions are quoted from the indicated references unless otherwise noted:

Activity: A generic term for either a function or a process within a business model (TI, 1993).

Activity Architecture: Activity architecture refers to the work being done by the enterprise with an emphasis on how information is being used. The activity architecture characterizes all work as a collection of activities transforming input information into output information (FHWA, 1995).

Activity Decomposition Diagram: A structure showing the breakdown of activities into progressively increasing detail (Martin, 1990).

Analysis: The stage in information engineering in which a more detailed study is performed on particular segments (called business areas). Each analysis project focuses on what the business area must do to accomplish its mission (TI, 1993).

Application System: The automated and related manual procedures within an information system that support a set of business processes. One or more applications comprise an information system. Applications are defined in the analysis phase of the methodology as a result of studying business areas (Martin, 1990).

Association: A meaningful link between two objects (e.g., entities, processes, goals, or critical success factors). Associations are used to capture data about the relationship between two objects (Martin, 1990).

Attribute: A characteristic of an entity type. Each occurrence of an entity type can have at most one value for the attribute at any time (TI, 1993).

Business Area: A collection of related business functions and entity types that defines the scope of an analysis project (TI, 1993).

Business Function: A group of business activities which together completely support one aspect of furthering the mission of the enterprise (Martin, 1990).

Business Function Decomposition: A decomposition of a business function into more detailed business functions (Martin, 1990).

Business Function Dependency: A dependency between two business functions which exists because information provided by one is required by the other (Martin, 1990).

Business Model: A representation of information about a business; its data, its activities, and the interactions between them (TI, 1993).

Business Process: A task or group of tasks carried out as part of a business function (Martin, 1990).

Business Re-engineering: The fundamental rethinking and radical redesign of business processes to achieve dramatic improvements in critical, contemporary measures of performance, such as cost, quality, service, and speed (Hammer and Champy, 1993).

Business System: A logical grouping of business activities which forms the basis for subsequent information systems development (TI, 1988).

Business Strategic Planning: The activity in which the objectives and strategies of the enterprise are set. This provides prime input to the information strategy planning stage (Martin, 1990).

Business Systems Architecture: A structure that represents the dependencies between the business systems of an enterprise (Martin, 1990).

Cardinality: The number of instances of one object type associated with an instance of another type. Cardinality is a property of an association (Martin, 1990).

Cell: In a matrix, the interaction between a row and a column (TI, 1993).

Conceptual Model: The overall logical structure of a database, which is independent of any software or data storage structure (Martin, 1990).

Construction: The stage in information engineering in which all executable components of a system are created. The Construction phase produces program code, database definition language, job control statements, etc. The goal is to create application systems that support an area defined during design stage (TI, 1993).

Critical Success Factor: An internal or external business-related result that is measurable and that will have a major influence on whether a business segment meets its goals (Martin, 1990).

CRUD Matrix: A tabular representation of the relationships between activities and entity types with an indication as to whether the type of involvement is created, read, updated, deleted, or a combination of these (paraphrase of Martin, 1990).

Data: Facts or figures from which conclusions can be inferred (Martin, 1990).

Database: A discrete collection of related records, linkages, and control data managed by one database management system (TI, 1993).

Data Architecture: Data architecture refers to the organization or design of data used by an enterprise where the emphasis is on what things are of interest. These data encompass all types including alpha/numeric, text, graphic, spatial, photographic, document image, voice, and video (FHWA, 1995).

Data Dependency: The situation where a process creates or modifies some data, which is subsequently used by some other process (Martin, 1990).

Data Flow: The movement of a data view between two objects, each being a process, procedure, data store, or external agent (Martin, 1990).

Database Management System: A software system that facilitates the creation and maintenance of a database. The DBMS also executes computer programs using the database (TI, 1993).

Data Model: A comprehensive representation of the fundamental things of relevance to the business (entity types) and their interrelationships (TI, 1993).

Decomposition: The step-by-step breakdown into increasing detail either of functions, eventually into processes, or of subject areas into entity types, or of organizational structure into organizational subunits (paraphrase of Martin, 1990).

Design: The stage in information engineering in which design project teams describe in detail the business systems that support a particular design area identified within a business area (TI, 1993).

Enterprise: An organization that exists to perform a mission and to achieve objectives. This information is typically stored in the encyclopedia (Martin, 1990).

Enterprise Information Architecture: A set of descriptive representations (models) that are relevant for describing an enterprise such that it (the enterprise) can be produced to management's requirements (quality) and maintained over the period of its useful life (change) (Zachman,1997).

Entity: A single occurrence of an item of interest (entity type) to the business and about which data can be kept. For example, John Doe might be an entity of the type CUSTOMER (TI, 1993).

Entity Relationship Diagram: A diagram representing entity types and the relationships between them, and certain properties of the relationship, especially its cardinality, optionality, and name (paraphrase of Martin, 1990).

Entity Type: A fundamental thing of relevance to the business about which facts can be kept and which is involved in associations of interest (relationships) with other entity types. Each entity type is defined in terms of its attributes, properties, and relationships (TI, 1993).

Function Decomposition: The breakdown of the activities of an enterprise into progressively increasing detail (Martin, 1990).

Function Decomposition Diagram: A structure that shows the breakdown of functions into progressively increasing detail (Martin, 1990).

Geographic Information System (GIS): A system of hardware, software, data, people, and institutional arrangements for collecting, storing, analyzing, and disseminating information about areas of the earth (Dueker and Kjerne, 1989).

Goal: A statement of an organization's medium- to long-term target or direction of development. A goal is achieved when all objectives relating to it have been achieved. Typically, goals do not have exact timetables or achievement measures associated with them (Martin, 1990).

Information Engineering: An interlocking set of formal techniques in which business models, data models, and process models are built up in a comprehensive knowledge base and are used to create and maintain information systems (Martin, 1990).

Information System: The combination of information technology, data, business procedures, and people applied to a business function, process, or activity (FHWA, 1995).

Integrated Transportation Information System: The combination of all transportation information systems developed as a single information systems architecture (FHWA, 1995).

Interaction Model: A comprehensive representation of the effects of activities on data (TI, 1993).

Management System: A systematic process, designed to assist decision makers in selecting cost-effective strategies/actions to improve the efficiency and safety of, and protect the investment in, the nation's infrastructure. A management system includes: Identification of performance measures; data collection and analysis, determination of needs, evaluation and selection of appropriate strategies/actions to address the needs, and evaluation of the effectiveness of the implemented strategies/actions (DOT 49 CFR Part 614 Management and Monitoring Systems; Interim Final Rule).

Objective: An end or target state that is achieved by accomplishing all critical success factors related to it. Objectives are short-term targets (12 to 24 months or less), with defined achievement measures (Martin, 1990).

Optionality: The characteristic of an entity relationship that describes whether it exists for all occurrences of the entity type pair or only for some (Martin, 1990).

Organizational Architecture: Organizational architecture refers to the people involved with an enterprise and to their organizational structure. The organizational structure also includes staffing-related policies, rules, and guidelines (FHWA, 1995).

Planning: The stage in information engineering in which the primary goal is to describe the enterprise, its business activities, and its overall information requirements (TI, 1993).

Procedure: A method by which one or more processes may be carried out (Martin, 1990).

Production: The stage in information engineering in which the enterprise realizes the full benefit of the application system as it executes to satisfy some portion of the business requirements identified during previous phases (TI, 1993).

Relationship: A reason (of relevance to the enterprise) why entities from one or two entity types may be associated. A named connection or association between entity types that embodies some relevant information of value to an organization (Martin, 1990).

Subject Area: A major, high-level classification of data. A group of entity types that pertains directly to a function or major topic of interest to the enterprise (Martin, 1990).

Technology Architecture: Technology architecture refers to the hardware, software, systems, methods, and standards that an enterprise uses to develop and operate computer systems. It includes computing and telecommunications equipment, operating systems, communications, and office automation software including E-mail and word processing software, methods for developing and maintaining computer systems, and enterprisewide technical standards (FHWA, 1995).

Transition: The stage in information engineering in which a newly constructed application system is installed in a production environment in an orderly manner, possibly replacing existing systems or portions of systems (TI, 1993).

Transportation Information System: A general term describing any information system used to identify, collect, store, retrieve, analyze, or distribute information used in the planning, development, operations, or deployment of transportation facilities and services (FHWA, 1995).

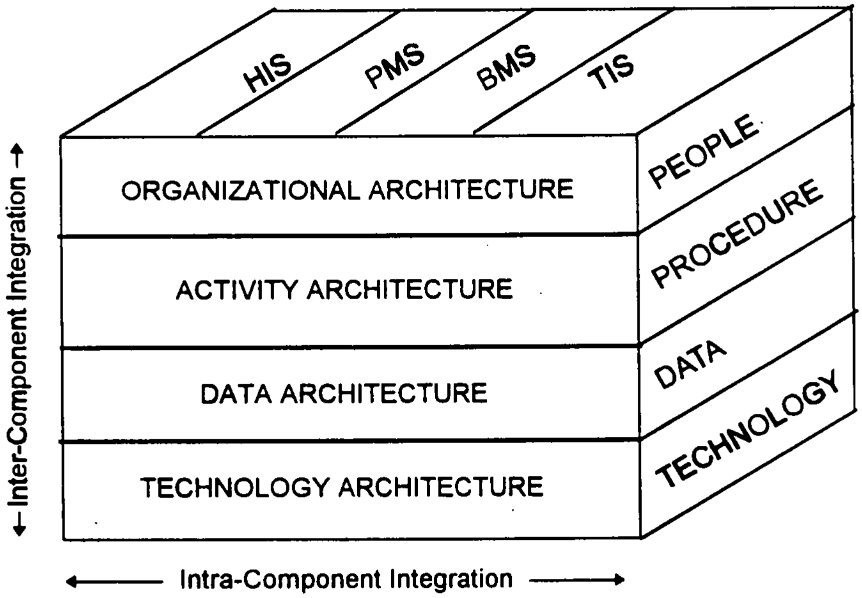
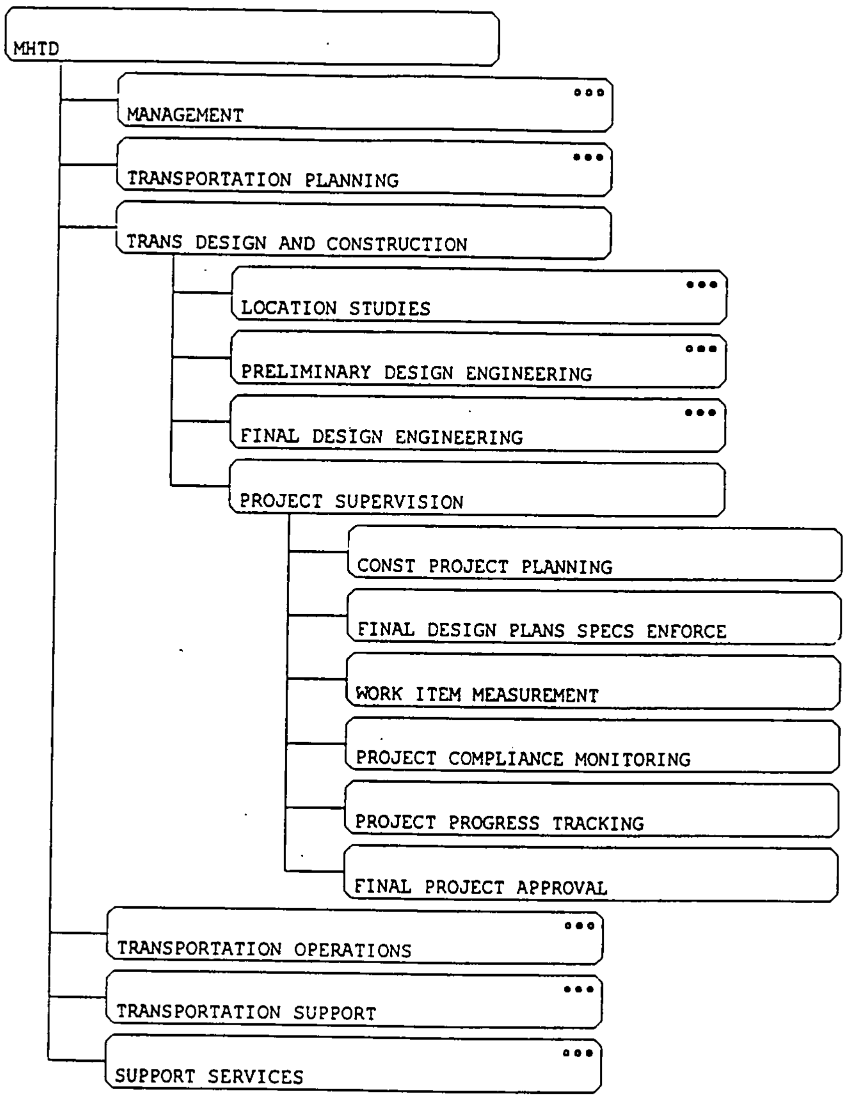


Figure 1. Enterprise information architecture and integrated information systems. (FHWA, 1995)



OOO indicates lower-level decomposition in the model

Figure 2. Missouri's activity hierarchy.

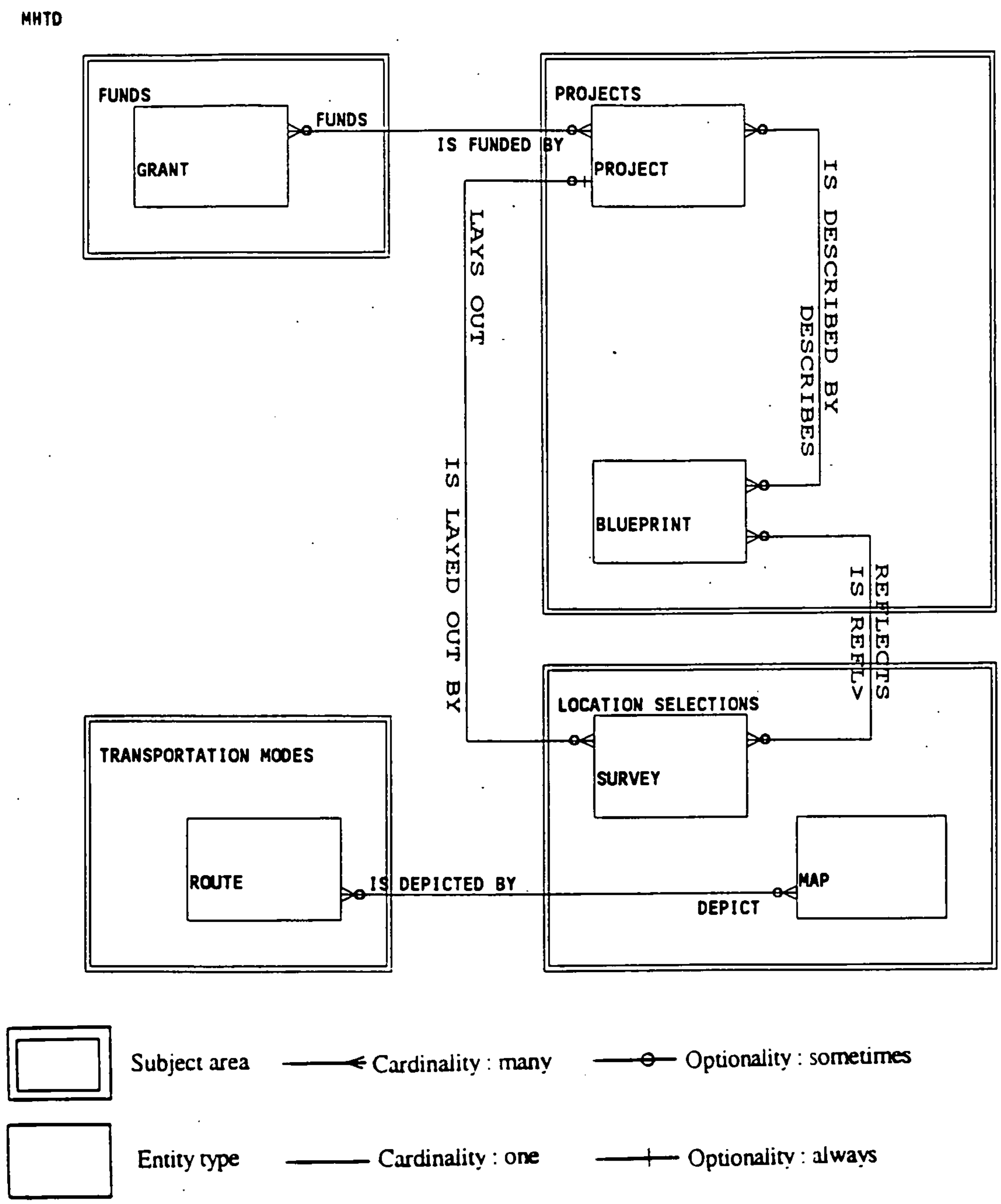


Figure 3. Part of the entity relationship diagram from Missouri Highway and Transportation Department's ISP.

Model :MHTD

Subset:ALL

Cell Values:
= Not referenced
C = Create
D = Delete
U = Update
R = Read only

Function \ Entity Type	GRANT	BLUEPRINT	PROJECT	SURVEY	ROUTE	MAP
CONST PROJECT PLANNING	R	R	U			
FINAL DESIGN PLANS SPECS ENFORCE		U	U	R		
WORK ITEM MEASUREMENT		U	U			
PROJECT COMPLIANCE MONITORING						
PROJECT PROGRESS TRACKING			U			
FINAL PROJECT APPROVAL		U	U		U	

Figure 4. Missouri's CRUD matrix showing the relationships between activities and entity types with an indication of involvement type.

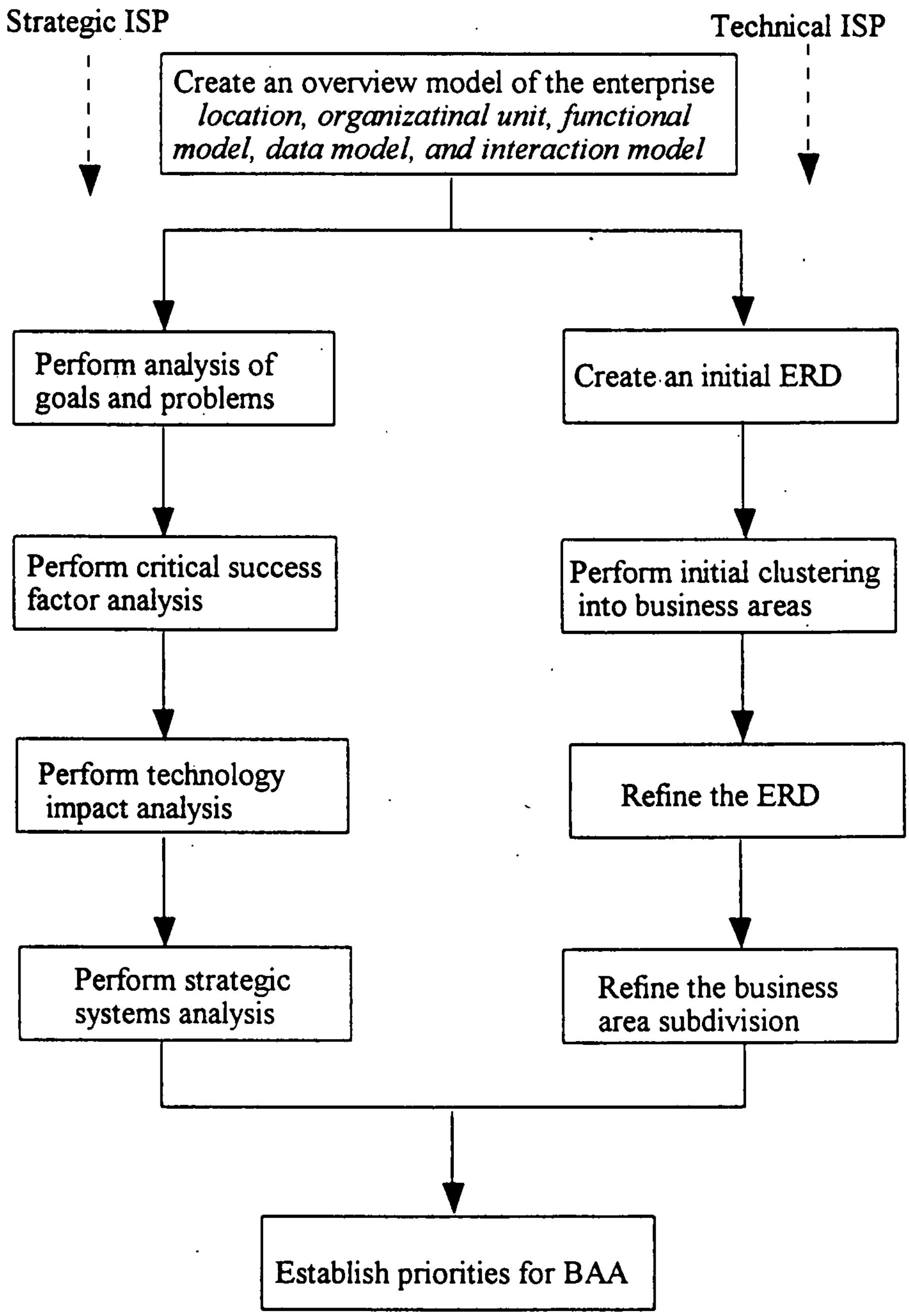


Figure 5. ISP procedures. Some can be performed concurrently. (After Martin, 1990)

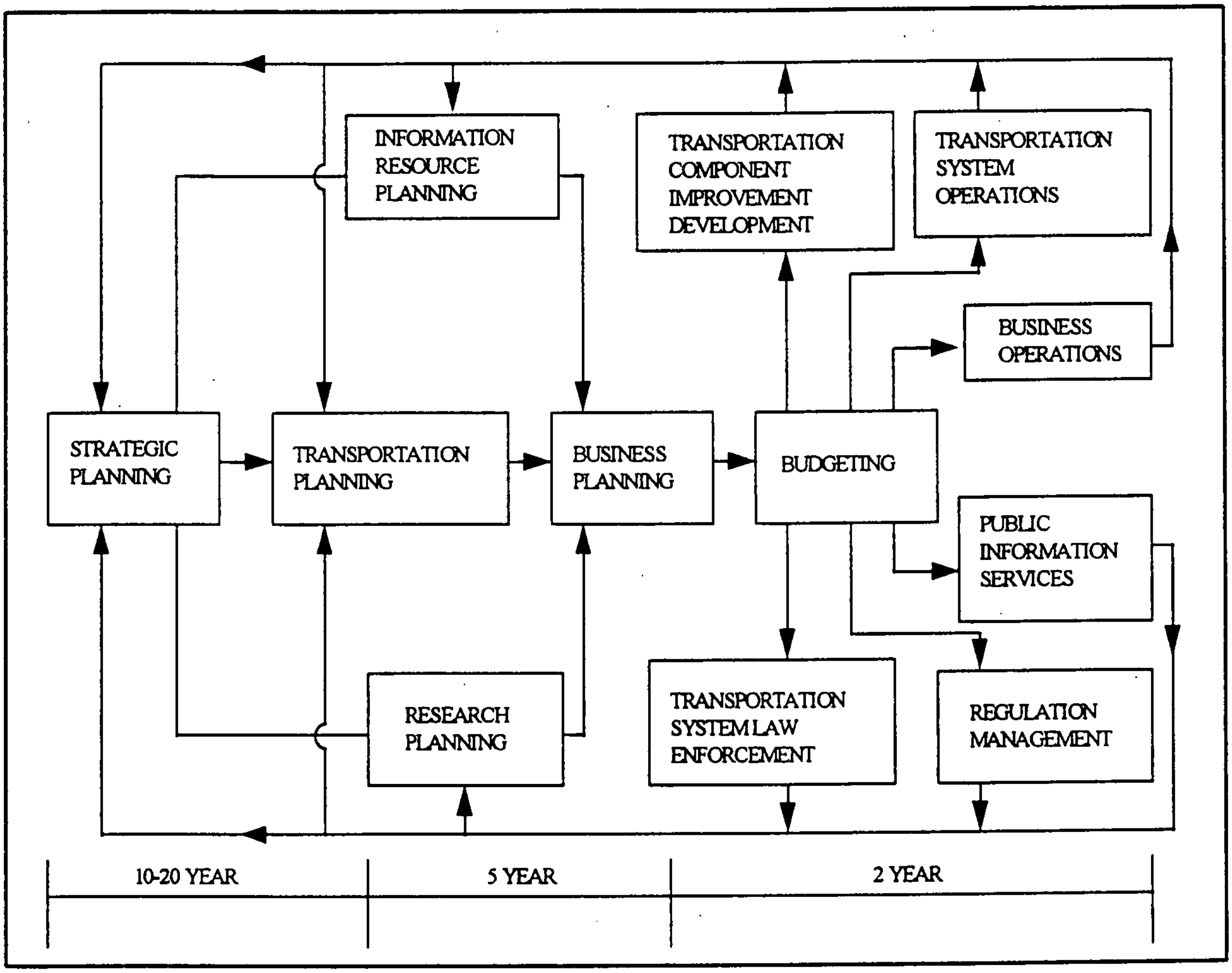


Figure 6. Resource allocation driven by planning.

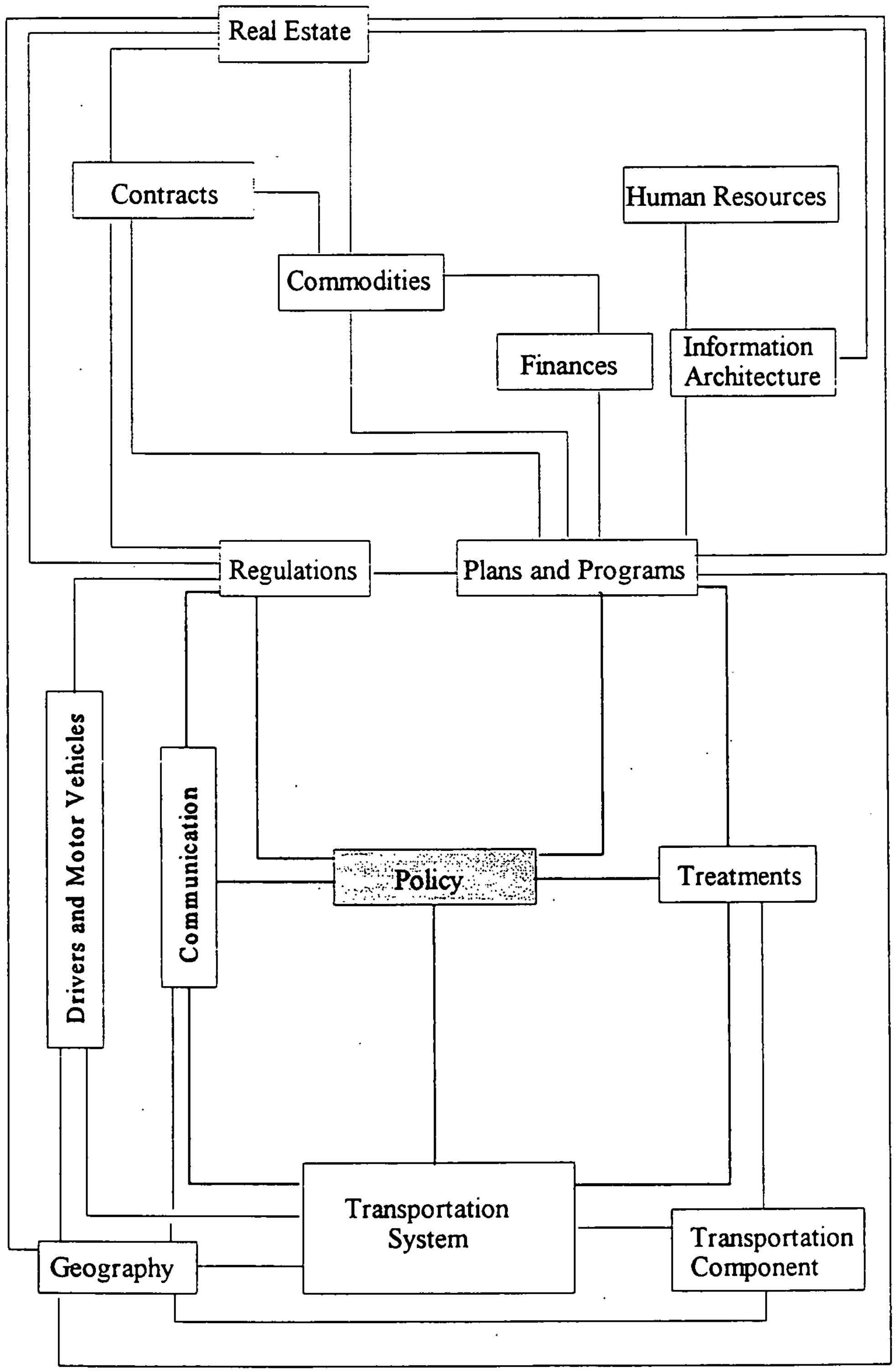


Figure 7. Subject area diagram derived by contraction of entity type relationships.

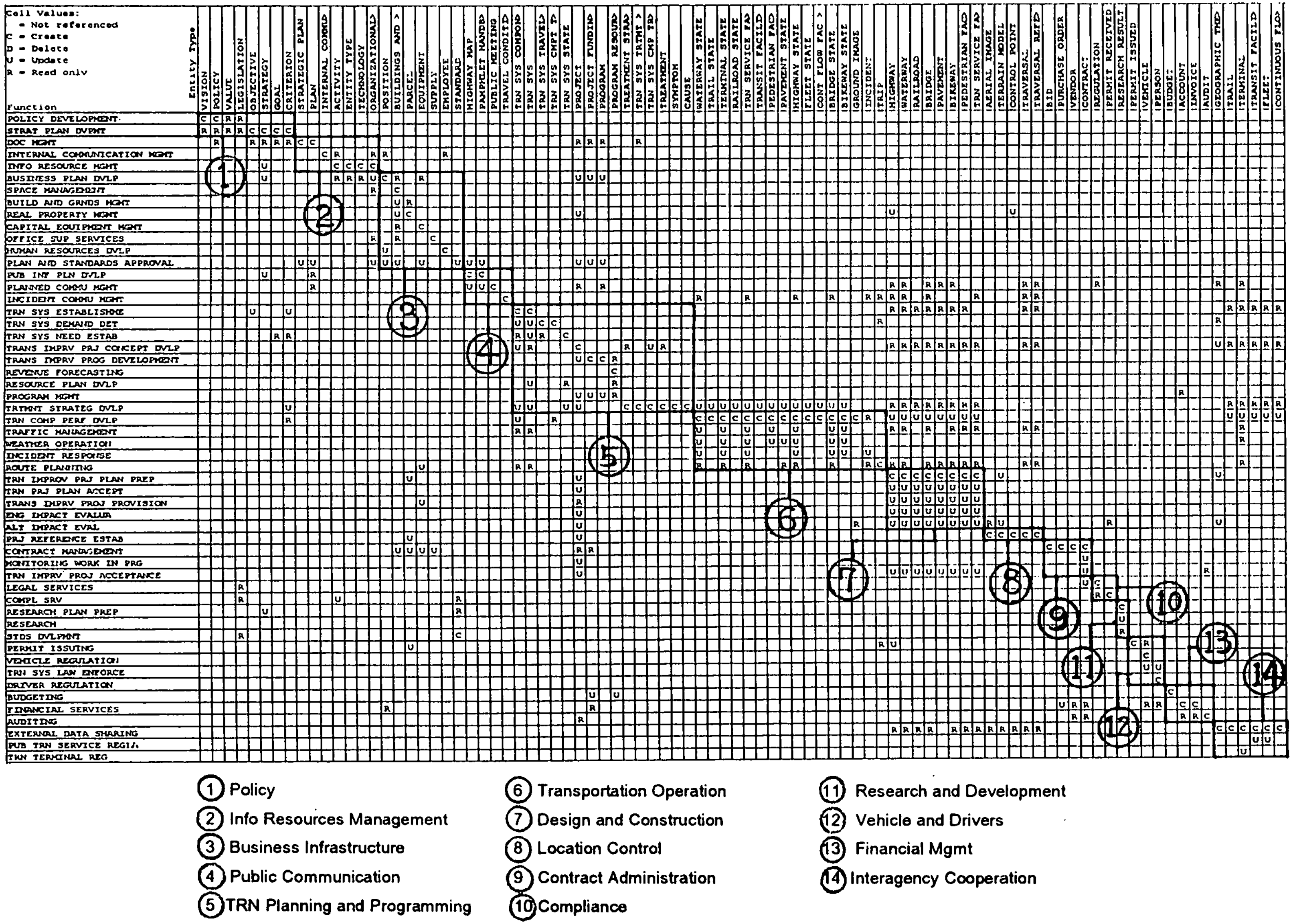


Figure 8. Clustered CRUD matrix with business areas.

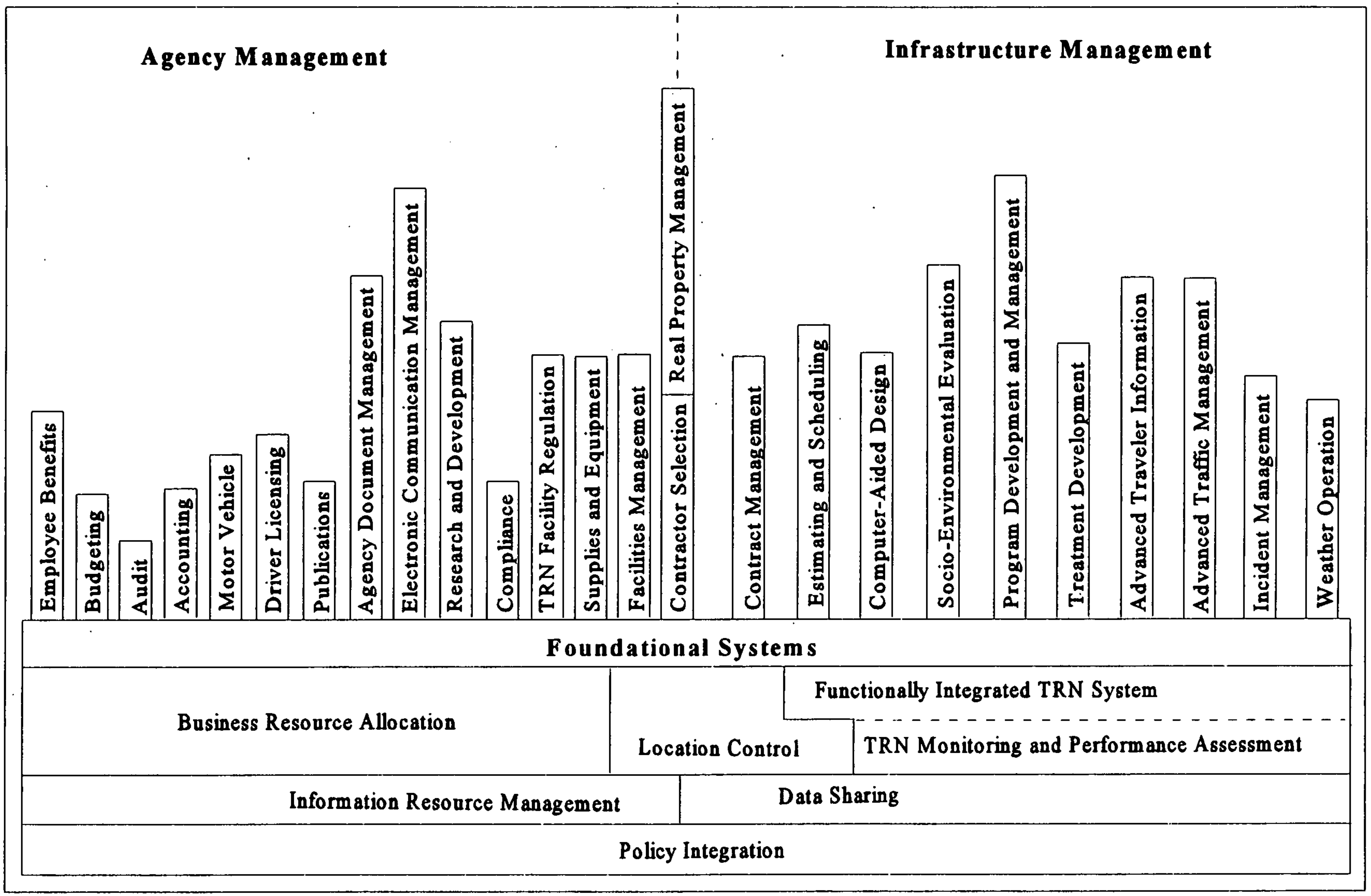


Figure 9. Business system relationships.

Cell Values:
= Not referenced
X = Include
1 2 3
4 5 6
7 8 9

SERVER / Business Svstem	SPATIAL DA>	ATTRIBUTE >	SPATIAL IM>	NONSPATIAL>	COMPLEX OB>	OVERLAY	ANALYTICAL>	USER INTER>	GIS APPLIC>	SPATIAL DA>	CARTOGRAPH>	NEW TECHNO>	GENERAL PU>	HISTORY	SPECIALIZE>
POLICY INTEGRATION	X	X				X		X			X		X		X
FUNCTIONALLY INTEGRATED TRN SYS	X	X	X	X		X	X	X			X		X	X	X
PROGRAM DVLP AND MGMT	X	X	X	X		X	X	X			X		X	X	X
TREATMENT DEVELOPMENT	X	X				X		X			X		X		X
TRN MONITORING AND PERF ASSESS	X	X				X	X	X			X		X	X	X
INFO RESOURCE MGMT								X	X				X		X
ELECTRONIC COMMUNICATION MGMT		X						X					X		
PUBLICATIONS		X		X				X					X		
ADVANCED TRAVELER INFORMATION	X	X										X			
CONTRACT MGMT	X	X			X			X					X		
LOCATION CONTROL	X		X				X	X		X	X		X		X
BUDGETING		X						X					X		
MOTOR VEHICLES		X						X					X		
FACILITIES MGMT	X	X	X		X	X	X	X			X		X		X
SUPPLIES AND EOUIPMENT	X	X						X					X		
BUSINESS RESOURCE ALLOCATION	X	X						X					X		
EMPLOYEE BENEFITS		X						X					X		
REAL PROPERTY MGMT	X	X			X			X			X		X	X	
INCIDENT MGMT	X	X				X	X	X				X			
AGENCY DOCUMENT MANAGEMENT		X		X				X					X	X	
WEATHER OPERATION		X													
ADVANCED TRAFFIC MGMT	X	X	X	X	X	X	X	X				X			X
COMPUTER AIDED DESIGN	X	X	X	X	X	X	X	X			X		X		X
ESTIMATING AND SCHEDULING	X	X			X			X					X		
SOCIO ENVIRONMENTAL EVALUATION	X	X	X	X		X	X	X			X		X	X	X
CONTRACTOR SELECTION		X						X						X	
COMPLIANCE	X	X						X							
DRIVER LICENSING		X		X										X	
AUDIT		X						X					X		
DATA SHARING	X	X	X	X	X					X					
ACCOUNTING		X						X					X	X	
TRN FACILITY REGULATION		X						X						X	
RESEARCH AND DEVELOPMENT		X						X					X		

Figure 10. Business system/server matrix.

TABLE 1 Time and cost of ISPs in Delaware, Kansas, Missouri, New York, and Utah DOTs

State DOTs	Time	Cost (dollars)	Methodology	ISP Team and Effort	Product
Delaware	1 year (Jan. 90' - Dec. 90')	90,400	From-scratch IE	1. 5-person team + 1 consultant 2. Full time first 3 months	Agencywide models
Kansas	10 months (Apr. 94' - Jan. 95')	200,000	Non-IE approach (not as rigorous as 89' plan used)	1. 7-person team + 1 consultant 2. 100 persons interviewed	No models
Missouri	6 months (Feb. 93' - Jul. 93')	115,000	From-scratch IE	1. 6-person team + 1 consultant 2. 1,700 person-hours 3. 200 people involved	Agencywide models
New York	8 months	500,000	Non-IE approach	1. 9-person team + consultants 2. 11,500 person-hours 3. 300 interviews with managers	Agencywide models
Utah	**4 months**	**75,000**	Template-based IE	1. 8-person team + 1 consultant 2. 1,000 person-hours	Highway engineering models

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