NCHRP

REPORT 460

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Guidelines for the Implementation of Multimodal Transportation Location Referencing Systems

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NCHRP REPORT 460

Guidelines for the Implementation of Multimodal Transportation Location Referencing Systems

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SUBJECT AREAS
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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

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

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

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

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

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

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FOREWORD

By Staff
Transportation Research Board

This report documents the findings of a project to develop a location referencing system (LRS) model that can be adopted by transportation agencies, geodata standards groups, and Geographic Information Systems for Transportation (GIS-T) software vendors. The contents of this report are, therefore, of immediate interest to transportation planners and to people in transportation agencies who are concerned with information systems management.

Transportation organizations constantly need to maintain, access, and share information related to multimodal transportation systems. GIS-T is increasingly used to capture, assemble, and disseminate much of this information. The results of the work performed under NCHRP Project 20-27(2), "Development of System and Application Architectures for Geographic Information Systems in Transportation," confirmed the assertion that the vast majority of transportation data are referenced to location. Moreover, the level to which transportation business data can be integrated directly depends on a robust model for location referencing. The timeliness and significance of the LRS data model developed in NCHRP Project 20-27(2) is evidenced by the application of the model in several state departments of transportation (DOTs).

Numerous efforts have shown that LRS data models vary significantly across transportation organizations and often within organizations as well (e.g., legacy data within a DOT may be based upon different LRSs). This variation has resulted in ineffective systems and even abandoned efforts as organizations attempt to implement improved transportation information systems and advanced GIS-T technology. NCHRP Projects 20-27, 20-27(2), and 20-27(3) were initiated in response to the need to provide detailed insights, functional requirements, models, and guidelines for transportation organizations. A comprehensive model for location referencing that can accommodate and integrate data expressed in one to four dimensions is necessary for a wide range of agency applications from facilities management to real-time monitoring.

The objectives of NCHRP Project 20-27(3) were to (1) establish consensus-based functional requirements for a multidimensional LRS data model for multimodal transportation systems, (2) develop an improved LRS data model, and (3) develop guidelines to implement an improved LRS data model in transportation organizations. The LRS data model should handle the functional requirements of multimodal transportation systems and should be stable and manageable over time, cost-effective to implement and maintain, and extensible to future technological innovations, including data access and visualization advancements.

A research team from the University of Wisconsin–Madison was selected to undertake this research, which began in early 1998. The research team's report presents the "next step" in the development of LRS data models in transportation by documenting and presenting a comprehensive data model that accommodates the elements necessary to use, store, operate, and share transportation-based multidimensional spatiotemporal data. The transportation multimodal, multidimensional location referencing system

(MDLRS) data model presented in this report was developed from a set of stakeholder-driven functional requirements, each based on existing research. Additionally, to facilitate interoperability of data sets, the MDLRS data model was formulated in the context of existing geospatial standards. To enable agencies to adopt the MDLRS data model or parts of it, implementation guidelines are provided. These implementation guidelines provide agencies with the basics for creating procurement documents or requests for proposals. The MDLRS data model and implementation guidelines provide the tools to support consistent location referencing across the transportation community.

CONTENTS

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Teresa M. Adams, Associate Professor of Civil and Environmental Engineering, University of Wisconsin–Madison, was the principal investigator. The other authors of this report are Alan P. Vonderohe, Professor of Civil and Environmental Engineering, University of Wisconsin–Madison, and Nicholas A. Koncz, Research Assistant, University of Wisconsin–Madison. Assistance on the project was provided by Jae-ho Choi, Kiran Manchikanti, and Janet Merlo.

SUMMARY

SUMMARY This research produced a data model that can be adopted by transportation agencies, by transportation geodata standards groups, and by Geographic Information System in Transportation (GIS-T) software vendors. The research (a) established consensus-based functional requirements for a transportation multimodal, multidimensional location referencing system (MDLRS) data model; (b) developed an MDLRS data model that meets these functional requirements; and (c) developed guidelines for implementing the MDLRS data model in transportation organizations.

Through a workshop of stakeholders, this research identified ten core functional requirements that form the essence of the MDLRS data model: spatiotemporal referencing methods, temporal referencing system/temporal datum, transformation of data sets, multiple cartographic/spatial topological representations, resolution, dynamics, historical databases, accuracy and error propagation, object-level metadata, and temporal topology/latency. A number of existing data models and standards were considered in the formulation of the MDLRS data model. None of these existing models and standards supported all of the functional requirements. However, as a group, they provided many of the building blocks for the MDLRS model.

Conceptual and logical schematics of the MDLRS were established. The conceptual model illustrates the semantics of the model as they relate to the central concepts of the transportation feature and event being referenced to systems that are based on linear and nonlinear data. To support interoperability, the logical model is expressed in unified modeling language (UML) notation. The UML local data model is in a normalized form in which object classes can be created directly from the model.

The MDLRS model uses Coordinated Universal Time (UTC) and the Gregorian calendar as the temporal datum and operates on the assumption that there is one temporal reality of a phenomenon along a timeline. Temporal relationships are used to derive temporal topology. The MDLRS model distinguishes between the spatial and temporal elements of objects. It uses scale applicability as the central notion for maintaining consistency of multiple geometric and topological representations.

CHAPTER 1

INTRODUCTION AND RESEARCH APPROACH

1.1 REPORT ORGANIZATION

This report presents and describes the transportation multimodal, multidimensional location referencing system (MDLRS) data model developed through NCHRP Project 20-27(3). The report contains four chapters, a glossary, a reference section, and an appendix.

This chapter contains a statement of the problem being addressed, in addition to the purpose, audience, objectives, and scope of this research. The remainder of this chapter provides an overview of the research approach, including the functional requirements synthesized from a transportation stakeholder's workshop, the approach used in developing the data model, and guidelines for the implementation of the data model. Additionally, the chapter includes an overview of the existing data models that were considered in formulating the MDLRS data model.

Chapter 2 presents the MDLRS data model and discusses the tools needed to understand and interpret the data model. This chapter begins with a discussion of object-oriented databases and modeling and uses object-oriented terminology and notation throughout the discussion. A high-level (i.e., conceptual) view of the data model is presented, followed by a low-level (i.e., logical) view. The logical model is described in detail through a discussion of primary classes and relationships essential for the data model. Next, the secondary classes and relationships that build on the primary classes and relationships are described. The descriptions of the components of the logical data model explain what each object class represents and how it functions.

Chapter 3 presents guidelines for interpreting and implementing the MDLRS data model. This chapter begins by explaining how the data model used existing geospatial data models to meet the functional requirements identified in Chapter 1 by transportation stakeholders. Next, each of the functional requirements is reviewed in detail. The discussion of the requirements explains how the MDLRS data model meets the functional requirements. Next, the assumptions that underlie the data model and the associated potential benefits and limitations are discussed. A structure for implementing parts of the data model, using user-specific requirements and examples, is provided. The chapter concludes with a discussion on how the data model supports the purpose of this research.

Chapter 4 describes how the MDLRS data model, as presented in Chapter 2, solves the problem identified in Chapter 1. Areas of future research and potential improvements are presented. The chapter concludes by demonstrating that this research exhibits continuity with past efforts.

Finally, the glossary defines terms and acronyms used in this report; the reference section cites sources; and the appendix lists the participants and agenda of the workshop on MDLRS functional specifications.

1.2 PROBLEM STATEMENT

The NCHRP 20-27(2) linear referencing system data model was developed in response to a growing awareness of the need to integrate increasing amounts of linearly referenced data used by the transportation community (*1*). The 20-27(2) data model includes multiple linear referencing methods, multiple cartographic representations, and multiple network representations. Data integration is supported through transformations among methods, networks, and cartographic representations by associating with a central object referred to as a "linear datum." The 20-27(2) linear referencing system data model was incorporated in the Geographic Information System in Transportation (GIS-T) Pooled Fund Study (PFS) Phase B architecture (*2*) and is being applied by several state departments of transportation (DOTs).

The focus of state DOTs is changing from planning, designing, building, and then rebuilding facilities to managing the entire lifecycle of facilities. This new focus means that DOTs are taking on the role of operating facilities. Consequently, the emerging data needs of DOTs not only include facility inventory and condition assessment, but also real-time data to support intelligent transportation systems (ITS), incident management, and driver information systems. Moreover, mandates for statewide planning and sharing of data across levels of government are broadening the scope of data requirements to include multi-organizational considerations.

Existing location referencing systems (LRSs) at the state and local levels are almost exclusively linear and highway or street oriented. The changing role and focus of DOTs, metropolitan planning organizations, and transit agencies—as well as the emergence of global positioning systems (GPS) and other spatial technologies—are driving the need for an

LRS that can accommodate and integrate data expressed in one to four dimensions. In fact, transportation agencies already manage data that are referenced in one, two, three, and four dimensions. However, these data are usually managed in incompatible ways and with technologies and databases that cannot be integrated because there is no comprehensive model for location referencing aspects of the data. For example, most GIS-T spatial databases consist of two-dimensional chains whose vertices have x,y-coordinates in some map projection referenced to North American Datum (NAD)27 or NAD83. Transportation improvement project designs are typically developed in map projection or project coordinates (for horizontal location) and in elevation (for vertical location). These horizontal and vertical location references are then integrated with engineering stationing (i.e., linear referencing) in the final designs.

Additional research is needed. LRS data models continue to vary across transportation agencies and often within organizations, as well. This variation has resulted in ineffective systems and even abandoned efforts as organizations attempt to implement improved transportation information systems and advanced GIS-T technology. Detailed functional requirements, a more comprehensive data model, and guidelines for implementation are necessary so that transportation agencies can effectively incorporate results into their operational systems.

The 20-27(2) LRS data model focused on the linearly referenced data that constitute the majority of data managed by transportation agencies. Associations between the linear datum and cartographic representations support linkages to higher dimensions. However, no further detail on data in higher dimensions was provided beyond the lines that make up a cartographic representation.

LRSs support transformations between methods. This functional requirement (i.e., “transform”) was one of four identified by the 20-27(2) workshop participants (the others were “locate,” “position,” and “place”). These requirements were identified quickly and were restricted to linear data considerations. Much more detail is needed on functional requirements for data in higher dimensions and for integration across dimensions.

Spatiotemporal representation (as in geographical information systems [GIS]) has been the subject of considerable research (*3, 4, 5, 6*). Approaches range from time stamping and versioning to incorporation of time as a metric in the specification of location. Spatiotemporal representation in GIS-T is just beginning to be addressed (*7, 8, 9, 10, 11*). An improved LRS data model must account for temporal representation.

Finally, although the 20-27(2) LRS data model meets multimodal needs for linearly referenced data, more representation of modes—such as rail, transit, and waterways—should be included in consensus-forming groups for an improved model. All transportation modes manage data referenced in multiple dimensions.

1.3 MODEL PURPOSE AND INTENDED AUDIENCE

The purpose of this research effort was to develop a data model that could be adopted by transportation agencies, by transportation geodata standards groups, and by GIS-T software vendors. The strategic objective of the research was to achieve interoperability. An interoperability approach is an alternative to current stand-alone systems, which are expensive to build and maintain, and to fully integrated systems, which are too impractical to design and build (*12*).

Interoperability is “the ability for a system or components of a system to provide information portability and interapplication, cooperative process control” (*13*). Three types of interoperability are possible: procedural interoperability through data and procedures that exchange information, technical interoperability through heterogeneous software and hardware component communications, and institutional interoperability through formal relationships between transportation agencies (*12*).

The project work plan focused on obtaining information to make the multimodal, multidimensional LRS data model support procedural transportation system interoperability. The model results reflect input from the GIS-T software vendor community, although technical interoperability was not a direct focus. The model includes input from other institutional location data modeling efforts, such as the ITS location referencing standards (*14, 15*) and the National Spatial Data Infrastructure (NSDI) Framework Transportation Identification Standard (*16*).

The benefits of interoperable geoprocessing include better integration of geodata into analyses and reports, better advantage from others’ investments in data development, less time spent manipulating data prior to use, and highly leveraged metadata efforts.

The intended audience for this report includes database developers and information systems managers in transportation agencies, GIS software vendors interested in transportation and network applications, geospatial network database developers, and researchers involved in the application of geospatial technology in transportation. This report involves the discussion of object-oriented databases and models and uses object-oriented terminology and notations throughout the discussion. It is strongly recommended that readers who are unfamiliar with object-oriented modeling carefully study Section 2.1 to get a basic understanding of the methodology and terminology used throughout this report.

1.4 RESEARCH OBJECTIVES AND SCOPE

The objectives of this research are to (a) establish consensus-based functional requirements for a multidimensional LRS data model for multimodal transportation systems, (b) develop an improved LRS data model that meets these functional requirements, and (c) develop guidelines to implement an improved LRS data model in transportation organizations.

The scope of this research is surface transportation (all modes) and four dimensions (three spatial, one temporal).

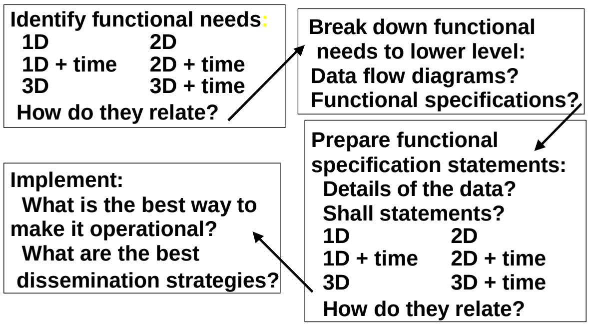
1.5 NCHRP 20-27(3) WORKSHOP

The primary objectives of the NCHRP 20-27(3) Workshop on Functional Specifications for Multimodal, Multidimensional Transportation Location Referencing Systems (held in Washington, D.C., on December 3–5, 1998) were to identify and define functional requirements of concern to the stakeholders that must be supported by a multimodal, multidimensional LRS data model. The appendix contains the list of participants and the agenda for this workshop.

Workshop participants were organized into four stakeholder groups for breakout discussions:

- Group 1—Transportation Planning, Highway Construction, and Asset Management;
- Group 2—Highway Safety and Incident Management;
- Group 3—Traffic Management and Highway Operation; and
- Group 4—Transit Facilities and Operation, Commercial Vehicles and Fleet Management.

The breakout groups were asked to identify data and functional requirements for a multimodal, multidimensional LRS data model as the data and functional requirements relate to the stakeholders. Figure 1-1 shows the four-phase activity plan for each breakout group. First, each group was asked to identify the broad needs for spatiotemporal transportation data from the perspective of the stakeholder group's business functions. Second, the groups were asked to analyze the functional needs to identify the spatiotemporal characteristics of the data needs. Third, the groups were asked to formally articulate the spatiotemporal data needs and functions. Finally, the groups were asked to discuss proactive strategies for implementation by the stakeholder group.



Note:
1D = one-dimensional.
2D = two-dimensional.
3D = three-dimensional.

Figure 1-1. Four-phase activity plan for the workshop breakout groups.

1.6 STATEMENT OF FUNCTIONAL REQUIREMENTS

Ten core functional requirements were synthesized from the results of the NCHRP 20-27(3) workshop. These core functional requirements form the essence of the MDLRS data model. The functional requirements deal with processes, attributes, or both. Section 3.2 reviews each of the functional requirements in detail. The ten functional requirements are as follows:

- **Functional Requirement I: Spatiotemporal Referencing Methods**—A comprehensive, multidimensional LRS data model must support the locate, place, and position processes for objects and events in three dimensions and time relative to the roadway.
- **Functional Requirement II: Temporal Referencing System/Temporal Datum**—A comprehensive, multidimensional LRS data model must accommodate a temporal datum that relates the database representation to the real world and must provide the domain for transformations among temporal referencing methods.
- **Functional Requirement III: Transformation of Data Sets**—A comprehensive, multidimensional LRS data model must support transformation among linear, nonlinear, and temporal referencing methods without loss of spatiotemporal accuracy, precision, and resolution.
- **Functional Requirement IV: Multiple Cartographic/Spatial Topological Representations**—A comprehensive, multidimensional LRS data model must support multiple cartographic and topological representations at both the same level and varying levels of generalization of transportation objects.
- **Functional Requirement V: Resolution**—A comprehensive, multidimensional LRS data model must support the display and analysis of objects and events at multiple spatial and temporal resolutions.
- **Functional Requirement VI: Dynamics**—A comprehensive, multidimensional LRS data model must support the navigation of objects, in near real time and contingent on various criteria, along a traversal in a transportation network.
- **Functional Requirement VII: Historical Databases**—A comprehensive, multidimensional LRS data model must support regeneration of object and network states over time and maintain the network event history.
- **Functional Requirement VIII: Accuracy and Error Propagation**—A comprehensive, multidimensional LRS data model must support association of error measures with spatiotemporal data at the object level and sup-

port propagation of those errors through analytical processes.

- **Functional Requirement IX: Object-Level Metadata**—A comprehensive, multidimensional LRS data model must store and express object-level metadata to guide general data use.
- **Functional Requirement X: Temporal Topology/ Latency**—A comprehensive, multidimensional LRS data model must support temporal relationships among objects and events and support the latency of events (i.e., the difference in time between scheduled events and actual events occurring at a particular location).

1.7 MODEL DEVELOPMENT APPROACH

Alternative strategies for developing the MDLRS data model were considered. This section describes the strategy used for formulating the MDLRS data model.

Initially, development of the MDLRS data model was to be based on the identification of deficiencies and necessary modifications to existing data models. The initial strategies for development included

- Extension of the NCHRP 20-27(2) data model,
- Synthesis of the 20-27(2) data model with selected components of existing data models, and
- Derivation of the MDLRS data model directly from the functional requirements.

The approach that was adopted combined the three strategies. The ten functional requirements and their specifications are so extensive (especially in the accommodation of space-time relationships and dependencies) that the formulation of the MDLRS model must be open, rather than strictly patterned after existing models.

The stages in formulating the MDLRS data model and the associated output of these stages are shown in Figure 1-2. The first goal was to develop fundamental concepts of space and time (e.g., temporal referencing method/system/temporal datum) using a high-level object modeling approach. The first stage's modeling sessions focused on spatiotemporal referencing methods and systems. The second stage of data modeling used these fundamental concepts to build basic components (e.g., object and event). The second-stage modeling sessions focused on cartographic and topological representation, resolution, accuracy, error propagation, and metadata. The third stage of the data model development built relationships between the basic components and extended the components' definitions to meet specific functional requirements (e.g., a conveyance object). This third stage of modeling focused on transformation of data sets, dynamics, historical databases, and temporal topology. After the conceptual model was complete, the fourth stage of data modeling developed individual objects and associations (i.e., logical model) and formulated an implementation guidelines document. At each stage, a data dictionary was compiled. The entries from this data dictionary are incorporated into the glossary of this report.

The research team is aware of the complexities of modeling space, time, and interdependencies between the two. For the MDLRS data model to be able to meet the needs of users, its foundation and construction cannot be limited to current conventions dictated by one model. The MDLRS data model builds on the strengths of existing models while avoiding the existing models' deficiencies. Concepts from existing models were adapted when there was a clear correlation between the functional requirement and the model concept.

1.8 RELATED MODELS, SPECIFICATIONS, AND STANDARDS

This section provides an overview of the existing data models considered in the formulation of the MDLRS data model.

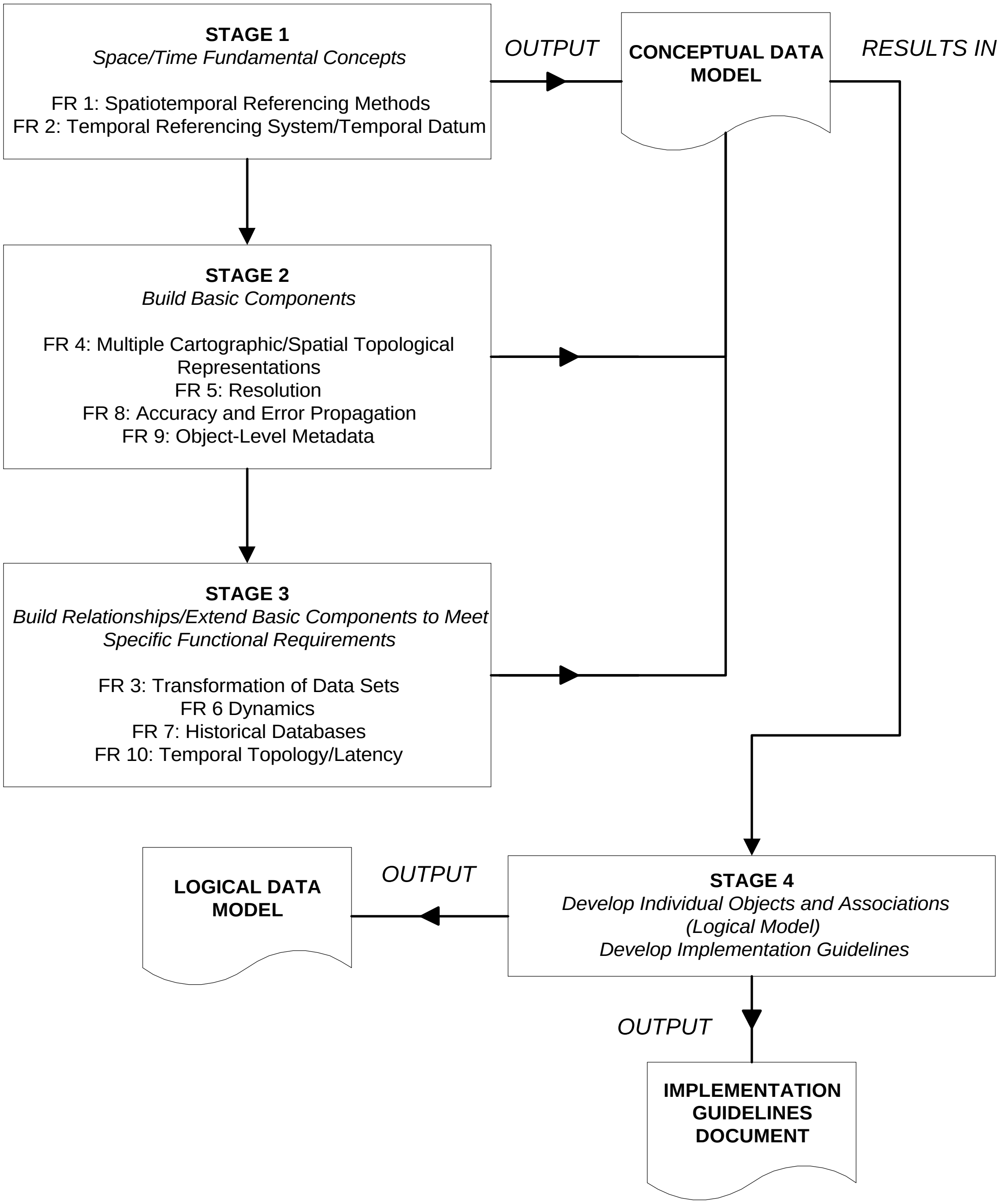
1.8.1 ISO-GDF

The International Standards Organization–Geographic Data Files (ISO-GDF) is a European standard that was developed to meet the needs of professionals and organizations involved in the creation, update, supply, and application of referenced and structured road network data (*17*). ISO-GDF is primarily used for vehicle navigation systems, but can be used for other transport and traffic applications, such as fleet management, dispatch management, highway maintenance systems, traffic analysis, traffic management, and automatic vehicle locations.

The major purpose of ISO-GDF is to improve efficiency in the capture and handling of data by providing a basic template on which applications and value-added services can be built. In addition, ISO-GDF facilitates the exchange of information by providing an exchange format. The basic foundation of the standard is a general, non–application-specific data model. In addition to this data model, a road network–specific application model has been built. Together, these models make up ISO-GDF.

1.8.2 DIGEST

The Digital Geographic Information Working Group (DGIWG) developed the Digital Geographic Information Exchange Standard (DIGEST) to support the exchange of geospatial data among producers and users (*18*). A primary objective for DIGEST is to harmonize with other international and national standards, such as the North Atlantic Treaty Organization (NATO) Secondary Imagery Format (NSIF), the



Note: FR = functional requirement.

Figure 1-2. Stages for the development of the MDLRS data model.

International Standards Organization–Technical Committee 211 (ISO TC211), the Spatial Data Transfer Standard (SDTS), and the Canadian Geomatics Interchange Standard–Spatial Archive and Interchange Format (CGIS-SAIF). DIGEST is a NATO standardization agreement (STANAG 7074). DIGEST defines data structures, format, feature coding scheme, exchange media, and administrative procedures for the exchange of digital geographic or geospatial information.

1.8.3 CGIS-SAIF

CGIS-SAIF formal definition standards were generated to share spatial and spatiotemporal geographic data. CGIS-SAIF is designed to facilitate interoperability in the context of data exchange by providing a vendor-neutral format. Some of the primary objectives of the CGIS-SAIF model (*19*) were to deal with both spatial and temporal information, to handle any kind of geographic data, to address time that temporal events and relationships can be represented, and to harmonize with other geographic standards.

1.8.4 SDTS

SDTS is a specification that serves as a national spatial data transfer mechanism for the United States (*20*). It is designed to transfer a wide variety of data structures that are used in the spatial sciences (such as cartography, geography, and geographic information systems).

SDTS specifies a structure and content for spatially referenced data in order to facilitate data transfer between dissimilar spatial database systems. SDTS specifies the data transfers from the conceptual level to the details of physical file encoding, including data quality for both vector and raster data structures. SDTS is appropriate for archive purposes because of its emphasis on self-documenting data transfers. It is also suited to blind transfers where the producer of the data is unaware of all potential data consumers.

1.8.5 ISO 15046

ISO 15046 is being prepared by the Technical Committee ISO/TC211 Geographic Information/Geomatics. ISO 15046 is a structured set of standards for information concerning objects or phenomena that are directly or indirectly associated with a location relative to the Earth (*21*). Its purpose is to provide a basis for standardization in the field of digital geographic information.

ISO 15046 specifies methods, tools, and services for data management (including definition and description), processing, analyzing, accessing, presenting, and transferring such data in electronic form between users, systems, and locations (*21*). ISO 15046 links to complementary standards for information technology and data when possible and provides a framework for developing applications using geographic data (*21*).

1.8.6 ITS Datum

The ITS Datum was developed by Oak Ridge National Laboratory and others to address the problem of location reference message exchange. The ITS Datum is “a network of reference control points that will be used to support . . . location referencing between databases of different kinds” (*22*). Some of the objectives of the ITS Datum are to support communication of location references by many location referencing methods, to provide a common spatial framework for transportation location referencing, and to support the interoperation of various spatial databases from different vendors and sources (*22*).

1.8.7 NSDI

The Draft NSDI Framework Transportation Identification Standard was prepared by the Federal Geographic Data Committee Ground Transportation Subcommittee as a component of the National Spatial Data Infrastructure Initiative (*16*). Additionally, the NSDI Framework Transportation Identification Standard was based, in large part, on the conceptual road data model developed under NCHRP Project 20-27(2) (*1*). NSDI framework data represent the best available geospatial data collected or compiled to a known level of spatial accuracy and currency, documented in accordance with established metadata standards, and made available for dissemination at little or no cost and free of restrictions on use (*16*).

NSDI was created to deal with the enforcement of topological integrity from current GIS software products; to provide a standard for the development of unique, sharable identifiers for roadway segments and segment endpoints; and to provide a national standard for the exchange of spatially based transportation data.

1.8.8 The NCHRP 20-27(2) LRS Data Model

The NCHRP 20-27(2) LRS data model was created to facilitate sharing of linearly referenced data across modes and agencies, across units and business areas internal to transportation organizations, and across applications within those units and business areas. The scope of the NCHRP 20-27(2) LRS data model is linear (although there are links to higher dimensions). The model is not intended to be comprehensive for all GIS-T location referencing; it serves as an articulation of requirements, not as a specification. It is a conceptual model requiring refinement and development of attribution prior to implementation.

1.8.9 GIS-T/ISTEA PFS

The Geographic Information Systems–Transportation/ISTEA Management Systems Server Net Prototype Pooled Fund Study was sponsored by FHWA, FTA, Sandia National Laboratories, several state DOTs, and several companies in the private sector to address management and monitoring systems, as well as statewide and metropolitan transportation planning requirements of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA).

One of the purposes of the study was to develop a system architecture for GIS-T. A component of the architecture is a set of data system models of transportation planning and project selection functions. These models are defined in Phase B of the GIS-T/ISTEA PFS (*23*). This system architecture can be used in support of the multijurisdictional, intermodal transportation facilities planning and management systems requirements.

1.8.10 GIS-T Enterprise

The GIS-T Enterprise data model was developed to address sharing of digital road map databases within and among transportation organizations by supporting all spatial and spatially referenced data, which include both linearly referenced data and non–linearly referenced data (*24*). This model encompasses a comprehensive, enterprise view of spatial and spatially referenced data. The GIS-T Enterprise model applies to all modes of transportation (e.g., aviation, highways, public transit, and railways), all map scales, all software products, and all methods of data collection (*24*).

1.8.11 National ITS Architecture

The purpose of the National ITS Architecture is to provide a common structure for ITS design to ensure system, product, and service interoperability without limiting the design options of the stakeholder (*14*). The National ITS Architecture is not a system design or a design concept. Rather, the architecture defines the framework around which multiple design approaches can be developed, each one specifically tailored to meet the individual needs of the user, while the benefits of a common architecture are maintained. For a given user service, the architecture identifies the functions (e.g., gather traffic information or request a route) that must be performed to implement the service, the physical entities or subsystems in which these functions reside (e.g., the roadside or the vehicle), the interfaces/information flows between the physical subsystems, and the communication requirements for the information flows (e.g., wireline or wireless). The National ITS Architecture provides guidelines for public agencies to prepare the request for proposals (RFP) and for the private sector to serve as the framework for responding to RFPs.

1.9 IMPLEMENTATION GUIDELINES APPROACH OVERVIEW

The implementation guidelines provided in this report enable agencies to adopt the MDLRS data model or parts of it. The implementation approach is to provide agencies with the basics for creating procurement documents or RFPs so that those agencies can obtain the necessary expertise for implementing the model. An RFP describes the services that are needed at a high level and the format to use. In the transportation community, the National ITS Architecture (*14*) is an excellent example of turning agency requirements into contract documents. In the National ITS Architecture, user services bundles and user services are identified. Then, for each user service, user service requirements are identified. On the basis of requirements, the logical architecture and data flows are identified. Therefore, preparing an RFP using the National ITS Architecture is a matter of pulling out elements and assembling them. The research team’s approach for implementation guidelines follows this concept. The guidelines for the implementation of the MDLRS data model are presented in Chapter 3.

CHAPTER 2

FINDINGS

2.1 MODELING LANGUAGE

This section provides a background for the reader on the modeling notation used in the MDLRS data model. It explains why the selected notation was used and briefly discusses key concepts behind the modeling notation. Finally, this section presents specific notation needed to understand the MDLRS data model.

2.1.1 Motivation for Object-Oriented Methodology

Data models are a simplification of reality and are a central part of all the activities that lead up to the deployment of good software. Data models help to visualize a system, specify the behavior of the system, provide a template for constructing the system, and document decisions made. Alternative data modeling choices include an object-oriented approach, using an object model or the traditional relational approach, which uses a variant of the entity-relationship (ER) model (*25*). Some of the benefits of using an object model approach are the following (adapted from Fletcher, Henderson, and Espinoza [*2*]):

- **Natural description:** The components representing complex phenomena are easily described as objects with associated operations and functionality.
- **Flexibility:** An object data model is adaptable to organizations in a particular field and is adaptable across many technologies. This flexibility is provided by the richer modeling constructs and concepts, such as inheritance and aggregation, found in object-oriented technology.
- **Reuse of other work:** Elements of other research can be incorporated more easily when using object models.

Advantages of using an object model in a spatiotemporal database are the following (*26*):

- The complete history of an entity can be encapsulated into one single object.
- Because the complete history of an entity can be represented as a single object, queries do not consider the dispersion of the entity over many tuples. Thus, queries have become less complicated.
- Because complex object queries are executed efficiently, the corresponding temporal data will probably be handled efficiently, as well.
- Handling of temporal and nontemporal data can be accomplished in a uniform way.

Several geospatial object data models exist in the transportation arena and internationally. Two prominent transportation-based data models use an object model approach: the NCHRP 20-27(2) linear reference model (*1*) and the GIS-T/ISTEA PFS model (*2*). International geospatial object data models include the CGIS-SAIF model (*19*) and the ISO 15046 model (*21*), both of which incorporate a temporal element.

Given the availability of existing geospatial object models on which to build a new model and the benefits of an object model, object modeling was selected for the MDLRS data model. This object model can be used with an object-oriented methodology for software design and development.

2.1.2 Key Concepts in Object-Oriented Modeling

Martin and Odell describe the object-oriented approach as follows: “[It models] the world in terms of objects that have properties and behaviors, and events that trigger the operations that change the state of the objects. Objects interact formally with other objects” (*27*). The foundation of object-oriented technology is formed by several key ideas, such as abstraction, encapsulation, and inheritance.

2.1.2.1 Abstraction

The goal of abstraction is to isolate aspects that are important for some purpose and suppress or ignore aspects that are unimportant (*28*). The level of abstraction indicates what level of detail is needed to accomplish a purpose. For example, on a small scale, a roadway network may be presented as a series of line segments, but on a large scale, the roadway network may be presented showing medians, edges of roadways, and roadway fixtures.

In object-oriented methodology, an object class defines an instance of an object. An object class can be thought of as the blueprint of an object or as a category of objects, with common attributes, operations, and relationships (*28*). Objects are specific examples or instances of a category class that can be tangible (e.g., the Brooklyn Bridge) or intangible (e.g., the North American Vertical Datum [NAVD] 88 Geoid) and are distinct from one another.

2.1.2.2 Encapsulation

Encapsulation consists of separating the external aspects of an object, which are accessible to other objects, from the internal implementation details of the object, which are hidden from other objects (*28*). The object, in effect, becomes a black box. Encapsulation allows the implementation of an object to be changed without affecting the applications that use it (*28*).

2.1.2.3 Generalization and Inheritance

Generalization is the relationship between a class and one or more refined versions of it (*28*). The class being refined is called the superclass and each refined version is called a subclass. For example, "motor vehicle" is the superclass, and "automobile" and "tractor trailer" are the subclasses. Attributes and operations common to a group of subclasses are attached to the superclass and shared by each subclass. Each subclass is said to inherit the features of its superclass. For example, the automobile class inherits attributes such as manufacturer, model, color, and transmission type from the motor vehicle class. Generalization is called an "is-a" relationship because each instance of a subclass "is a[n]" instance of the superclass, as well. Inheritance is analogous to creating a new house blueprint from an existing blueprint that has similar characteristics. The primary purpose for inheritance is software reuse and consistency (*29*).

2.1.3 Object-Oriented Notation

The object model used for the MDLRS data model is built using the unified modeling language (UML) specification (*30*), an accepted industry object-oriented modeling notation. UML is a successor of the object-modeling technique described by Rumbaugh et al. (*28*) and employed by existing transportation models (NCHRP 20-27[2] and the GIS-T/ISTEA PFS model). This section discusses the object-modeling concepts that are needed to understand the MDLRS data model. Booch, Rumbaugh, and Jacobson provide a more complete description of the UML specification (*30*).

2.1.3.1 Objects and Classes

An object class represents a group of objects with common operations, attributes, and relationships (*2*). An object is a specific instance of a class. Objects are typically nouns in the problem statement document. Each object can have attributes and operations. An attribute is a data value held by objects in a class (*28*). An operation is a function that may be applied to or by objects in a class.

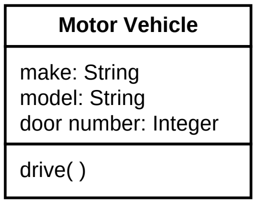
Using UML notation, a class is represented by a box that may have four sections. The sections contain, from top to bottom, the following: class name, list of attributes, list of operations, and list of responsibilities (i.e., a text note on the behavior of the class). Figure 2-1 shows an example of a class diagram with attributes and operations.

2.1.3.2 Associations

An association is a structural relationship specifying that object classes or instances are connected to other objects. Associations are indicated by single lines connecting object/class boxes (*30*). Figure 2-2 shows an example of a binary association taken from the NCHRP 20-27(2) generic data model. Figure 2-2 shows that a point event references one and only one traversal reference point. "References" is the name of the association (i.e., relationship) connecting the point event object and the traversal reference point object.

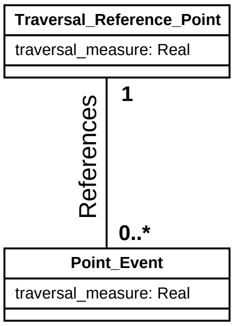
An association that has classlike properties—such as attributes, operations, and other associations—is designated as an "association class" (*30*). An association class is shown as a class symbol attached by a dashed line to an association (*30*). Figure 2-3 shows an example of an association class taken from the NCHRP 20-27(2) generic data model. Figure 2-3 shows that a line can represent zero or more anchor sections and an anchor section can be represented by zero or more lines. The association class "represents" between the line and anchor section objects has "from position" and "to position" attributes (*1*).

Multiplicity specifies how many instances of one class may relate to a single instance of an associated class (*28*). A multiplicity specification is shown as a text string of integer intervals in the format *lower-bound . . upper-bound* (*30*). Figure 2-4 illustrates the UML notation for multiplicity.



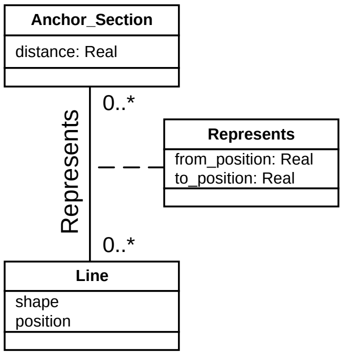
Note: Diagram modeled after D. Fletcher, T. Henderson, and J. Espinoza, "Geographic Information Systems–Transportation ISTEA Management Systems Server—Net Prototype Pooled Fund Study Phase B Summary" (Albuquerque, New Mexico: Sandia National Laboratory, 1995).

Figure 2-1. Example of class diagram with attributes and operations.



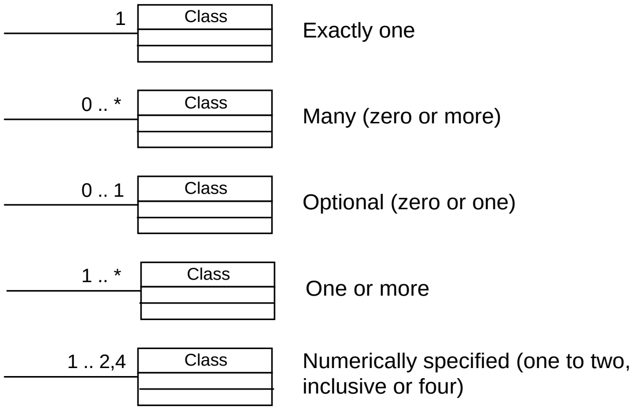
Note: Relationship modeled after A.P. Vonderohe, C.L. Chou, F. Sun, and T.M. Adams, "A Generic Data Model for Linear Referencing Systems," *NCHRP Research Results Digest 218* (Washington, D.C.: Transportation Research Board, National Research Council, 1997).

Figure 2-2. Example of a relationship.



Note: Relationship modeled after A.P. Vonderohe, C.L. Chou, F. Sun, and T.M. Adams, "A Generic Data Model for Linear Referencing Systems," *NCHRP Research Results Digest 218* (Washington, D.C.: Transportation Research Board, National Research Council, 1997).

Figure 2-3. Example of an association.



Note: Multiplicity modeled after G. Booch, J. Rumbaugh, and I. Jacobson, *The Unified Modeling Language Users Guide* (Reading, Massachusetts: Addison-Wesley, 1999).

Figure 2-4. Multiplicity of relationships.

2.1.3.3 Aggregation

Aggregation is a special type of relationship, in which objects representing the components of something are associated with an object representing the entire assembly (*28*). Aggregation is an "a-part-of" or "has-a" relationship, drawn like a relationship, except a small diamond indicates the assembly end of the relationship. Figure 2-5 shows an example of aggregation. A company is made up of many divisions, each of which is composed of many departments (*28*).

2.1.3.4 Generalization

Generalization is the relationship between a more general class, called a superclass, and one or more specific versions of that class, called subclasses (*2*). Generalization has been called an "is-a" relationship because each instance of a subclass is an instance of the superclass, as well (*28*). Graphically, generalization is shown as a solid directed line with a large open arrowhead pointing toward the parent (*30*). Figure 2-6 shows the motor vehicle hierarchy, in which an electric powered automobile (subclass) "is-a[n]" automobile (superclass), and in which an automobile (subclass) "is-a" motor vehicle (superclass).

2.2 THE CONCEPTUAL MODEL

2.2.1 Introduction

This section presents the conceptual data model for MDLRSs and describes the meaning of objects and relationships in the model.

2.2.2 Purpose of the Conceptual Model

To communicate about phenomena in the real world, it is necessary to describe phenomena at the conceptual level (*31*). At the conceptual level, the real world is represented as an abstraction. A conceptual data model, then, is independent of implementation details and expresses the structure of the information, such as the types of data and their interrelationships (*32*). The main objective in conceptual data modeling is to represent an application domain—in a manner that is understandable to the user, is complete, and does not require

Note: Aggregation modeled after J. Rumbaugh, M. Blaha, W. Premerlani, F. Eddy, and W. Lorensen, *Object-Oriented Modeling and Design* (Englewood Cliffs, New Jersey: Prentice Hall, 1991).

Figure 2-5. Example of aggregation.

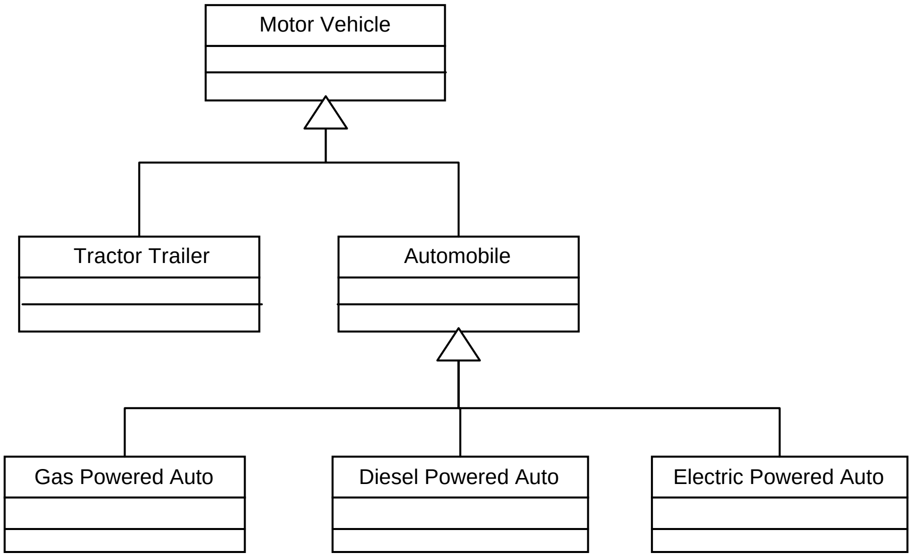


Figure 2-6. Example of generalization.

any computer metaphors—so that this representation can be translated into a corresponding logical schema without any further user input (*33*).

The result of conceptual data modeling is a semantic (or conceptual) schema—that is, a diagram that uses the notation or grammar of the chosen conceptual data model to capture the desired aspects of the reality modeled at a high level of abstraction (*33*). The notation used for conceptual modeling is performed using one of several variants of the ER model (*25*) or semantic models as semantic data modeling (*34*) or using object-oriented software design tools like object-modeling technique (*28*) and UML (*30*). The object-oriented approach uses elements from the ER model, as well as from the data flow diagram model (*31*). The most widely used object-oriented notation currently for data modeling is UML (*30*).

2.2.3 Conceptual Data Model for MDLRSs

The MDLRS conceptual data model is presented in Figures 2-7 and 2-8 and uses a variant of the ER model (*25*). Each ellipse represents a concept. Lines between ellipses represent relationships between concepts.

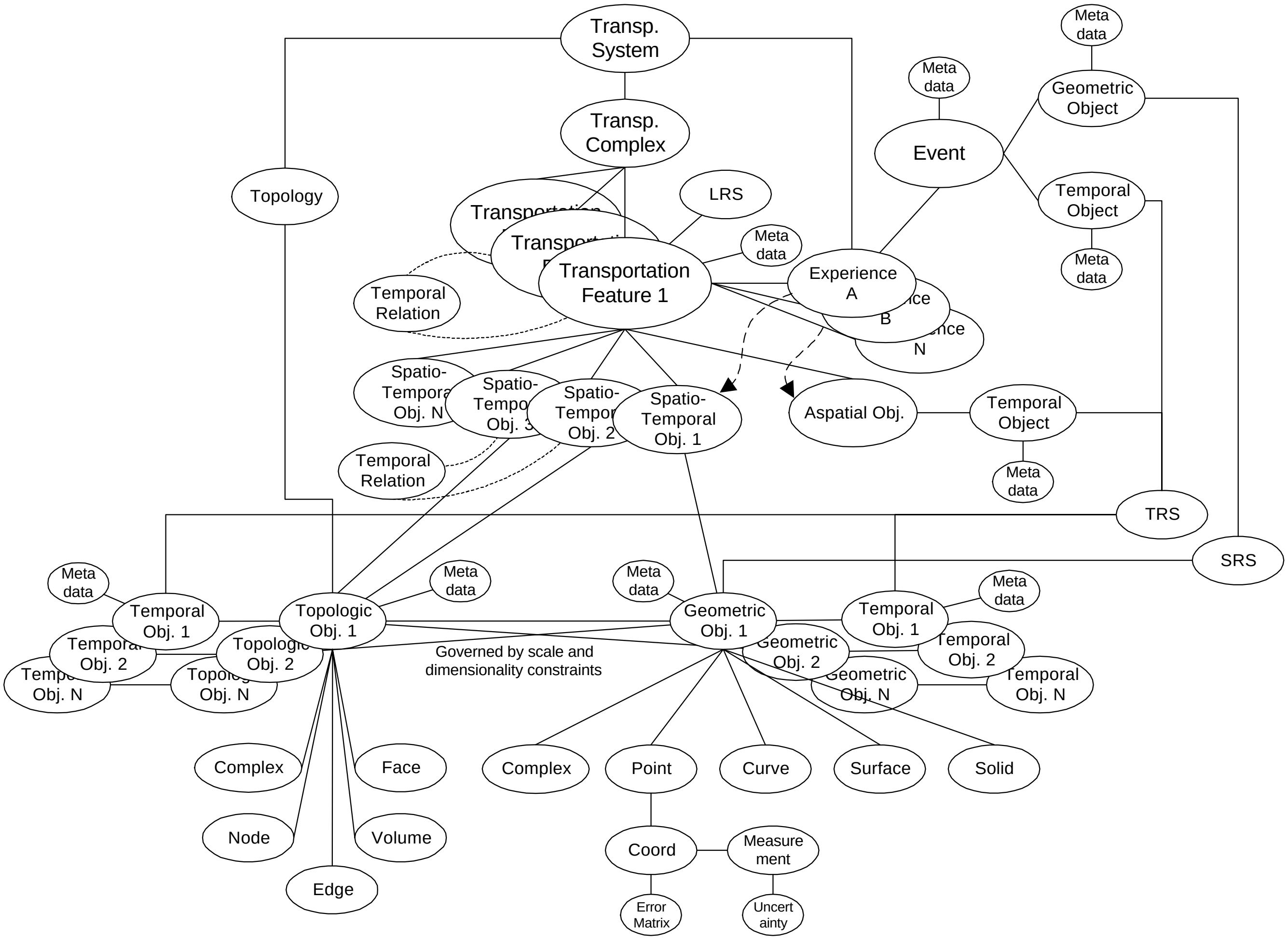
In Figure 2-7, the central concept is "transportation feature." A transportation feature is an object representing a real-world or virtual phenomenon that exists in a spatial or spatiotemporal transportation domain. This feature has associated metadata that describe its source. The transportation feature has aspatial objects (i.e., attributes) that may be associated with a temporal object (e.g., the operating period of a high-occupancy vehicle [HOV] lane). The temporal object has metadata that describe its source and lineage and is referenced by a temporal referencing system (TRS).

The transportation feature comprises one or more spatiotemporal objects. These spatiotemporal objects are represented as topological or geometric objects that are valid for a period and a certain scale. Associated with topological or geometric objects are metadata that describe their source, history, and quality. Topological objects can be a node (zero-dimensional), an edge (one-dimensional), a face (two-dimensional), a volume (three-dimensional), or a complex. Geometric objects can be a point (zero-dimensional), a curve (one-dimensional), a surface (two-dimensional), a solid (three-dimensional), or a complex and are referenced to a nonlinear spatial referencing system (SRS).

A topological object can be associated with one or more geometric objects and constrained by the attribute "scale applicability" and, optionally, by business rules that govern dimensionality. Likewise, a geometric object can be associated with one or more topological objects with similar constraints.

Associated with a point is a coordinate consistent with the SRS. If the coordinate is derived from measurements, which contain uncertainty, the coordinate has an associated error matrix that assists in error propagation.

Events are concepts external to transportation features that alter features. An event occurs during a defined period (temporal object) at a defined location (geometric object). These temporal and geometric objects are referenced to TRSs and SRSs, respectively. An event that causes changes—spatially, aspatially, or temporally—to a specific transportation feature is called an experience. The experience concept is the historic registry in the transportation feature and indicates which events cause changes to the feature. An example of an event is a "crash," while "damage" is the vehicle's experience of that "crash" (*35*). Over time, the transportation feature participates



Note:
TRS = temporal referencing system.
SRS = spatial referencing system.

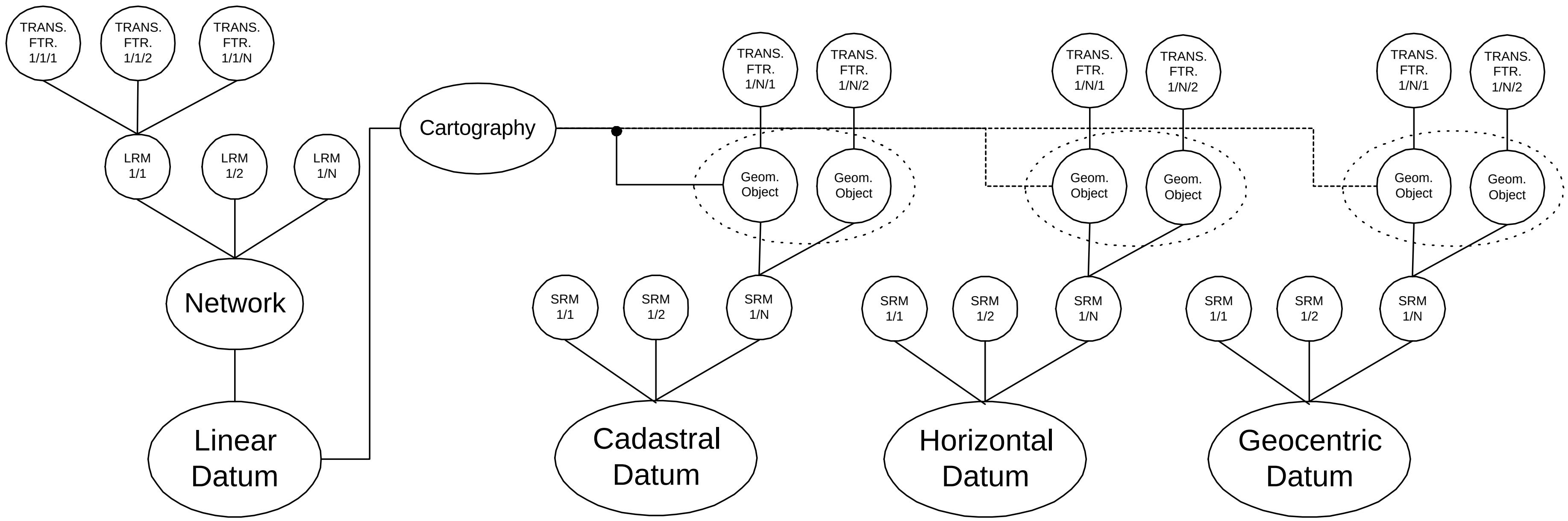
Figure 2-7. Conceptual data model of a transportation feature.

in several events, producing additional experiences. The collection of experiences represents the history of the transportation feature (*2*).

Through the temporal objects associated with transportation features and their associated spatiotemporal objects, temporal relationships can be examined. Examples of temporal relationships include follows, simultaneous, during, and overlaps and can operate on concepts within a transportation feature (e.g., to find the most recent spatiotemporal object) and between transportation features (e.g., to determine if one transportation feature was created before another feature).

Collections of transportation features are called transportation complexes, and collections of transportation features and transportation complexes are called transportation systems. Transportation systems have a derived topology (network or areal), produced from aggregations of topological representations of transportation features at a certain applicable scale. Additionally, the history of the transportation system is the result of the aggregated histories or experiences of the transportation features that make up the transportation system.

Figure 2-8 shows the conceptual model of the data in the MDLRS data model. In linear referencing systems, business data (i.e., transportation features) are referenced to a linear referencing method. Each linear referencing method is referenced to a network that is tied to a linear datum composed of anchor points and anchor sections. In a linear referencing system, a cartographic representation can be mapped to a linear datum. In nonlinear referencing systems (e.g., geocentric, horizontal, or cadastral), business data (i.e., transportation features) have one or more geometric representations (i.e., geometric objects) that reference a spatial referencing method composed of reference objects (e.g., GPS satellites, control stations, and corner points). These reference objects are tied to the datum through datum objects (e.g., three-dimensional



Note:
LRM = location referencing method.
N = total number of LRMs per SRM.
SRM = spatial referencing method.
TRANS. FTR. = transportation feature.

Figure 2-8. Conceptual data model of linear and nonlinear data.

Cartesian axes, ellipsoids, and corners). In the MDLRS data model, a cartographic representation comprises one or more geometric objects referenced to a nonlinear datum. To transform data between linear and nonlinear systems, the linear datum (i.e., anchor section object) has to know which geometric object it represents. Two coordinate pairs (i.e., from/to position linear and nonlinear) are needed to allow this type of transformation to occur.

The concepts shown in Figures 2-7 and 2-8 satisfy the ten functional requirements identified in Section 1.4. The requirements and their supporting MDLRS concepts are as follows:

- Functional Requirement I, "Spatiotemporal Referencing Methods," is satisfied by the coordinate concept.
- Functional Requirement II, "Temporal Referencing System/Temporal Datum," is satisfied by the TRS concept.
- Functional Requirement III, "Transformation of Data Sets," is satisfied by the relationship between linear and nonlinear datum concepts.
- Functional Requirement IV, "Multiple Cartographic/Spatial Topological Representations," is satisfied by the relationship between topological and geometric object concepts.
- Functional Requirement V, "Resolution," is satisfied by the multiplicity of spatiotemporal objects.
- Functional Requirement VI, "Dynamics," is satisfied by conveyance objects.
- Functional Requirement VII, "Historical Databases," is satisfied by the event and experience concepts.
- Functional Requirement VIII, "Accuracy and Error Propagation," is satisfied by the coordinate concept and the associated error matrix.
- Functional Requirement IX, "Object-Level Metadata," is satisfied by the metadata concept.
- Functional Requirement X, "Temporal Topology/Latency," is satisfied by the temporal relationship and temporal object concepts.

2.3 THE LOGICAL MODEL

2.3.1 Introduction

This section presents the logical data model for MDLRSs and describes the meaning of objects and relationships in the model. The intent in describing the meaning of the logical data model objects and relationships is to describe the role of each object and relationship in the overall data model (i.e., what each object does and how it interacts with other objects). In certain situations when a notable construct or relation that demands an explanation has been employed, one is given. Chapter 3 explains why certain objects and relationships were used, provides the source of the objects, and describes how the objects fit within the functional requirements.

2.3.2 Purpose of the Logical Model

A conceptual data model is independent of implementation details; instead, it expresses the structure of the information, such as the types of data and their interrelationships (*32*). The purpose of logical data modeling is to carefully define, standardize, and normalize the data elements into the entities established in the conceptual data model (*36*). These data elements are the logical facts based on stakeholders' information requirements. The logical data model tailors the conceptual data model to the particular kind of database management system on which the system will be implemented (*37*). In the case of a relational database management system, relation schemes are created from an ER diagram (*25*). The MDLRS data model is object oriented. In an object-oriented database management system, the UML object model (*30*) can be used instead of an ER diagram for conceptual and logical data modeling. The UML object model used for logical data modeling is in a normalized form in which object classes can be created directly from the model.

2.3.3 Logical Data Model for MDLRSs

The MDLRS logical data model is presented in Figures 2-9 through 2-14. These figures use the UML notation as described by Booch, Rumbaugh, and Jacobson (*30*) and explained in Section 2.1.3.

Figure 2-9 provides a high-level view of the MDLRS data model. The central object is the transportation feature. The transportation feature contains attributes that describe aspatial data and is associated with one or more spatiotemporal objects. Spatial and time (i.e., temporal) objects are referenced to SRSs and a TRS. Events alter transportation features through experiences. Temporal relationship objects allow for various types of temporal queries to occur. A type of moving transportation feature is a conveyance, which moves along a collection of transport links for a duration. That collection represents the time-dependent route, or traversal, that the conveyance takes to go from an origin to a destination. A collection of conveyances is called a fleet.

Figure 2-10 provides a low-level hierarchy of transportation features and the objects resulting from aggregations of transportation features. A transportation feature can be "point" based (e.g., transport node), "linearly" based (e.g., transport link), "areally" based (e.g., parking lot), or moving (e.g., conveyance). The transportation feature hierarchy shows the subclasses of the transportation feature superclass. Each transportation feature subclass "is a" transportation feature, but has additional functionality. Collections of transportation features are called transportation complexes, and collections of transportation features and transportation complexes are called transportation systems. Because transportation systems are aggregations of transportation features, they derive their topology and history through the topological objects and experiences of the aggregated features, respectively.

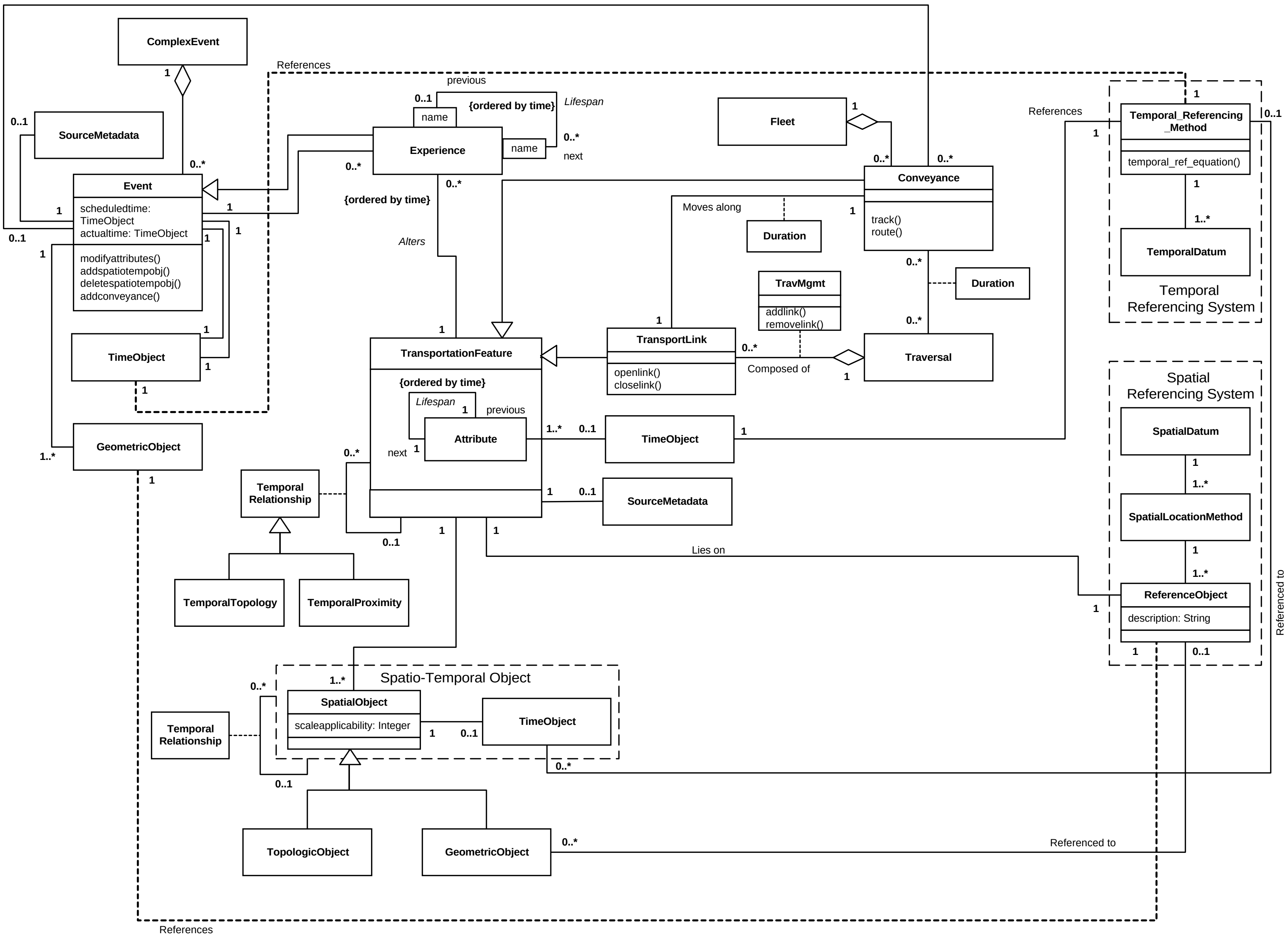


Figure 2-9. High-level view of MDLRS data model.

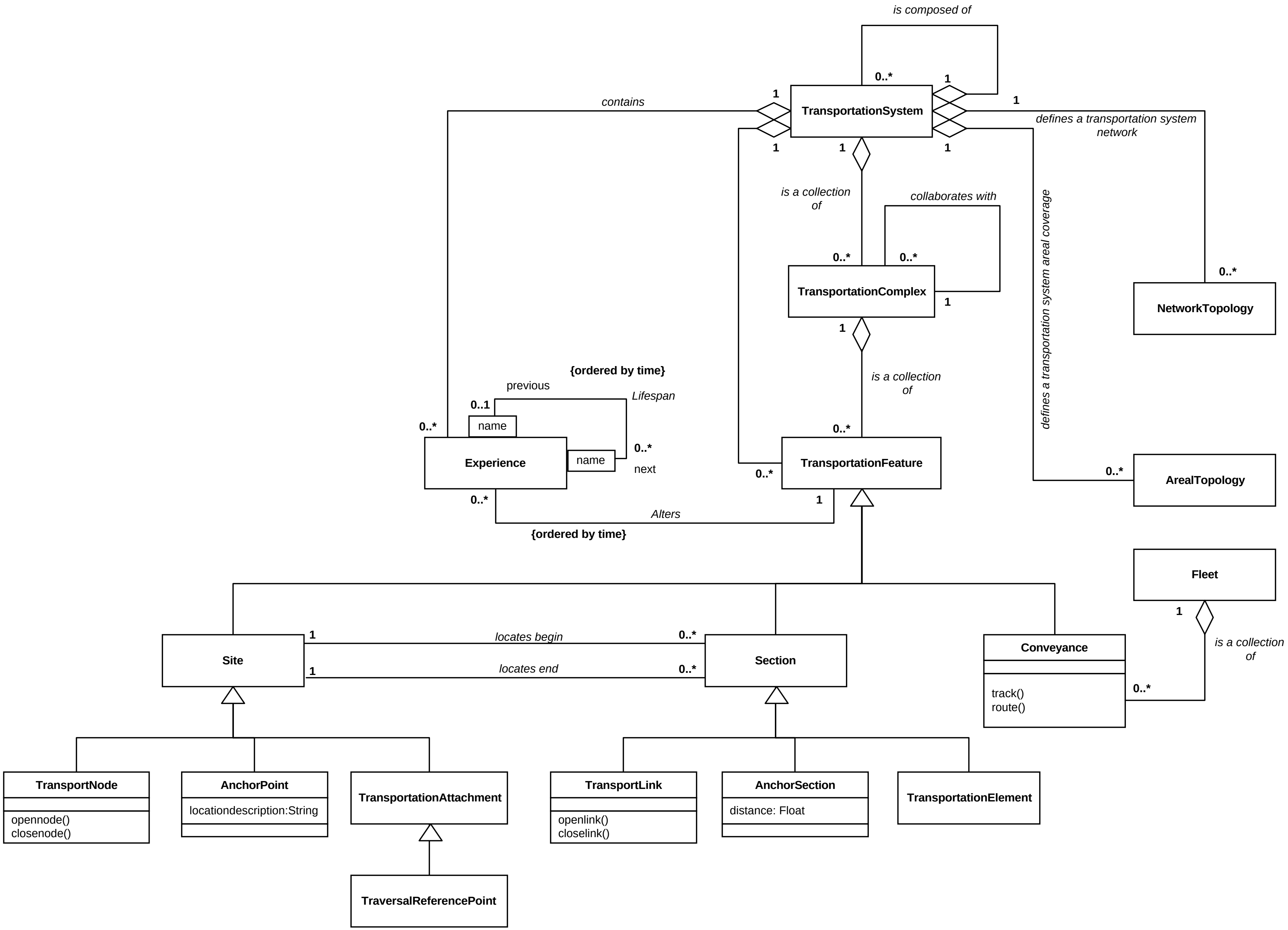


Figure 2-10. Transportation feature hierarchy.

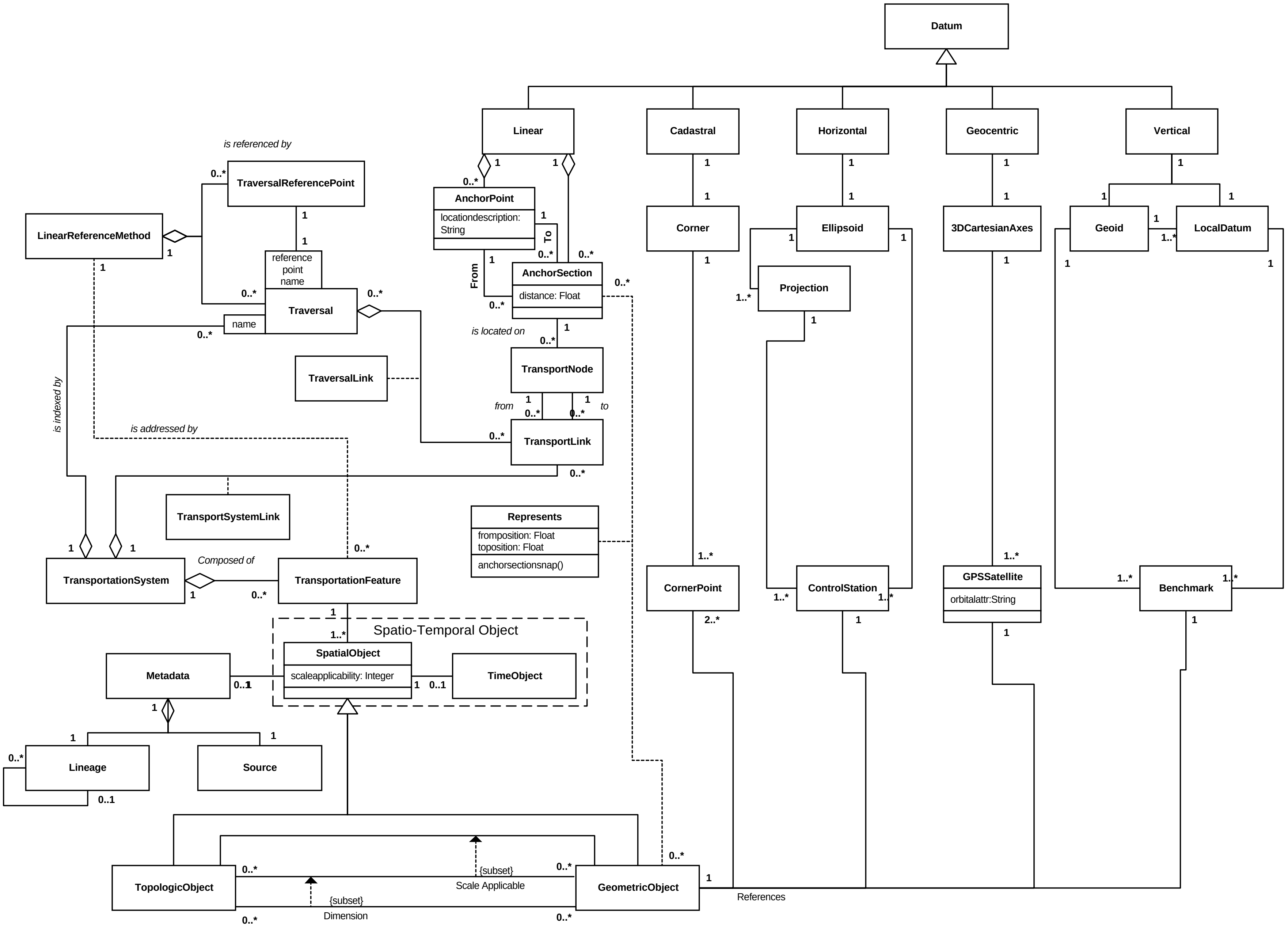


Figure 2-11. Spatial referencing system constructs.

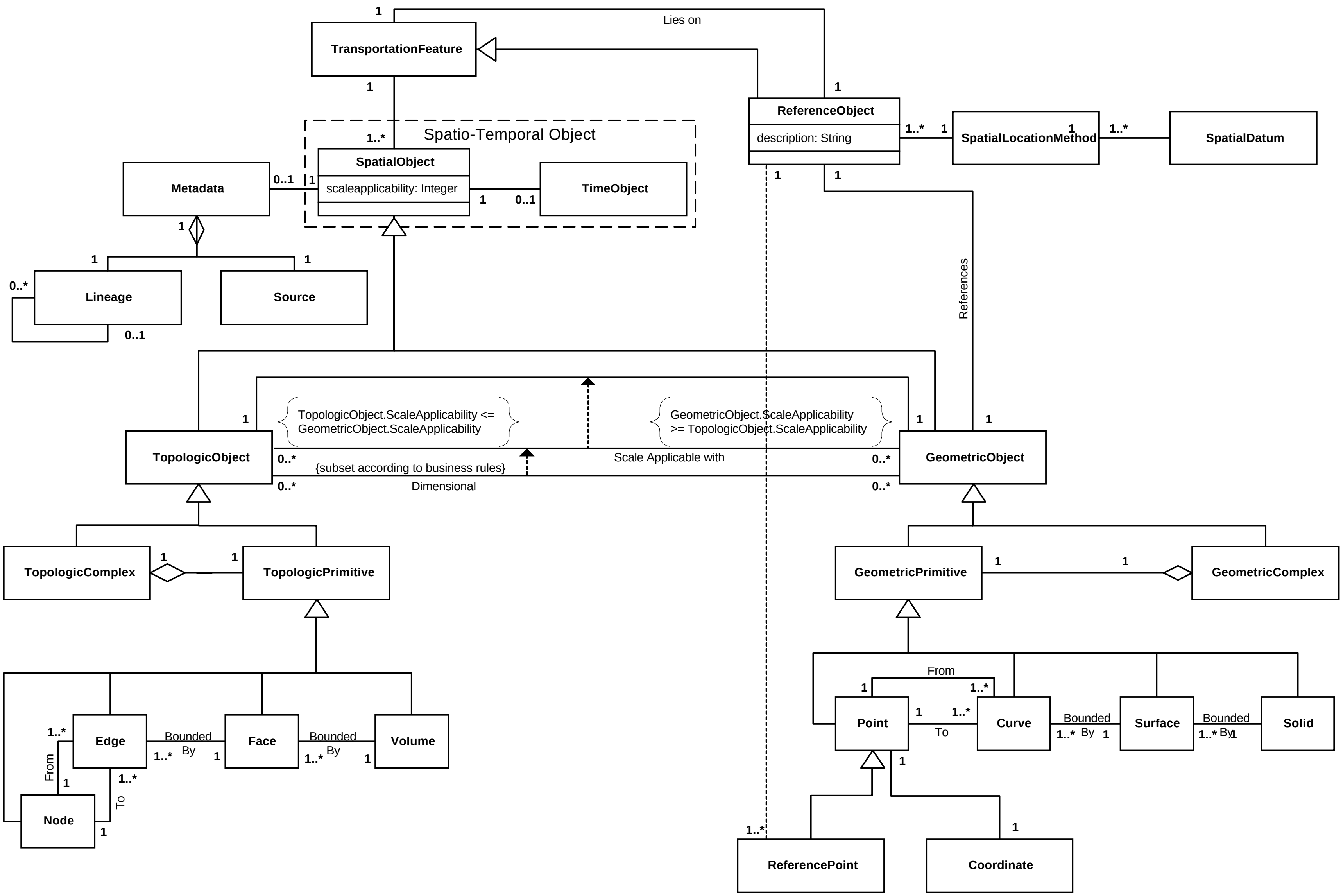
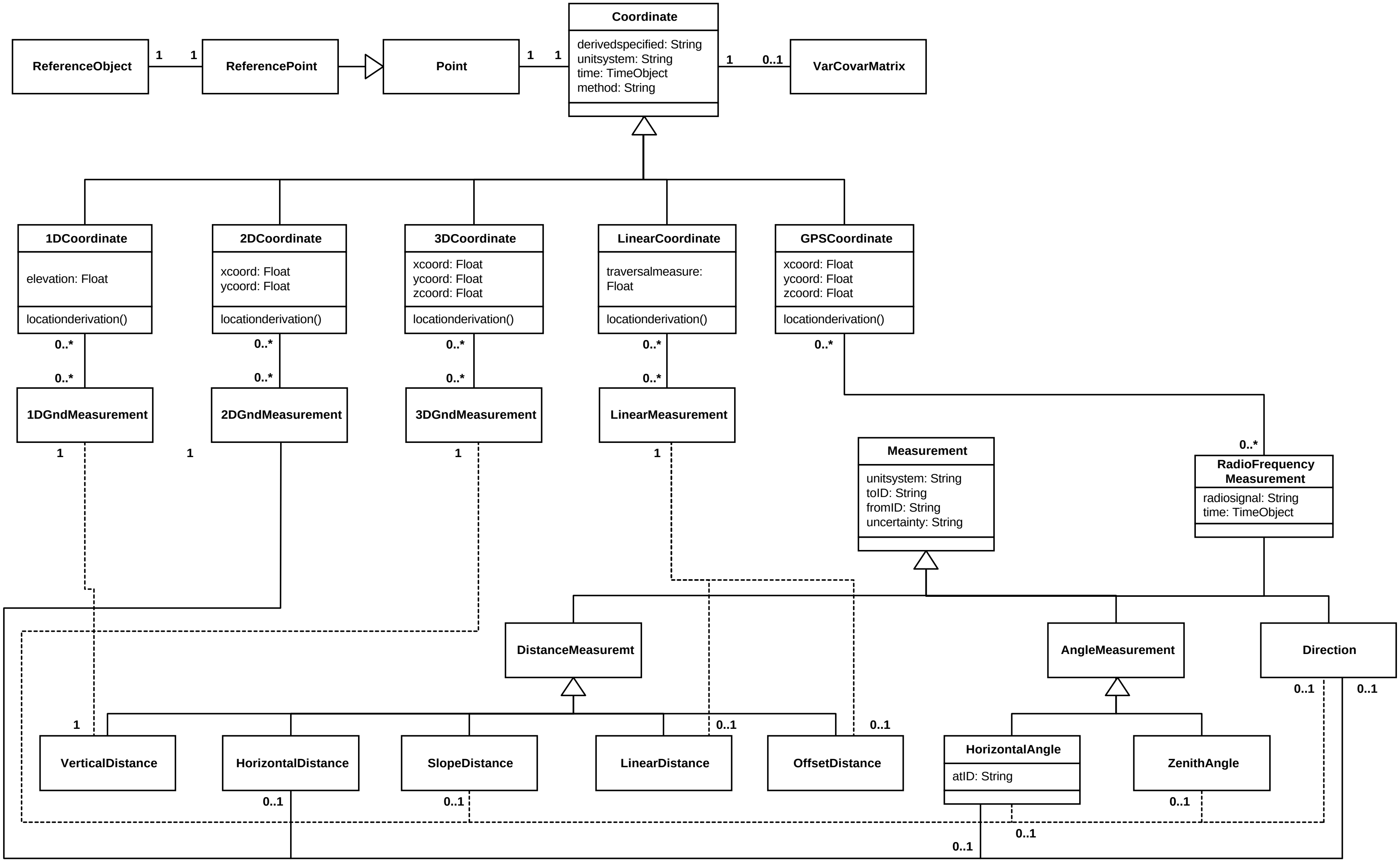


Figure 2-12. Spatial object constructs.



Note:
1D = one-dimensional.
2D = two-dimensional.
3D = three-dimensional.
Gnd = ground.

Figure 2-13. *Coordinate and measurement constructs.*

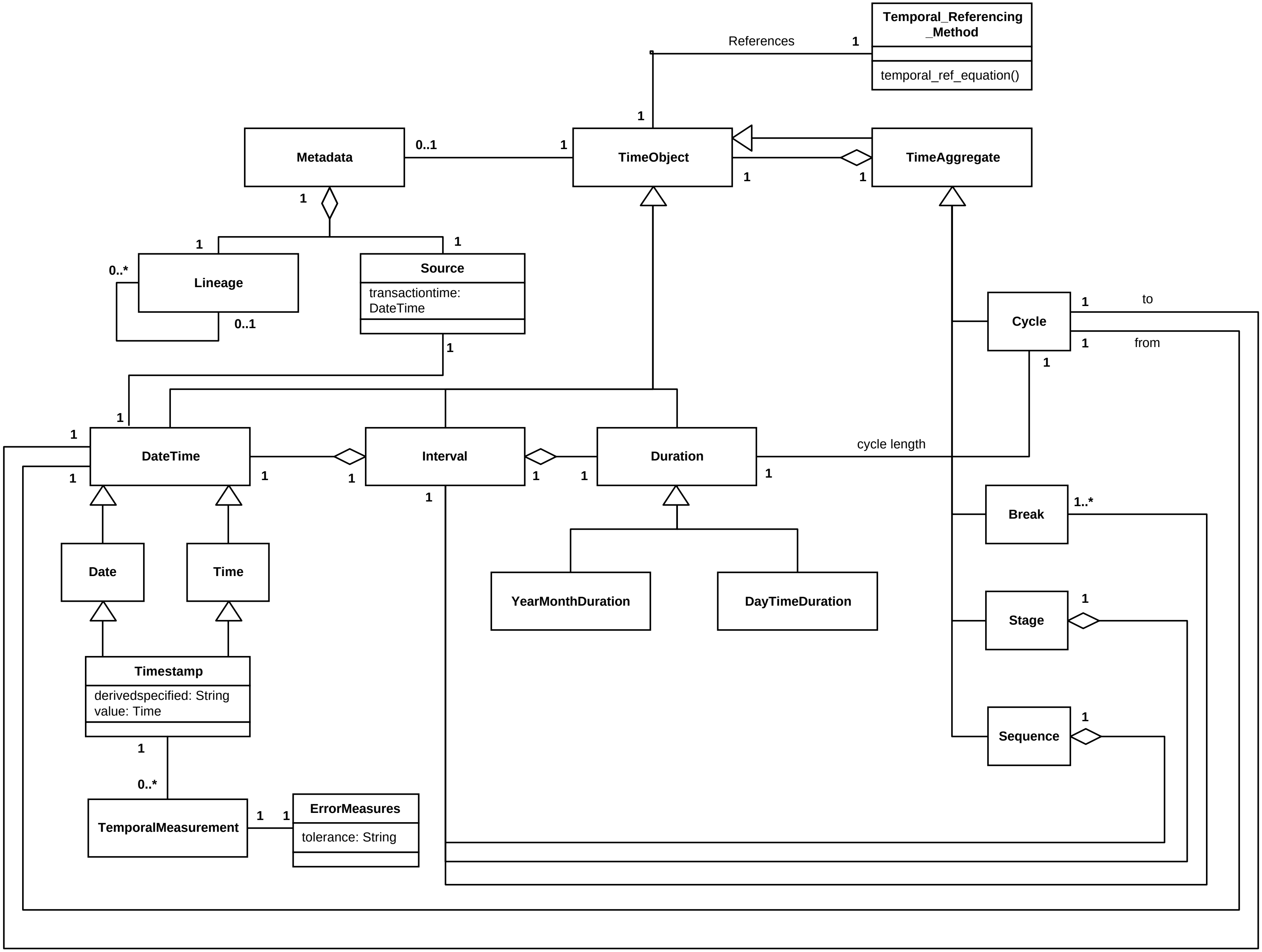


Figure 2-14. Time object construct.

Figure 2-11 provides a low-level view of the objects that make up the SRSs and shows how the objects are tied to the transportation feature. The following SRSs are represented: vertical, geocentric, horizontal, cadastral, and linear. Datum objects for each SRS, as well as reference objects, are presented. The linear referencing system model relies on the work of Fletcher, Henderson, and Espinoza (*2*) and Vonderohe et al. (*1*). The SRS model represented in Figure 2-11 provides the basis for the transformation of data.

Figure 2-12 provides a low-level view of the spatiotemporal object. In this model, geometric (i.e., cartographic) constructs are separated from topological constructs to allow for multiple cartographic and topological representations. Constraints on the relationship between topological and geometric objects from the scale applicability and from optional dimensional business rules allow changes in a topological representation to lead to appropriate cartographic references, and the converse. The geometric and topological primitives rely on the ISO 15046 geostandard (*21*).

Figure 2-13 provides a low-level view of the coordinate object. This model has five classes of coordinate objects corresponding to the SRSs. Because coordinates are artifacts or derived from measurements to a reference object, this model supports a framework for a measurement management system. A measurement management system stores measurements and their associated uncertainty and derives coordinates with variances and covariances from measurements. Covariances from derived coordinates are necessary for the modeling of error propagation.

Figure 2-14 provides a low-level view of the time object, which represents the bi-temporal metrics of transportation features and events. In representing the temporal metrics (i.e., position and length along a time scale) in a database, two aspects of time have been used: "valid" (or "world") time and "transaction" (or "system") time. A database model that uses both "valid" and "transaction" time is called a bi-temporal model (*38*) or a temporal database and has been identified by others (*39*) as the best method of temporal data organization for spatiotemporal models. Most attempts at a spatiotemporal data model use only "world" time. The time object can be represented as temporal primitives (e.g., date time, duration, and interval objects) or as time aggregates (e.g., cycle or sequence). Temporal primitives and time aggregates describe "valid" time, or the time when the activity occurred. The "transaction" time, or the time when the activity was recorded in the database, is stored in the source metadata object.

2.3.4 Discussion of Primary Classes and Relationships

This section presents the primary classes and relationships needed for an MDLRS logical data model. The classes in this section are essential and lay the foundation for the MDLRS data model (i.e., the MDLRS data model could not be constructed without these classes and relationships).

2.3.4.1 Transportation Feature

In the MDLRS data model, the transportation feature is the central object. The basis for the transportation feature relies on current geospatial standards and research. These standards and research use an object-oriented approach to model the interaction of phenomena in space and time.

In modeling phenomena (tangible or intangible) and their interactions with each other using an object-oriented approach, the basic building blocks are objects and events. Objects represent the phenomena that users want to keep information about. An event is something that happens either in a point or period of time that changes the state of an object (*28*). The state of an object is defined by the object's attributes (spatial or aspatial) and its values, which are valid for a period.

In some geospatial standards (e.g., CGIS-SAIF and ISO 15046) the generic term "object" is specified as a "geographic object." A geographic object is defined as an object representing a real or artificially defined phenomenon that has or potentially has some kind of spatial or spatiotemporal position (*2*). In the GIS-T/ISTEA PFS (*2*), a special type of geographic object is used, representing the transportation domain. That object is called a transportation component and generally represents a non-decomposable phenomenon in the transportation domain. Examples of transportation components are anchor points, anchor sections, highways, trails, airports, interchanges, roadways, bridge elements, and business data (e.g., pavements and signs).

The MDLRS data model adopted the GIS-T/ISTEA PFS concept of a "transportation component," calling the concept a "transportation feature." This transportation feature is the central object of the MDLRS data model. The model is extended with a dynamic transportation feature called a "conveyance." Figure 2-9 shows the transportation feature object, its subclasses, and its relationships.

The transportation feature contains attributes that describe its aspatial characteristics. These attributes can be quantitative (e.g., pavement index and vehicular volume), qualitative (e.g., color of a sign), or temporal (e.g., operating conditions of an HOV lane and a signal-timing sequence). The attributes of a transportation feature can also have a validity period (e.g., January's signal-timing sequence or the period when a volume was counted). Old values of a single attribute are stored in the transportation feature as a linked list, allowing for rollback of attributes. The administrative aspects of where the transportation feature came from and when it was instantiated are stored in the source metadata object.

The region of space and time occupied by a transportation feature is represented by a spatiotemporal object (see Figure 2-12). The spatiotemporal object consists of a spatial object with an associated time object. The time object describes when the spatial object is valid. In this model, to allow for multiple spatial representations resulting from historical or cartographic/topological changes, a transportation feature can have one or more spatiotemporal objects. In the MDLRS data model, temporal relationships between transportation features and temporal relationships between spatiotemporal objects are through the use of explicit temporal relationship objects: temporal topology and temporal proximity (see Figure 2-9).

2.3.4.2 Event and Experience Objects

An event is something that happens in an instant or over a period of time and changes the state of a transportation feature (*2*). Figure 2-9 shows the event object and its interaction with the transportation feature. All events have a spatial component, which allows the events to be graphically displayed and analyzed and which allows users to identify the transportation features affected by the events. An event is essentially temporal (i.e., an event is valid for a period or instant) with a location. Therefore, an event has an associated time object. In many situations, events are planned beforehand, which results in a scheduled time. When the planned event occurs, however, the actual time at which the event began may differ from the scheduled time because of delays. The delay in time between when an event was scheduled to occur and when it actually occurred is called "latency." In transit systems, a synonym for latency is "on-time performance." The MDLRS data model represents the latency of events by using two temporal attributes called "scheduled time" and "actual time." To compute latency, both scheduled time and actual time must be recorded. Associated with each event is a source metadata object, which describes the administrative aspects of the event.

An event, by its definition, produces changes in a transportation feature. Therefore, an event contains several methods that act on transportation features. An event can add or modify attributes of a transportation feature (e.g., updated traffic volume), can add or modify a spatiotemporal object of a transportation feature, can add or modify attributes of a spatiotemporal object (e.g., widening of a roadway), and can retire or instantiate transportation features (e.g., installation of guard rail). In the case of a conveyance, events can initiate and stop the movement of the conveyance (e.g., the use of daily public transport vehicle assignments or "blocking"). Collections of related events are called complex events and allow for modeling of multiple activities (e.g., a construction schedule for a certain year, the logistics of the Olympic Games, the parade schedule for a major city, or the transit schedule for a weekday).

Although an event can change the state of a transportation feature spatially, aspatially, or temporally, there must be a registry in the feature that indicates which events caused which changes. An event may change all or a subset of the transportation features in a transportation system. Each event that the transportation feature participates in is called an experience (see Figure 2-9). An experience does not exist without a participatory event, so experiences know their parent event. One event can cause many experiences, but each experience is related to one event.

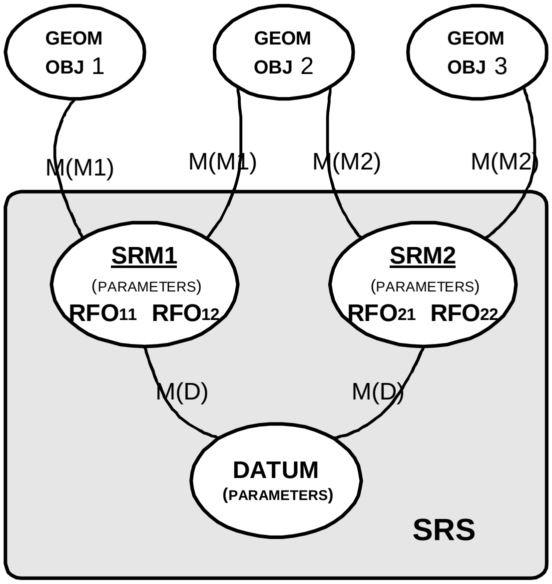
Although the experience object is an event object, the experience object does not contain any data. The experience object contains references to the activating event, as well as references to the new or modified transportation feature. Users can perform historical queries because the experience object contains references between event and transportation feature objects. To perform the historical queries, users trace an event to the affected objects of a feature. Having the experience object contain references also works in reverse (i.e., tracing the affected objects of a feature to an event through an experience). Rollback of an entire transportation system is possible through the experience objects of its transportation features.

Over time, a transportation feature participates in several events, producing additional experience objects. These experience objects form a time-ordered, linked list and represent the event registry, or the "container of memories," for the transportation feature. The life span of a transportation feature (i.e., the entire time that the feature is known to the database) is the time-ordered sequence of all its experiences (*2*). The collection of experience objects allows for historical rollback of the transportation feature. For the transportation feature, the experience and its participatory event form the end or beginning of a new state. The collection of experience objects represents the transportation feature's function of location with respect to time.

2.3.4.3 SRSs and TRSs

2.3.4.3.1 SRSs. To handle geographic information, it is important to consider the measurement concepts required for time and space. Spatial measurement requires a set of geometric assumptions to create an SRS. An SRS provides a mechanism to situate measurements on a geometric body, such as the earth; establishes a point of origin and orientation of reference axes; and provides geometric meaning for measurements, as well as units of measure (*40*).

A spatial referencing method can be thought of as a method for finding and stating the location of an unknown point by referencing it to a known point (adapted from the Transportation Research Board [*41*]). An example of a spatial referencing method can be a state plane grid system based on a Universal Transverse Mercator (UTM) projection. A schematic of a generic spatial referencing system is provided in Figure 2-15. Reference objects are objects (a) whose locations are known and (b) from which measurements are made in the real world to determine the unknown locations of other objects and to provide the relationships needed to link a spatial referencing method to an SRS datum. The datum, plus reference objects, plus methods comprise an SRS.



Note:
GEOM OBJ = geometric object.
M(D) = metrics of datum.
M(M#) = metrics of Method (#).
RFO = reference object.
SRM = spatial referencing method.
SRS = spatial referencing system.

Figure 2-15. Schematic of a generic spatial referencing system.

The MDLRS data model has five categories of SRSs: vertical, geocentric, horizontal, cadastral, and linear (see Figure 2-11). Each SRS has one or more datum objects and an associated reference object. Reference objects are transportation features, can lie on other features, and are spatially represented as reference points (see Figure 2-12). Table 2-1 presents the datum objects and reference objects for each of the five SRSs.

In the MDLRS data model, to determine the location of a transportation feature in a nonlinear SRS, the transportation feature's geometric object must reference a reference object (see Figure 2-11). In a linear SRS, to determine a transportation feature's linear location, the transportation feature refers to the linear reference method object. A linear reference method consists of a collection of traversal reference points and traversals. Traversals consist of transport links defined by transport nodes, which are located on anchor sections defined by anchor points. In this model, transport nodes, transport links, anchor points, anchor sections, and traversal reference points are all types of transportation features (see Figure 2-10).

To transform data between linear and nonlinear systems, a relationship between the anchor section object and geometric object is present (see Figure 2-11), requiring that an anchor section object knows which geometric object it represents. This relationship has an association that provides the missing coordinates (linear or nonlinear) to allow the transformation to occur. A method, anchor section snap, is included in the association to generalize a two- or three-dimensional geographic object to a one-dimensional geometric object compatible with the associated anchor section object. The anchor-section-snap method can also map an anchor section object to the centerline or centroidal axes of a surface or solid to obtain a two- or three-dimensional location, respectively.

2.3.4.3.2 TRSs. The measurement and storage of time invokes the concept of a referencing system, or an agreed measurement scheme. The concept of a TRS is implied because most measurements use the same units of measure and are calibrated to some external reference (e.g., an official clock). However, when using temporal data based on other clocks, zones, and calendar systems, there needs to be an explicit TRS.

There exists a clear analogy between an SRS with many spatial referencing methods (e.g., projections and grids) and a TRS with many temporal referencing methods. A point in time occupies a position that can be identified in relation to a known reference time in a TRS. By adopting a common referencing system, time measurements can be compared and mathematical operations like subtraction become valid (*40*). A temporal datum and temporal referencing method objects can be modeled as a spoke and hub, in which all methods relate to one designated method, or as a network, in which all methods understand all other methods. The network approach

TABLE 2-1 Characteristics of spatial referencing systems

Name	Dimension	Datum Object	Reference Object
Geocentric	3 D	3D Cartesian Axes	GPS Satellite
Horizontal	2 D	Ellipsoid	Control Station
Cadastral	2 D	Corner	Corner Point
Vertical	1 D	Geoid/Local Datum	Benchmark
Linear	1 D	Anchor Point/Anchor Section	Traversal Reference Point

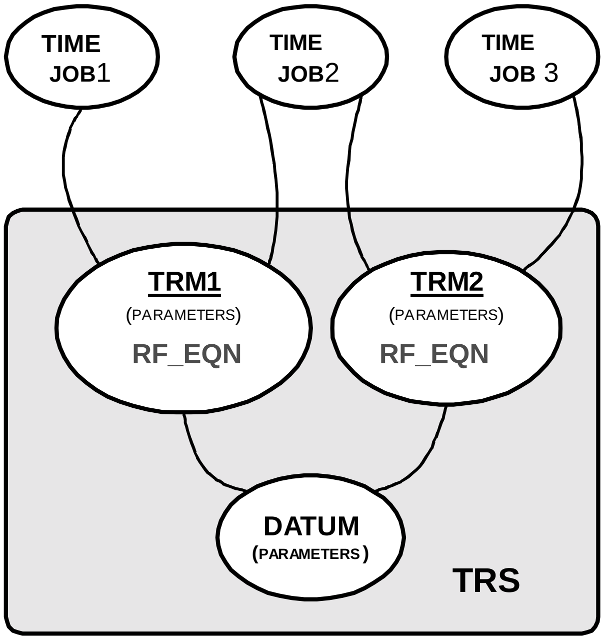
Note: Table modeled after A. Vonderohe and T. Hepworth, "A Methodology for Design of a Linear Referencing System for Surface Transportation," *SAND97-0637* (Albuquerque, New Mexico: Sandia National Laboratories, 1997).
1D = one-dimensional.
2D = two-dimensional.
3D = three-dimensional.

would need $(N-1)^2$ functions, where N equals the number of temporal referencing methods.

The most common TRS is Greenwich time, which is based on a temporal referencing datum—Coordinated Universal Time (UTC). Temporal referencing methods, such as zonal time, can be tied to UTC by calibration and consistency of measurement, making a minute the same measurement across all methods (*40*).

As shown in Figure 2-16, a TRS consists of a temporal datum and temporal referencing methods containing temporal reference equations. The MDLRS data model uses a temporal datum object and one or more temporal referencing method objects to represent the TRS (see Figures 2-9 and 2-14).

In the MDLRS data model, the temporal referencing method object contains a temporal reference equation method, which is a derivable equation that relates the temporal datum to the temporal referencing method. The equation consists of two parts: a reference offset (e.g., –3 h for zonal time), and a metric scaling function that relates the metric of the method to the metric of the datum (e.g., to convert between Julian dates and Gregorian calendar time). Although the MDLRS data model can accommodate various metrics and various temporal representations, the data model concentrates on temporal referencing methods whose metrics are the same as the datum and assumes UTC and the Gregorian calendar as the temporal datum.



Note:
RF_EQN = temporal reference equation.
TIME OBJ = time object.
TRM = temporal referencing method.
TRS = temporal referencing system.

Figure 2-16. Schematic of a generic temporal referencing system.

2.3.5 Discussion of Secondary Classes and Relationships

This section presents and describes classes and relationships needed for an MDLRS logical data model using the classes and concepts of transportation features, events, and experiences, and spatiotemporal referencing systems as foundational elements.

2.3.5.1 Types of Transportation Features

This section describes some of the subclasses of the transportation feature superclass and some of the classes resulting from aggregation of transportation features (see Figure 2-10).

2.3.5.1.1 Transportation Complexes and Systems. Transportation features are considered non-decomposable objects and are based on some business rule. Examples of transportation features are signs, guard rail, pavement sections, intersections, anchor points, and abutments. Although some of these transportation features can be decomposed physically (e.g., guard rail, signs, or intersections), the user may be concerned with a certain level of detail needed to represent the phenomena. For certain purposes, the user may want to aggregate transportation features to form a transportation complex. Transportation complexes are collections of interconnected transportation features and other transportation complexes (adapted from Fletcher, Henderson, and Espinoza [*2*]). An example of a transportation complex is a section of a roadway represented as a collection of the following transportation features: signs, guard rail, lanes, HOV lane, pavement, shoulder, bridge deck, and bridge abutment. When a user refers to the section of roadway, the collection of transportation features is often implied. Another example of a transportation complex is an interchange consisting of bridge and ramp transportation features.

Transportation systems are a collection of transportation features, transportation complexes, and other transportation systems that serve a transportation function in support of transportation objectives (adapted from Fletcher, Henderson, and Espinoza [*2*]). A transportation system can be functionally based (e.g., a highway system, a public transportation system, or a trail system) or physically based (e.g., a pavement system or a bridge system). Transportation complexes and systems are shown in Figure 2-10.

Transportation complexes and transportation systems are not transportation features, but are collections of them. The collection of the topological objects of transportation features at a certain level of detail forms a topology of the complex or system. This topology of the transportation system or transportation complex (e.g., network or areal), as shown in Figure 2-10, is abstract, or not “hard coded,” but is the result of the topological connections of the aggregation of transportation features.

2.3.5.1.2 Conveyance. In the MDLRS data model, a conveyance is a type of moving transportation feature (see Figure 2-10). A conveyance object is anything that moves in a spatiotemporal reference frame (*42*). A conveyance can be a vehicle, a person, or a group of people and executes navigation. A collection of conveyances is called a fleet and represents a group of vehicles with fleet management capabilities. There are two focal issues for conveyances. The first issue regards the modeling of conveyance movement and the history of its movement. The second issue regards how the conveyance interacts with its environment (i.e., transportation system).

Associated with a conveyance are methods that allow navigation. In navigation, the conveyance moves in space and time; it essentially associates a route with a vehicle and says "go." There are two primary navigational activities for a conveyance: tracking and routing (i.e., prescribing movement).

Tracking is a two-phase process. First, a conveyance or an outside entity executes a "locate," which indicates the location in space and time of the conveyance in the real world. The result of the locate operation may be a series of coordinates from a variety of sensors that collect real-time locations and times (e.g., GPS, radar, laser, microwave, loop detectors, gyroscopes, and accelerometers). The locates are transmitted to the outside entity or dispatcher (or any facility that has the network topology and is able to do transformations and route guidance). The dispatcher, or traveler information center, represents an authority that is responsible for managing a fleet of transit vehicles in a transit transportation system or for directing automobiles on a roadway transportation system, respectively. The dispatcher executes a position operation on the data—that is, translates the radio frequency coordinates into a database location. This database location indicates which link the conveyance is on, and the location may be a linear reference. From the track operation, the dispatcher can generate a path (i.e., route operation) indicating which links and turning movements the conveyance should take. The path is then transmitted to the conveyance, and the conveyance executes the path. Following the route operation, a track operation may be performed indicating the conveyance's updated position. From the updated position of the conveyance and any new information provided to the dispatcher (e.g., road closures or gridlock delays), the dispatcher may perform a new route operation and transmit that path to the conveyance. Therefore, the track and route operations depend on each other and form a repeating cycle until the end of a trip.

The routing method of a conveyance in a transportation system can rely on historical predictive algorithms, dynamic vehicle assignment algorithms, or time-space diagrams in the case of fixed-route transit. The mathematical model for location prediction or route guidance is located at the dispatcher. The MDLRS data model does not provide the mathematical models for location prediction or route guidance and leaves the choice of models up to the user. The MDLRS data model provides data to support the algorithms.

Figure 2-17 presents the object model to support the implementation of navigation and shows how the conveyance interacts with its environment. A conveyance will move along a transport link for a certain duration. During that time, one or more track operations will be performed. From the track

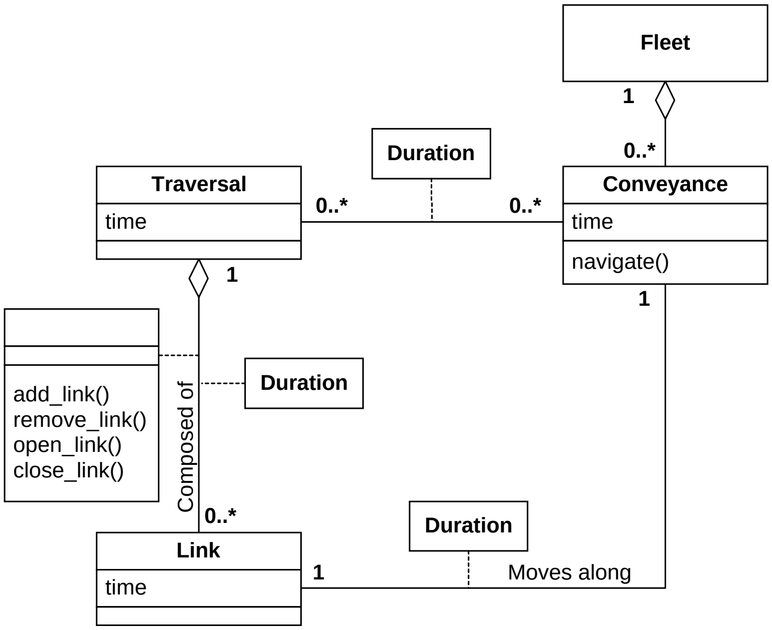


Figure 2-17. Unified modeling language object model to support implementation of "navigate."

operation, the transport link on which the conveyance is moving is identified. That transport link is then added to the traversal or route that is being created for the conveyance. As the conveyance moves along other transport links, those links are being registered in the traversal of the conveyance (i.e., the traversal is being built). The result of a complete trip is a traversal made up of a collection of transport links that the conveyance has navigated for a certain duration. Both the traversal and transport links are valid for a certain time. In this context, the semantics of the term "traversal" are those of a generated path. In other contexts (e.g., linear referencing), the term "traversal" can mean a named route. The definition of "traversal" is broad to cover both meanings, and in the GIS-T/ISTEA PFS, a traversal is meant to be a superclass of named routes or generated paths (*2*).

As a conveyance is navigating along a traversal, the conveyance is transmitting locational coordinates through its tracking method. The dispatcher may discard these coordinates or use them to retrace the movement of the conveyance. The movement of a conveyance can be replayed with a traversal and a space-time function generated by the dispatcher. The space-time function represents the location as a function of time for the conveyance and can be derived through connecting the dots of locational coordinates. When a link is traversed, tracked locational points do not need to be stored and can be replaced efficiently by a smoothed space-time function or a traversal step function. An example of a simplified space-time function for a public transit vehicle is shown in Figure 2-18. In this figure, time is on the horizontal axis and space is on the vertical axis. Each segment of the diagram is represented by the function

$$x = v\Delta t + x_0 \qquad (1)$$

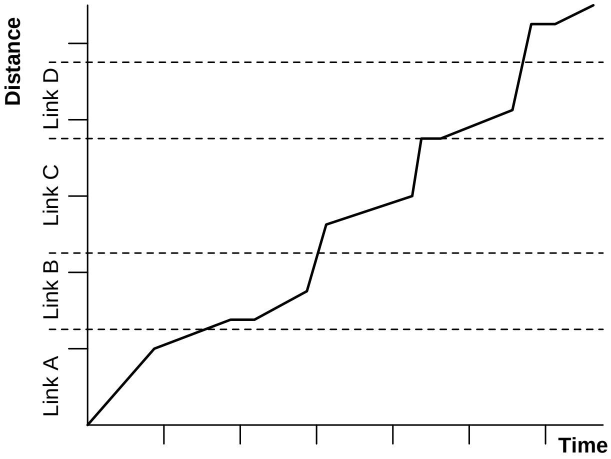
where

x = distance,
v = velocity, and
t = time.

The slope of each segment represents the velocity of the length. Where the slope is zero, the vehicle is stopped (because of delays or passengers who are boarding and alighting). This space-time diagram assumes no acceleration during each segment.

2.3.5.2 *Spatial Objects*

A transportation feature can be associated with multiple spatiotemporal objects, consisting of a spatial object and an associated time object. The time object indicates the period of time (i.e., from time of creation to time of retirement) in which the spatial object is valid. In the MDLRS data model, the spatial object provides the spatial characteristics of a transportation feature and is described by one or more geometric or topological objects. Each instance of a spatial object has one coordinate representation or storage format that is consistent with its referenced SRS. Figure 2-12 presents the data constructs associated with the spatial object. The representation of separate geometric and topological constructs allows multiple spatial cartographic (i.e., geometric) and topological representations to occur. Geometry provides the means for the quantitative description, through coordinates and mathematical functions, of the spatial characteristics of features, including dimension, position, size, shape, and orientation (*21*). Spatial topology involves properties of spatial configurations that remain invariant if space is deformed elastically and continuously (*21*).



Note: Each segment of the diagram is represented by the function $x = v\Delta t + x_o$, where x = distance, v = velocity, and t = time. The slope of each segment represents the velocity of the length.

Figure 2-18. Example of a space-time diagram for a public transit vehicle.

2.3.5.2.1 Topological and Geometric Association. The MDLRS data model shows a many-to-many relationship between geometric and topological objects (see Figure 2-12), so that each geometric (i.e., cartographic) representation may have zero or more associated topological representations, and each topological representation may have zero or more associated geometric representations of the same transportation feature. This relationship allows transportation features such as roadways to be represented topologically as centerlines while being cartographically displayed as two-dimensional lines. However, the associations are constrained by scale applicability and, optionally, dimensionality.

A transportation feature (e.g., a road) may have one topological representation (e.g., edge) with several geometric or cartographic representations (e.g., curves, surfaces, and solids), each with varying degrees of detail. For display purposes, the geometric representation that is most appropriate for the map scale being shown needs to be retrieved. In the MDLRS data model, the capability to handle spatial objects with multiple scales is provided through the scale applicability attribute in the spatial object abstract class (see Figure 2-12). The scale applicability attribute is user defined and indicates which map scale the spatial object is best suited for.

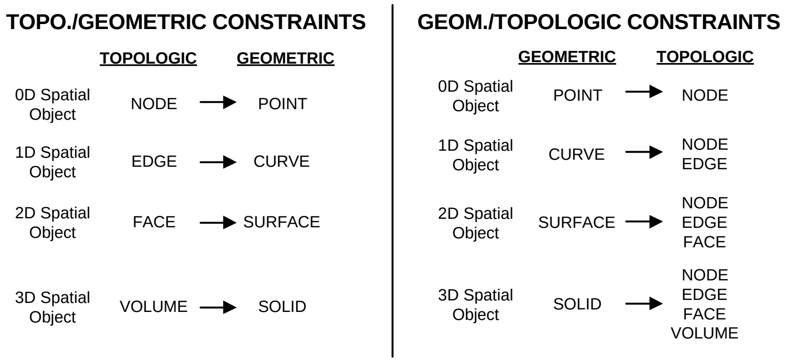
The scale applicability constraint between topological and geometric objects allows an association among spatial objects with scales compatible with the scale of the focal spatial object. The geometric objects associated with a topological object would need to have a scale applicability greater than or equal to the scale applicability of the topological object. For example, if an edge had a scale applicability of 1:5000 and available geometric objects were a solid with a scale applicability of 1:1200, a surface at a scale applicability of 1:3600, a curve (C1) at a scale applicability of 1:4800, and another curve (C2) at a scale applicability of 1:7200, then the edge would be associated with the solid, the surface and curve C1. Conversely, the topological objects associated with a geometric object would need to have a scale applicability less than or equal to the scale applicability of the geometric object. The topological representation would be associated with a cartographic representation of the same detail or greater. This constraint is due to cartographic generalization (e.g., in displaying a complete street network at a scale of 1:1,000,000, streets would be displayed on top of each other).

Another constraint in the association between geometric and topological objects deals with dimensionality. The optional dimensionality constraint is a set of user-defined business rules that helps maintain dimensional compatibility between geometric and topological objects on the basis of user expectations. For example, if the user is given or shown a bridge (i.e., a transportation feature) with a geometric object representation as a point, the user should expect to be able to perform topological analysis consistent with the dimension of the point. If the map scale changes such that the bridge is represented as a three-dimensional solid, the user should know that the underlying topological representations are dimensionally consistent and support analysis for that scale. Conversely, if the user uses a topological representation at a given level of generalization (i.e., a complex interchange with all nodes and edges shown), a dimensionally consistent geometric representation (for display) should be referenced to the topological representation. Changes in the topological representation due to the level of generalization (i.e., reducing an interchange to a single node) should be referenced to consistent geometric representations. Figure 2-19 is one example of dimensionality constraints derived from user-defined business rules and is meant to be a guide. Figure 2-19 indicates that if given a geometric representation as a curve, one can reasonably associate (defined by a set of business rules) with that curve a topological edge or a topological node.

In the MDLRS data model, the dimensionality constraint is meant to guide the user in potential representational choices and is optional. Using the prior example, under the scale applicability constraint, an edge was associated with a solid, a surface, and a curve. The dimensionality constraint would guide the user to that geometric object best suited for use.

The scale applicability constraint and the optional dimensionality constraint provide the capability to handle multiple spatial cartographic and topological representations, their changes, and their references.

2.3.5.2.2 Geometric Object. In the MDLRS data model, the geometric object is the region in space occupied by a transportation feature (adapted from the BC Ministry of Environment, Lands, and Parks [*19*]). Geometric objects (see Figure 2-12) have known positions and can either be geometric primitives or geometric complexes. Geometric primitives are non-decomposable objects representing a single, homogeneous element of geometry (*21*) and include points



Note:
0D = zero-dimensional.
1D = one-dimensional.
2D = two-dimensional.
3D = three-dimensional.
TOPO. = topological.

Figure 2-19. Example of dimensionality constraints.

(zero-dimensional), which bound curves (one-dimensional), which bound surfaces (two-dimensional), which bound solids (three-dimensional). Reference points are a subclass of the object point and represent the position of a reference object. Geometric complexes are collections of geometric primitives, other geometric complexes, or both.

2.3.5.2.3 Coordinate Object. In all geostandards, points are associated with coordinates either as attributes or as separate objects. In actuality, coordinates are artifacts or derived values based on measurements to reference objects. Some coordinates are not generated by ground measurements (e.g., digitizing and coordinate geometry), but can contain error. A distinct advantage in storing measurements in addition to coordinates is the ability to recompute coordinates when there is a change in the datum (i.e., if the datum changes and the user only has coordinates, errors are introduced by transforming coordinates). The MDLRS data model provides the framework for a measurement management system in which spatial measurements are stored and coordinates are derived from those measurements.

In the MDLRS data model, associated with each point is a coordinate object (see Figure 2-13). The abstract data type "coordinate object" contains attributes that indicate (a) whether the coordinate was derived or specified, (b) the unit system of the coordinate, (c) the time interval (i.e., time object) in which the coordinate object is valid, and (d) the method associated with the coordinate type (e.g., the projection method or the linear referencing method). Storing a time object along with the coordinate allows for more efficient temporal searches. For example, if a polygon changes shape, users can use the time object to run a search on the vertices and get the history of the polygon. So, if a polygon's boundary changes because of a changed vertex, the user does not need to store a new polygon. The alternative to timestamping coordinates is to have a timestamp for every version of a polygon and to historically search through each polygon.

There are five types of coordinate objects, each with different attributes indicating the coordinate's position value: one-dimensional coordinate, two-dimensional coordinate, three-dimensional coordinate, linear coordinate, and GPS coordinate. Associated with each coordinate is an optional set of measurements consistent with the type of the coordinate (e.g., a three-dimensional ground measurement with a three-dimensional coordinate). The measurements are optional when coordinates are not generated by ground measurements (e.g., digitizing and coordinate geometry). Each measurement can be associated with several coordinate objects of the same type. Each dimensional measurement abstract class (i.e., one-dimensional ground measurement, two-dimensional ground measurement, three-dimensional ground measurement, and linear measurement) can be represented as an instance of a measurement object subclass. For example, a three-dimensional ground measurement can be a slope distance, a horizontal angle, a zenith angle, or a direction.

2.3.5.2.4 Measurement Objects: Distance, Angle, Radio Frequency, and Direction. The measurement abstract object class (see Figure 2-13) contains attributes that indicate its unit system, identifiers, its value, and the uncertainty associated with the observed value. The subclasses of the measurement object are the distance measurement object, the angle measurement object, the direction object, and the radio frequency measurement object. The distance measurement subclasses include different types of distance measurements, such as vertical distances, horizontal distances, slope distances, linear distances, and offset distances. The two types of angular measurements include horizontal angles and zenith angles. The direction measurement indicates the bearing or azimuth between two points, while the radio frequency measurement object represents the observed radio frequency signal and time recorded using a receiver at a point.

Each coordinate object contains a method called location derivation (see Figure 2-13). The location derivation method derives a set of optimal coordinates out of the collection of measurements for that coordinate type. For example, given a set of two-dimensional ground measurements from a traverse, the location derivation method under the two-dimensional coordinate would reduce the traverse, make adjustments to the traverse, and compute coordinates from the traverse and associated surveyed points. If additional measurements are added (e.g., from or to a new survey), the location derivation method would introduce the new measurements with their associated tolerances to existing measurements and derive a new set of coordinates with improved precision (e.g., a weighted mean and an uncertainty in the weighted mean). Additional measurements with large uncertainties would be given low weights, while measurements that contained blunders would be excluded. The location derivation method is polymorphic in that it does not need to be defined for each coordinate type and can distinguish between different coordinate types.

2.3.5.2.5 Variance/Covariance Matrix. All measurements have associated uncertainties and variation. When a user positions (i.e., puts a measure into a database), the user introduces uncertainty in the database. That uncertainty is passed along to applications that use the data, but no additional error is introduced. When a location is placed from the database to the field, the position error is present along with an introduced place error. Errors accumulate in transformations of data. These uncertainties or errors propagate from use of measurements.

When coordinates are the result of measurements, errors are introduced. These errors and their interdependencies are represented by variances and covariances. In error propagation, the variances and covariances are carried through each spatial object derivation as a matrix. After several spatial operations, this variance/covariance matrix could be very large and unmanageable. A 2×2 variance/covariance matrix is needed for individual two-dimensional points, and a 3×3 variance/covariance matrix would be needed for individual three-dimensional points. A 2×2 variance/covariance matrix for two-dimensional points would grow to a 4×4 matrix for points, resulting in the intersection of two linear layers. If these new points were used to derive another set of points, the resultant points would have an 8×8 variance/covariance matrix. Imagine how large the matrix would be after several more operations and after the matrices for each point in a layer are stored. The 2×2 variance/covariance matrix for two-dimensional data objects is made up of the variance in the x-coordinate of Location A, the variance in the y-coordinate of Location A, and the covariances between the two coordinates.

An alternative to maintaining an $N \times N$ variance/covariance matrix (where N equals the dimension times the number of operations) for each spatial object carrying all variables from prior operations is to maintain the functional lineage (full ancestry) of the spatial object from its ultimate source and to maintain a final 2×2 variance/covariance matrix (for two-dimensional points). A functional lineage provides operations on how a spatial object was computed and includes references to the objects from which the new object was created. A disadvantage with this approach is that the full functional lineage back to the ultimate source needs to be stored with the spatial object. This approach could produce unmanageable lineage objects.

Another alternative to maintaining an $N \times N$ variance/covariance matrix is to store the immediate or familiar functional lineage of the spatial object and a final 2×2 variance/covariance matrix (for two-dimensional points). In this alternative, the spatial object would point to its parent spatial object only. The parent spatial object would refer to *its* parent spatial object, as in a family tree structure. The user could find the sources of data or go back as his or her needs require. The user would have to find the physical source of parent data to re-compute the child's variance/covariance matrix. To find if a spatial object is related (i.e., a sibling), the user would need to go up the spatial object family tree to reach a common ancestor and then down to the appropriate level. The MDLRS data model uses this option to model error propagation by creating $D \times D$ variance/covariance matrix objects (where D equals the dimension of the spatial object) for each derived coordinate object.

In addition to the variance/covariance matrix object (see Figure 2-13), the lineage metadata object is used to model error propagation. The lineage metadata object (see Figure 2-12) indicates the history or parentage of the data, including their compilation and processing history. The lineage metadata object contains pointers or references to its parent objects. The user determines the propagation of error by using the spatial object's variance/covariance matrix and tracing the parentage of the spatial object through the lineage metadata object backward as the user's needs require. Using this approach to error propagation eliminates the need to carry a potentially immense variance/covariance matrix with all variables from prior operations and eliminates the need to carry a full ancestry of the spatial object from its ultimate source.

2.3.5.2.6 Topological Object. Topological objects are objects that remain invariant if the space is deformed elastically and continuously—for example, when geographic data are transformed from one coordinate system to another (*21*). Topological objects can be derived by removing the location or metrics from geometric objects. Topological objects can be either topological primitives or topological complexes (see Figure 2-12). Topological primitives include nodes (zero-dimensional), connected to edges (one-dimensional), which bound faces (two-dimensional), which bound volumes (three-dimensional). Topological complexes are aggregations of topological primitives.

2.3.5.3 Time Objects

The storage of the temporal element of phenomena and its behavior is represented in the MDLRS data model as a time object. The time object is the temporal equivalent of a spatial geometric object, where the time object provides the quantitative description, by means of temporal primitive and aggregate objects, of the temporal characteristics of transportation features and events. Time objects represent a specific or relative portion of a time line, and the portion's associated TRS for which the object is valid (adapted from the BC Ministry of Environment, Lands, and Parks [*21*]).

Time objects represent the temporal metrics of phenomena (see Figure 2-14). The time object is more complex than a pure timestamp. It can be represented as a timestamp or as a point on a time line (date time object). The time object can also be represented as a duration object, which gives only temporal length and not position (e.g., 5 h, Monday, or January); as an interval object, in which two date time objects (e.g., date of creation and date of retirement) or one date time object and a duration define a segment of time; or as a time aggregate object, the temporal equivalent of a geometric complex object. The time aggregate object can represent temporal structures, such as cycles, breaks, stages, and sequences. Each type of time aggregate object can be decomposed into date time, interval, and duration objects.

The date time object represents a timestamp in which the date, time of day, or both are given. The timestamp object is the temporal equivalent of the coordinate object. While coordinates can be reproducible by measurements to a fixed, known reference object, a timestamp for an activity is not repeatable. However, there are situations in which, for a given activity, several temporal observations can be made (e.g., the observed finish time for a race). From these temporal observations, a derived timestamp at one resolution can be generated. Time objects at lower resolutions can be derived. Multiple temporal observations can reduce precision error. However, errors can be associated with temporal measuring devices. A clock may run slow or fast, producing a temporal bias. In the MDLRS data model, temporal bias is assumed to be removed by calibration. In performing temporal measurements, there is also an uncertainty associated with the measurement. This uncertainty can be due to the resolution of the temporal measuring device or due to user-perceivable time, when a measuring device is unavailable. For example, in recording the time a sunset occurred, if the user does not know exactly when the sunset occurred he or she may state that "sunset was at 7:00 p.m. +/−10 min." This uncertainty (+/−10 min) is modeled as a temporal tolerance in the error measures object.

Associated with each time object are source and lineage metadata objects (see Figure 2-14). The lineage metadata object provides the parentage of the time object (i.e., how the time object was derived) and the source metadata object. The lineage metadata object allows for temporal correlation with other objects, similar to spatial correlation. In addition to providing the administrative aspects of the time object, the source metadata object records when the time object was recorded in the database. The time object primitives and aggregates record when an activity actually occurred. In temporal GIS research, recording of the time when an activity occurred is called "valid," or "world," time (*39*). However, the time when the activity was recorded in the database may differ from when the activity actually occurred. The time when the activity was recorded in the database is called "transaction," or "system," time (*39*). Most temporal GIS models assume that the difference between world and transaction time is negligible and, therefore, use world time. In the MDLRS data model, transaction time is recorded in the source metadata object. The time object represents a bi-temporal model because both valid and transaction times are maintained. A bi-temporal model is key for the development of a temporal database, identified as the best method of temporal data organization (*39*).

2.3.5.4 Temporal Relationships

To use temporal metric objects (i.e., time objects) to perform spatiotemporal queries, temporal relationships need to be established. These relationships operate on objects within a transportation feature (e.g., to find the most recent spatiotemporal object) and between transportation features (e.g., to determine if one transportation feature was created before another feature was). There are two types of temporal relationship objects used in the MDLRS data model (see Figure 2-9): temporal topology and temporal proximity. Only these two temporal relationship objects are adopted from the CGIS-SAIF model (*19*).

In the MDLRS data model, temporal relationships are to be computed when needed (i.e., acting as operators). The results of the temporal relationships are Boolean answers. The alternative to creating temporal functions is to create hard-coded temporal relationships, where every transportation feature would need to pre-compute its temporal relationships to all other features. The use of pseudocode from the temporal relationship section of CGIS-SAIF allows users to specify temporal relationship functions.

2.3.5.4.1 Temporal Topology. Temporal topology is a temporal relationship object involving nonmetric temporal relationships involving two transportation features. Transportation Features A and B may be temporally disjoint, when no part of A is simultaneous with any part of B, or temporally intersect. The cases in which two temporal objects may intersect temporally are as follows (*19*):

- **At start**—A occurs at a point in time simultaneous with the start of the interval of B.
- **At end**—A occurs at a point in time simultaneous with the end of the interval of B.
- **Follows**—A begins when B ends.
- **Overlaps at start**—The start of A does not intersect B, and the end of A intersects B, but not at B's start or end, and the start of B intersects A, but not at A's start or end.
- **Overlaps at end**—The end of A does not intersect B, and the start of A intersects B, but not at B's start or end, and the end of B intersects A, but not at A's start or end.
- **During**—All of A is simultaneous with some part of B, excluding the start and end of B.
- **During from start**—All of A is simultaneous with some part of B, excluding the end of B, and the start of A is simultaneous with the start of B.
- **During to end**—All of A is simultaneous with some part of B, excluding the start of B, and the end of A is simultaneous with the end of B.
- **Simultaneous**—A in its entirety and B in its entirety occur at exactly the same time (i.e., they occupy exactly the same portion of the time line).

These terms are defined using set theory constructs based on boundary (i.e., start and end) and interior (i.e., interval) comparisons. The start (i.e., birth) and end (i.e., death) of Transportation Feature A are indicated as A_s and A_e, respectively. The interval between the start and end is designated as A_i. The temporal topological relationships between Transportation Features A and B and their conditions are shown in Table 2-2. These relationships provide the pseudocode to allow the generation of temporal topology operators (*19*). The relationships of Transportation Feature B in relation to Transportation Feature A are the inverse of the listed relationships.

2.3.5.4.2 Temporal Proximity. The temporal proximity object is a temporal relationship that operates like a temporal buffer. It uses two transportation features and answers the question of whether Transportation Feature A occurred within a given time (i.e., duration) of Transportation Feature B (*19*). In this example, Transportation Feature B is given a temporal buffer (i.e., an added duration), and the temporal characteristics of Transportation Feature A are checked to see if they lie within Transportation Feature B's temporal buffer.

TABLE 2-2 Temporal topological relationships between Transportation Features A and B and their conditions

Temporal Topological Relationships		Condition
A and B are temporally disjoint B (A occurs before B or B occurs before A)		$\{A_i \cap B_i = \emptyset)$ is true *and* $\{A_s \cap B_e = \emptyset\}$ is true and $\{A_e \cap B_s = \emptyset\}$ is true
A and B temporally intersect	A is *at start* of B	$\{A_i \cap B_i = \emptyset\}$ is true *and* $\{A_i \cap B_s = \emptyset\}$ is false
	A is *at end* of B	$\{A_i \cap B_i = \emptyset\}$ is true *and* $\{A_i \cap B_e = \emptyset\}$ is false
	A *follows* B	$\{A_i \cap B_i = \emptyset\}$ is true *and* $\{A_s \cap B_e = \emptyset\}$ is false
	A *overlaps* B *at start* of B	$\{A_i \cap B_i = \emptyset\}$ is false *and* $\{A_i \cap B_s = \emptyset\}$ is false
	A *overlaps* B *at end* of B	$\{A_i \cap B_i = \emptyset\}$ is false *and* $\{A_i \cap B_e = \emptyset\}$ is false
	A occurs *during* B	$\{A_i \cap B_i = \emptyset\}$ is false *and* $\{A_s \cap B_i = \emptyset\}$ is false and $\{A_e \cap B_i = \emptyset\}$ is false
	A occurs *during* B *from start* of B	$\{A_i \cap B_i = \emptyset\}$ is false *and* $\{A_s \cap B_s = \emptyset\}$ is false and $\{A_e \cap B_i = \emptyset\}$ is false
	A occurs *during* B *to end* of B	$\{A_i \cap B_i = \emptyset\}$ is false *and* $\{A_e \cap B_e = \emptyset\}$ is false and $\{A_s \cap B_i = \emptyset\}$ is false
	A and B are *simultaneous*	$\{A_i \cap B_i = \emptyset\}$ is false *and* $\{A_s \cap B_s = \emptyset\}$ is false and $\{A_e \cap B_e = \emptyset\}$ is false

Note:
A_e = the end of Transportation Feature A.
A_i = the interval between the start and end of Transportation Feature A.
A_s = the start of Transportation Feature A.
B_e = the end of Transportation Feature B.
B_i = the interval between the start and end of Transportation Feature B.
B_s = the start of Transportation Feature B.

2.3.5.5 Metadata

A notable feature of the MDLRS data model is the use of metadata objects for individual transportation features, as well as the parts that make up the transportation feature. Metadata objects are used to describe the characteristics of data in transportation features, events, spatiotemporal objects, and time objects (see Figures 2-9 and 2-14). There are two types of metadata objects: source metadata objects and lineage metadata objects. The source metadata object identifies the administrative aspects of where the data come from, possible restrictions on the use of the data, and when the data were entered into the database. The lineage metadata object indicates the history or parentage of the data, including the data's compilation and processing history. The lineage metadata object contains pointers or references to the data's parent objects. Additionally, for spatial objects, the lineage metadata object contains the positional accuracy of spatial objects derived from the variance/covariance matrix or provided elsewhere. In the case of spatial objects, the lineage metadata object becomes critical in modeling the propagation of spatial error.

CHAPTER **3**

INTERPRETATION, APPRAISAL, AND APPLICATIONS

3.1 INFLUENCE OF OTHER MODELS, STANDARDS, AND SPECIFICATIONS

3.1.1 Introduction

This section explains how the MDLRS data model uses existing geospatial data models to meet the functional requirements identified by transportation stakeholders. Table 3-1 provides a matrix of the relationship between MDLRS data model objects and the geospatial standards used. Each row identifies the objects in each standard that corresponds to the MDLRS data model objects. Some MDLRS data model objects were derived from research literature or communication with experts in that field. For example, the spatial datum hierarchy (e.g., geocentric and horizontal) with datum objects (e.g., three-dimensional Cartesian axes and ellipsoid) and reference objects (e.g., GPS satellite and control station) were derived from Vonderohe and Hepworth (*43*). Additionally, the measurement objects in the MDLRS data model were derived from the work of Hintz and Onsrud (*44*) and Jeffress, Hintz, and Onsrud (*45*).

3.1.2 CGIS-SAIF

CGIS-SAIF formal definition standards (*19*) were generated as a means of sharing spatial and spatiotemporal geographic data.

In CGIS-SAIF, objects representing real-world phenomena are called geographic objects. The region in space occupied by a geographic object is called a spatial object and consists of geometric and spatial referencing elements (*19*). The CGIS-SAIF spatial referencing objects can accommodate many nonlinear referencing systems (e.g., geodetic, UTM, State Plane Coordinate System [SPCS], Universal Polar Stereographic [UPS], planar projection, rectangular, and polar), but they do not provide the constructs to accommodate linear referencing systems.

CGIS-SAIF has no primitive topological constructs, but only primitive geometric constructs, such as a point, vector line, vector area, and vector volume. Associated with a point object is a coordinate object. In this standard, the coordinate object is represented as a superclass, with subclasses representing coordinates of different dimensions (e.g., one-dimensional coordinates, two-dimensional coordinates, and three-dimensional coordinates). CGIS-SAIF is unique among standards. These coordinate subclasses have attributes c1, c2, and c3, depending on the coordinate dimension. The meaning of c1, c2, and c3 is defined through the coordinate system specified by the spatial referencing object. This process thereby allows for the storage of a variety of spatial expressions. Additionally, in CGIS-SAIF, each of the coordinate subclasses can have a time coordinate associated with each object, indicating whether the coordinate has a time relevance (e.g., one-dimensional time coordinate, two-dimensional time coordinate, and three-dimensional time coordinate).

In CGIS-SAIF, the region of space and time occupied by a geographic object is called a spatiotemporal object. The spatiotemporal object is a spatial object with time values and temporal referencing.

CGIS-SAIF includes the temporal element in the modeling of phenomena and the temporal relationships between phenomena. This inclusion of the temporal element and temporal relationships is a major strength of this standard. The storage of the temporal element is in a time object. A time object can carry a value for a time, a date, an interval, a duration, or a collection of such values. A unique feature of this standard is the inclusion of an object for temporal referencing. In CGIS-SAIF, a temporal referencing object provides information on (a) whether UTC is being used or whether GPS timing applies and (b) the offset from UTC in hours and minutes (i.e., UTC offset object). In this standard, all time objects are associated with a temporal referencing object, which accommodates a temporal datum that is either UTC- or GPS-based (*19*). The UTC offset object is provided to allow for offsets to different temporal referencing methods and allows for transformation between temporal referencing methods.

Through the use of time coordinates as represented by the time object, temporal topological relationships can be derived. The CGIS-SAIF model provides for explicit temporal topology through the temporal relationship object. The temporal relationship object defines the temporal relationships between geographic objects. The CGIS-SAIF model is unique from other geospatial standards in that it provides a rich set of temporal relationship objects and also provides the pseudocode to implement several of these objects. Examples of temporal relationship concepts in this standard include temporal topology (e.g., overlap, during, and simultaneous), precedence, temporal proximity, temporal neighborhood, and temporal offset.

TABLE 3-1 Shared objects between MDLRS data model objects and the geospatial standards used

MDLRS data model object	CGIS-SAIF	ISO 15046	NCHRP 20-27(2)	GIS-T/ISTEA PFS
Transportation Feature	Geographic Object	feature		transportation component
Conveyance				
Transportation Complex				transportation complex
Transportation System				transportation system
Experience				experience
Event				event
Complex Event				
Spatial Referencing System	Spatial Referencing	Spatial Referencing System		
Spatial Datum				
Vertical Datum				
Geoid				
Local Datum				
Benchmark				
Geocentric Datum				
3D Cartesian Axes				
GPS Satellite				
Horizontal Datum				
Ellipsoid				
Projection				
Control Station				
Cadastral Datum				
Corner				
Corner Point				
Linear Datum			Linear Datum	reference network
Linear Reference Method			Linear Referencing Method	linear references
Anchor Point			Anchor Point	anchor point
Anchor Section			Anchor Section	anchor section
Transport Node				transport node
Transport Link				transport link
Transport System Link				transport system link
Traversal			Traversal	traversal
Traversal Link				traversal link
Traversal Reference Point			Traversal Reference Point	traversal reference point
Temporal Referencing System				
Temporal Datum	Temporal Referencing	Temporal Referencing System		
Temporal Referencing Method	UTC Offset	Temporal Coordinate		
Spatial Object	Spatial Object	Spatial Object		
Scale Applicability Constraint				
Dimensionality Constraint				
Geometric Object	Geometric Object	GM_Object		
Geometric Primitive		GM_Primitive		
Point		GM_Point		
Reference Point				
Curve		GM_Curve		
Surface		GM_ Surface		
Solid		GM_Solid		
Geometric Complex		GM_Complex		

Another strength of CGIS-SAIF is the extensive set of provided metadata objects. Virtually all of the metadata objects refer to the geometric object. Of special note are the source and lineage metadata objects. The source metadata object identifies the administrative aspects of where the data come from and possible restrictions on the use of the data. The lineage metadata object indicates the history or parentage of the data, including their compilation and processing history.

3.1.3 ISO 15046

ISO 15046 is being prepared by the Technical Committee ISO/TC211 Geographic Information/Geomatics. ISO 15046

TABLE 3-1 (*Continued*)

MDLRS data model object	CGIS-SAIF	ISO 15046	NCHRP 20-27(2)	GIS-T/ISTEA PFS
Coordinate	Coordinate			
1D Coordinate	Coord1DT			
2D Coordinate	Coord2DT			
3D Coordinate	Coord3DT			
GPS Coordinate				
Linear Coordinate				
Measurement				
1D Gnd Measurement				
2D Gnd Measurement				
3D Gnd Measurement				
Radio Frequency Measurement				
Linear Measurement				
Distance Measurement				
Angle Measurement				
Direction				
Variance/Covarience Matrix				
Topological Object		TP_Object		
Topological Primitive		TP_Primitive		
Node		TP_Node		
Edge		TP_Edge		
Face		TP_Face		
Volume		TP_Solid		
Topological Complex		TP_Complex		
Network			Network	
Time Object	Time Object			
Date Time	Date Time	Instant		
Date	Date			
Time	Time			
Timestamp	Timestamp			
Temporal Measure				
Temporal Error Measures				
Duration	Interval	Duration		
Year Month Duration	Year Month Interval			
Day Time Duration	Day Time Interval			
Interval	Duration	Period		
Time Aggregate	Time Aggregate			
Cycle				
Break				
Stage				
Sequence				
Temporal Relationship	Temporal Relationship			
Temporal Topology	Temporal Topology			
Temporal Proximity	Temporal Proximity			
Metadata				
Source Metadata	Source			
Lineage Metadata	Lineage			

Note:
1D = one-dimensional.
2D = two-dimensional.
3D = three-dimensional.
Coord1DT = one-dimensional time coordinate.
Coord2DT = two-dimensional time coordinate.
Coord3DT = three-dimensional time coordinate.
Gnd = ground.
GM_ = geometric.
GPS = global positioning systems.
TP_ = topological.
UTC = Coordinated Universal Time.

is a structured set of standards for information concerning objects or phenomena that are directly or indirectly associated with a location relative to the Earth (*21*).

In this standard, features are the representations of real-world phenomena associated with a location relative to the Earth, about which data are collected, maintained, and disseminated (*21*). A feature may have associated with it one or more spatial attributes. The value of a spatial attribute is a spatial object that describes one or more characteristics, such as location, size, shape, and spatial relationships to other spatial objects in the same "world," or SRS (*21*). In ISO 15046, spatial objects are classified into separate geometric objects and topological objects. These geometric and topological objects are both subclassified into primitives and complexes. A spatial object can consist of a single geometric or topological primitive of zero, one, two, or three dimensions, or a set of these.

Geometry provides the means for the quantitative description, by means of coordinates and mathematical functions, of the spatial characteristics of features, including dimension, position, size, shape, and orientation (*21*). A geometric object is the combination of a coordinate geometry and an SRS. The geometric object is the root class of the geometric object taxonomy. The geometric object can be subdivided into geometric primitive and geometric complex objects. A geometric primitive is a geometric object that is not decomposed further into other primitives in the system. Types of geometric primitives are geometric point (zero-dimensional), geometric curve (one-dimensional series of one or more geometric curve segments), geometric surface (two-dimensional), and geometric solid (three-dimensional).

Topology deals with the characteristics of geometric figures that remain invariant if the space is deformed elastically and continuously—for example, when geographic data are transformed from one coordinate system to another (*21*). The root class for the topological system is the topological object. The topological object can be subdivided into topological primitive and topological complex objects. Topological primitives are the non-decomposed elements of a topological complex. The topological primitive object can be subdivided into topological node (zero-dimensional), topological edge (one-dimensional), topological face (two-dimensional), and topological solid (three-dimensional).

The temporal schema in ISO 15046 is provided in great depth. Temporal schema defines standard concepts needed to describe the temporal characteristics of geographic information (*21*). Time, like space, has geometry. A point in time occupies a position that can be identified in relation to a TRS. Time in ISO 15046 is measured on two types of scales: ordinal and interval. An ordinal time scale provides information only about relative position in time, whereas an interval time scale provides a basis for measuring duration (*21*). ISO 15046 is unique among geospatial standards in that it separates the temporal dimension, like the spatial dimension, into separate geometric and topological constructs.

The two geometric primitives in the temporal dimension are the instant and the period (*21*). The instant is the zero-dimensional temporal geometric primitive, equivalent to a point in space. An instant is associated with a single temporal position in a given TRS. The period is the one-dimensional temporal geometric primitive, equivalent to a curve in space. Like a curve, it has beginning and end points (each an instant), and a length (its duration). Because time is one-dimensional, there are two temporal topological primitives: the zero-dimensional temporal node and the one-dimensional temporal edge (*21*).

A value in the time domain is a temporal position measured relative to a TRS (*21*). In ISO 15046, the primary TRS uses the Gregorian calendar and 24-h local time or UTC. Two unique features of ISO 15046 are that it uses a TRS model and that the model includes three types of TRSs: calendars (used with clocks for greater precision), temporal coordinate systems, and ordinal TRSs.

3.1.4 The NCHRP 20-27(2) LRS Data Model

The NCHRP 20-27(2) LRS data model (*1*) was created to facilitate sharing of linearly referenced data across modes and agencies. This data model is a conceptual model, not a specification, and its scope is linear (although there are links to higher dimensions).

The NCHRP 20-27(2) LRS data model provides the framework to manage and transform linearly referenced data. In this framework, the central notion is that of a linear datum that supports multiple cartographic representations (at any scale) and multiple network models (for various application areas). The linear datum is composed of anchor points and anchor sections connecting these points. The datum provides the fundamental referencing space for transformations among various linear referencing methods, network models, and cartographic representations (*1*).

Cartographic representations provide coordinate references and the basis for to-scale visualization of the model. They are collections of geometric objects that have shape and position. The NCHRP 20-27(2) LRS data model provides an association between linear references and two- and three-dimensional references by associating the linear datum with the geometric objects that compose the cartographic representation. This association to two- and three-dimensional GIS databases provides the framework for transformations between linear and nonlinear data.

In the NCHRP 20-27(2) LRS data model, collections of business data are tied to the model by linear referencing methods. These methods might be those associated with infrastructure management, such as reference post, milepoint, or engineering stationing. They might also be those associated with navigation (requiring recognizable landmarks or navigation aids), with transit (timing points), or with a host of other application areas. These linear referencing methods consist of traversals and associated traversal reference points that together provide a set of known points, a metric, and a direction for referencing the locations of unknown points. A traversal is an ordered and directed, but not necessarily connected, set of whole topological links, whereas a traversal reference point is a zero-dimensional location along a traversal that is used to reference business data along the traversal (*1*).

A number of linear referencing methods might be associated with a network model, which references a linear datum. A network model provides the topological framework for pathfinding, routing, location/allocation, transshipment, and flow operations. Within the context of the linear referencing system data model, a network is an aggregate of nodes and links and is, thus, a purely topological object.

3.1.5 GIS-T/ISTEA PFS

The GIS-T/ISTEA Management Systems Server Net Prototype PFS (*2*) was initiated to support ISTEA requirements for multijurisdictional, intermodal transportation facilities planning and management systems.

The PFS model provides a transportation-based model of geospatial data and relationships. In the PFS model, one of the key objects is the transportation component. The transportation component represents a transportation-based phenomenon that can be considered by the transportation stakeholder as non-decomposable. Examples of transportation components are signs, guard rail, pavement, and HOV lanes. Business data or point/linear events can be considered synonyms for transportation components. Transportation complexes are collections of transportation components, and transportation systems are collections of transportation components, complexes, and other transportation systems.

The PFS model represents the history of transportation-based phenomena. In the PFS model, events change the state or attributes of objects (i.e., transportation components). Events represent action while transportation components are acted on (*2*). Associated with a transportation component is a registry of individual events that acted on the transportation component. These individual events that change an attribute of a transportation component aspatially, spatially, or temporally are called experiences. For example, a “crash” is an external event, while “damage” is the vehicle’s experience of that crash (*35*). Over time, the experiences of a transportation component accumulate, and each experience marks the beginning of a new component state. The life cycle of a component (i.e., the entire time that the component is known to the database) is the time-ordered sequence of all its experiences (*2*). This event registry, or “container of memories,” for the transportation component allows for the regeneration of object and network states over time.

The PFS adopted the NCHRP 20-27(2) LRS data model. In the PFS model, a traversal reference point and a traversal (e.g., route) describe a transportation component location. The traversal consists of a collection of transport links defined by transport nodes. The transport nodes are located on anchor sections defined by anchor points. The collection of anchor points and anchor sections make up the linear datum.

In the PFS data model, the set of transport links and transport nodes is equivalent to the topological network consisting of links and nodes in the NCHRP 20-27(2) model. However, transport links and transport nodes are transportation components with topological representations. Additionally, anchor points and anchor sections are transportation components in the PFS data model.

3.2 DISCUSSION OF THE MDLRS MODEL AS RELATED TO FUNCTIONAL REQUIREMENTS

3.2.1 Introduction to Functional Requirements and Specifications

This section shows how the MDLRS data model satisfies the functional requirements recommended by the participants of the stakeholder’s workshop held in Washington, D.C., on December 3–5, 1998.

One of the first steps in developing a comprehensive, multidimensional transportation LRS is to identify the system’s functional requirements (i.e., what it is intended to do). Webster (*46*) defines a requirement as “something needed; necessity; need.” Functional requirements are model independent and lead to data requirements—that is, the information needed to perform the desired functions (*47*). According to Martin (*48*), some functional requirements are indirect statements of business rules. Business rules characterize relationships between data (e.g., a divided highway must have a median type and width, and a bus stop must be assigned to a bus route). Additionally, functional requirements may be driven by technology. These requirements can be traced back to a recognized potential use of technology that is limited by the current representation of data.

Details of functional requirements are provided through functional specifications. Webster (*46*) defines a specification as “a detailed description of the parts of a whole; statement or enumeration of particulars, as to actual or required size, quality, performance, terms, etc.”

Functional requirements and specifications are the basis for the development of a detailed data model. A data model, as defined by Date (*49*), is “a standard way of describing data requirements as a set of entities—things we want to know about and include in the information system—and the relationships between them.”

Ten core functional requirements were synthesized from the results of the NCHRP 20-27(3) workshop. These core functional requirements form the essence of the MDLRS data model. Supporting each functional requirement is a set of functional specifications. The specifications represent the details of each functional requirement and are the basis for examining existing data models.

The following sections review each of the ten functional requirements. Each section contains a discussion of the requirement, the functional requirement statement, the functional specifications, and an explanation of how the MDLRS data model meets the functional requirement.

3.2.2 Functional Requirement I: Spatiotemporal Referencing Methods

A comprehensive, multidimensional LRS supports multiple alternative spatiotemporal referencing methods. The locations of objects and events in a multidimensional transportation system can be expressed in a variety of spatiotemporal methods, some of which are

- Coordinates (e.g., latitude-longitude and UTM),
- Cross streets or intersections (e.g., Birch between Ash and Cedar plus offset),
- Civic addresses (e.g., 1725 Birch),
- Linear referencing (identifier plus offset),
- Landmark referencing,
- Custom grid references (e.g., Thomas Brothers),
- Identifications for nodes and links,
- Bus route and offset, and
- Bus route and time.

Time is defined as "a system for measuring duration" (*46*). Time can be represented or sampled as static (in which a snapshot is taken of conditions at a measurable interval) or as dynamic or real time (in which the interval of measurement is so small that one snapshot flows into another and the change becomes undetectable, like a movie).

For planning and analysis applications, the temporal dimension can be thought as being linear and branching. Movement is bi-directional (i.e., goes both forward and backward), and the rate is variable. Events such as crashes can be viewed as breaks in the continuum. The days of the week and months or seasons of the year can be thought of as cyclical.

In actuality, location in space does not exist without time. Both location and time are necessary to provide a complete reference. This reference for an object can be formulated if given a spatial or a temporal location only. Because space and time depend on each other, if given one dimension of an object (e.g., space or location), then the other dimension can be derived (e.g., the time of existence). Thus, if the location of an object is known, then the time(s) of its occurrence can be found. Conversely, if the time of the occurrence of an event is known, then the unambiguous location of the event can be found.

There are several manifestations of time in GIS-T applications, including

- Event,
- Life-cycle (e.g., of a project),
- Arrival/departure,
- Movement through time,
- Latency, and
- Duration.

Some temporal referencing methods are zonal standard time, zonal daylight time, and military time. For GIS-T applications, temporal referencing methods must support the articulation of "start," "end," and, optionally, "schedule." "Start" is a time expression for a point in time. "End" is a time expression for an offset from the start point in time. "Schedule" is a sequence of activities and breaks. Schedules may follow natural cycles according to season, day of week, time of day (e.g., day/night or a.m./p.m. peak/off-peak). Objects can change character or attributes (e.g., bus routes or reversible lanes) on the basis of time of day.

Multidimensional spatiotemporal expressions must also be able to express a variety of locational representations with dimensional requirements and uncertainty estimates. The dimensional requirement can be satisfied by a measurement and offset. The measurement locates objects and events relative to a roadway longitudinally in the proper relative order with respect to other objects and events. The offset specifies laterally the appropriate lane of the highway. The vertical location should be sufficient to place an event or object on the proper feature and to perform functions such as separating planar-coincident facilities (e.g., road-on-bridge versus road-under-bridge).

Participants of the NCHRP 20-27(2) workshop identified four functional requirements of an LRS in the linear data domain: "locate," "position," "place," and "transform" (*1*). "Locate" means to establish the location of a point in the field in relation to another object. "Position" means to define a real-world location in a database. "Place" means to convert the database description into a real-world location. "Transform" means to convert location references made in one method to another. The NCHRP 20-27(2) requirements dealt with locations in space. The participants of the NCHRP 20-27(3) workshop expanded the four NCHRP 20-27(2) requirements to include locations in both space and time.

Functional Requirement I is as follows: A comprehensive, multidimensional LRS data model must support the locate, place, and position processes for objects and events in three dimensions and time relative to the roadway.

The functional specifications for this requirement are as follows:

- I.a: A model must store spatiotemporal expressions that specify location and time, in as many as four dimensions, for objects and events. This requirement is more than storage of x-, y-, z-, and t-coordinates. For example, spatial expressions may include linear locations, elevations (as opposed to z), and three-dimensional rectangular coordinates.
- I.b: A model must store the known spatiotemporal expressions for location and time of reference objects.

- I.c: A location of spatial reference objects must be recoverable in the field. A field crew is assumed to carry the temporal reference objects (e.g., clocks, watches, and calendars).
- I.d: A model must distinguish between referenceable and nonreferenceable objects. Referenceable objects are physical objects that can be used as references for measurements, whereas nonreferenceable objects are logical objects. For example, a tree or a signpost could be considered “referenceable,” but the centerline of a roadway would not.

The MDLRS data model satisfies Functional Specification I.a through the use of coordinate and time objects. The coordinate object (see Figure 2-13) specifies the location in space of transportation features and events through a geometric object. The abstract data type, coordinate object, contains both the time interval of the object and the method associated with the coordinate type (e.g., the projection method or the linear referencing method). The coordinate object subclasses correspond to five SRSs: one-dimensional coordinate (vertical), two-dimensional coordinate (map projection), three-dimensional coordinate (local), linear coordinate, and GPS coordinate (geocentric). The coordinate object hierarchy allows for storage of locations in as many as four dimensions and provides the flexibility to accommodate a variety of spatial expressions from different SRSs and different spatial referencing methods instead of providing storage of x-, y-, z-, and, optionally, t-coordinates.

The temporal location of transportation features and events is through the time object. The time object (see Figure 2-14) is used in the MDLRS data model whenever the temporal element needs to be stored. For a transportation feature, the time object is used to store the validity period (i.e., the time of creation through time of retirement) of an attribute and a spatial object. For an event, the time object is used to store when an event is expected to occur and when the event actually occurred. The time object is referenced to a temporal referencing method object, which allows for different calendars, metrics, and offsets to be used. The time object hierarchy supports a variety of temporal expressions, in addition to a timestamp. In the MDLRS data model, the time object can be expressed as a temporal point (i.e., date time object or timestamp), as a temporal curve (i.e., interval object), as a temporal measure (i.e., duration object), or as a temporal complex (i.e., time aggregate object).

The MDLRS data model satisfies Functional Specification I.b through the use of reference objects and reference points. Reference objects (see Figure 2-12) are objects whose locations are known and from which measurements are made in the real world to determine the unknown locations of other objects. In the MDLRS data model, a reference object is a transportation feature and inherits the temporal characteristics of a transportation feature. The spatial location of the reference object is represented by a reference point, which is a point object, and inherits all the characteristics of the reference point. Therefore, a reference point can store the location of reference objects in as many as four dimensions. In the real world, reference objects can be represented by more than one coordinate, each in a different SRS or spatial referencing method. A reference object can be associated with one or more reference points, each having only one coordinate representation.

The MDLRS data model satisfies Functional Specification I.c through the use of reference objects, reference points, and measurement objects (see Figures 2-12 and 2-13). The reference object contains a description so that it can be recovered in the field.

In certain situations, the location of a reference object is derived from measurements to specified reference objects. If a reference object is un-recoverable from a description, the location of the reference object can be recovered from measurements. In the MDLRS data model, the spatial location of a reference object is realized through its associated reference points. Each reference point has an associated coordinate object. If the coordinate is derived, measurement objects associated with the coordinate object can be retrieved from the database. The location of the reference object can then be “placed” by the provided measurements.

The MDLRS data model satisfies Functional Specification I.d by distinguishing between “referenceable” and “nonreferenceable” objects through the use of an attribute, “referenceable,” in the transportation feature superclass.

3.2.3 Functional Requirement II: TRS/Temporal Datum

The most common TRS is Greenwich time, which is based on a temporal datum (i.e., UTC). All temporal referencing methods can relate to UTC. Local temporal referencing methods, such as zonal time, are tied to UTC through calibration and consistency of measurement (i.e., a minute is the same duration across all methods).

In a way, a linear LRS of multiple linear referencing methods (e.g., milepost-offset) is similar to a TRS of multiple temporal referencing methods. Because movement in time is restricted to one dimension (i.e., because time is uni- or bi-directional), many of a linear LRS’s components apply to a TRS. Temporal references can be relative to an origin (e.g., A.D. 0), analogous to route-mile-point spatial references (e.g., Rt 12 MP 2.1). Alternatively, temporal references can be relative to local reference points (e.g., 3 p.m., January 12, 2001), analogous to route-reference-point spatial references (e.g., I-93 RP 200 + 100′). Local temporal references can be transformed into universal temporal references if we know the universal reference of the local reference point (e.g., today’s date). Events in time can be instantaneous, analogous to spatial point events. In addition, events in time can have durations with beginnings and ends, analogous to linear spatial events.

Functional Requirement II is as follows: A comprehensive, multidimensional LRS data model must accommo-

date a temporal datum that relates the database representation to the real world and must provide the domain for transformations among temporal referencing methods.

The functional specifications for this requirement are as follows:

- II.a: A model must provide for transformation among temporal referencing methods.
- II.b: A model must provide for multiple temporal referencing methods (e.g., zonal times, solar time, and military time). A model must provide storage for an explicit temporal datum (e.g., UTC) that is used as the basis for transformation among temporal referencing methods. Alternatively, a model must provide for the explicit definition of one temporal referencing method to be the temporal datum.

The MDLRS data model satisfies Functional Specification II.a through the use of a temporal reference equation in the temporal referencing method object (see Figure 2-9). A temporal reference equation relates the temporal datum to the temporal referencing method. The temporal reference equation is derivable and consists of two parts: a reference offset (e.g., –3 h for zonal time) and a metric scaling function that relates the metric of the method to the metric of the datum (e.g., to convert between Julian dates and Gregorian calendar time). The temporal reference equation can accommodate various metrics and various temporal representations. Through the reference offset and metric scaling function, the temporal reference equation method allows for transformation among temporal referencing methods.

The MDLRS data model satisfies Functional Specification II.b through the use of temporal referencing method objects (see Figure 2-9). The temporal referencing method object provides the means (i.e., the temporal reference equation) to relate the metrics of the temporal datum to the metrics of time objects. Each temporal referencing method object can represent different temporal referencing methods.

The MDLRS data model uses a "spoke-and-hub" approach to model the relationship between the temporal datum and temporal referencing method objects: all methods relate to one designated method, which becomes the defined temporal datum. The MDLRS data model concentrates on temporal referencing methods whose metrics are the same as the datum and assumes UTC and the Gregorian calendar as the temporal datum.

3.2.4 Functional Requirement III: Transformation of Data Sets

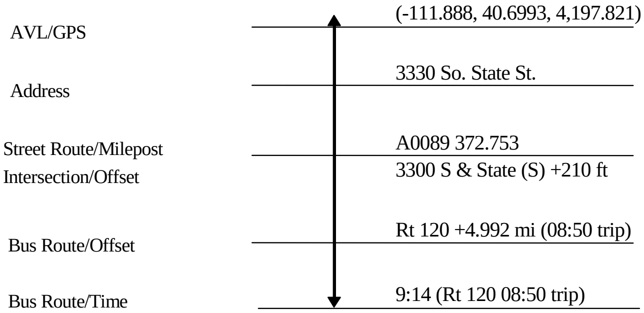
Transformation of the spatiotemporal locations from one method to another is fundamental to the utility of a comprehensive, multidimensional LRS data model. The transformation of data provides the necessary key for the interoperability of data sets in and among stakeholders. Transformation among linear location referencing method, location referencing method, and temporal referencing method should be accomplished without loss of information and with an error not greater than that inherent in the source methods. Issues such as the accuracy, resolution, and source of data sets and individual objects become critical in that they provide limits on the results of the transformation process.

There are several categories of the transformation of data sets. The first category is a purely spatial transformation, with time being a constant. This category includes the transformation from one linear location referencing method to another (addressed by the NCHRP 20-27[2] data model), the transformation of a linear location referencing method to or from a two- or three-dimensional location referencing method, and transformation among two- or three-dimensional location referencing methods. The transformation of a linear location referencing method to and from a two- or three-dimensional location referencing method requires additional data, such as offset measurements, and the use of a "snapping" function, respectively. Transformation among two- or three-dimensional location referencing methods is performed through traditional cartographic transformation methods, such as "rubber-sheeting," or from one map projection to another.

The second category of transformation involves converting a location referencing method address at a specific time to the equivalent location referencing method address at a different time (e.g., finding the route-post-offset in 1990 of the location that is now Route 30 Post 15 Offset 10). This spatiotemporal transformation supports historical analysis and data integration.

The third category of transformation involves converting a location referencing method to a temporal referencing method. Figure 3-1 illustrates some of the methods that the transformation function must use to operate. These transformations may be achieved through piecewise linear (possibly stochastic) functions.

An alternative approach to defining the transformations among representations is to use a mathematical language and



Note:
AVL = automatic vehicle locations.
GPS = global positioning systems.

Figure 3-1. Multiple spatiotemporal referencing methods.

notation in conjunction with a data model. If the transformations are directly mapped to each other (i.e., without approximation), the mathematical model can guarantee the data model relationships.

Functional Requirement III is as follows: A comprehensive, multidimensional LRS data model must support transformation among linear, nonlinear, and temporal referencing methods without loss of spatiotemporal accuracy, precision, and resolution.

The functional specifications for this requirement are as follows:

- III.a: A model must provide for transformation among purely spatial location referencing methods (with time as a constant), including
  - III.a.i: Transformation from one linear location referencing method to another (addressed by the NCHRP 20-27[2] data model).
  - III.a.ii: Transformation to or from a linear location referencing method to a two- or three-dimensional location referencing method, and
  - III.a.iii: Transformation among two- or three-dimensional location referencing methods.
- III.b: A model must provide for transformation from a linear location referencing method address at a specific time to the equivalent linear location referencing method address at a different time.
- III.c: A model must provide for transformation from a linear location referencing method with a linear datum to a pure temporal referencing method with a temporal datum (e.g., converting a spatial location of a bus stop into a temporal location).
- III.d: A model must provide a spatiotemporal referencing system that was designed to provide a certain level of accuracy and precision. If a model supports a datum to be used for transformation, then it is assumed that there is no loss of precision, accuracy, and resolution during transformation among methods.

The MDLRS data model satisfies Functional Specification III.a.i through the linear location referencing data model shown in Figure 2-11. The linear location referencing data model is adopted from the GIS-T/ISTEA PFS for location referencing (*2*), which is derived from the NCHRP 20-27(2) generic data model for location referencing (*1*). In the PFS linear referencing model, the linear datum is made up of anchor point and anchor section objects. Traversals are collections of transport links that are bounded by transport nodes, which are located on anchor sections. A linear reference method is an aggregation of traversals and traversal reference points.

The MDLRS data model satisfies Functional Specification III.a.ii through the relationship "represents" and its association between the geometric object and the anchor section object (see Figure 2-11). To transform between linear and nonlinear systems, an anchor section object has to know what geometric object it represents. The relationship "represents" has an association that provides the missing coordinates (linear or nonlinear) to allow the transformation to occur. The association requires an anchor section snap method to generalize a two- or three-dimensional geographic object to a one-dimensional geometric object compatible with the associated anchor section object.

An anchor section can be associated with more than one geometric object with different applicable scales. For each geometric object at a different scale, a separate "represents" association is needed. A problem may arise when transforming the geometric object into a nonlinear datum (e.g., NAD 83) other than the nonlinear datum indicated in the "represents" association (e.g., NAD 27). The transformed geometric object may not fit with other existing geometric objects in terms of shape, size, and position because of the characteristics of the nonlinear datum. Therefore, one cannot assume that dually registered data, when transformed, will line up with other dimensionally compatible data. This limitation is a function of geodesy, not of the data model.

The MDLRS data model satisfies Functional Specification III.a.iii through the use of reference objects and geometric objects (see Figure 2-11). In the MDLRS data model, two- and three-dimensional reference objects reference geometric objects. Transformation between two- and three-dimensional location referencing methods for the same geometric object occurs when the reference from one location referencing method is changed to another through the use of traditional mathematical cartographic functions. These cartographic transformation equations do not introduce error when the origin of the Earth's center is the same for the two location referencing methods. Users accept as fact the error in transforming between two- and three-dimensional location referencing methods when the origins differ. The MDLRS data model does not add error to the transformation.

The MDLRS data model satisfies Functional Specification III.b through the linear referencing model and the experience objects of the transportation feature (see Figures 2-9 and 2-11). This specification takes a transportation feature with a linear location defined by a linear referencing method and moves it forward or backward in time and lays the same linear referencing method on the feature. Going forward or backward in time is a matter of adding or rolling back experiences of the transportation feature. For example, to find the route-post-offset in 1990 of the location that is now Route 30 Post 15 Offset 10, one would have to (1) find the transportation feature presently with that linear location, (2) rollback the transportation feature to 1990, (3) tie the route-post-offset linear location referencing method to the transportation feature, and (4) find the route-post-offset of the transportation feature.

The MDLRS data model satisfies Functional Specification III.c through the conveyance, linear reference method, and radio frequency measurement objects (see Figures 2-9, 2-11, and 2-13). Functional Specification III.c pertains to moving objects or conveyances and covers two situations. The first situation involves a given location and a requirement to find the time the conveyance will arrive at that location. To find the time when the conveyance will arrive at a location requires either knowing the conveyance's current location and a prediction algorithm or knowing its predefined schedule (for transit vehicles) and linear interpolation. Using a prediction algorithm or predefined schedule, the resultant time value is an approximation with a confidence interval. If one wants to find historically when a vehicle arrived at a location, one can go to a time-space diagram derived for that route from the conveyance's tracking and routing routines. The second situation involves a given time value and a requirement to find where the conveyance is. Again, one can consult a predefined schedule of a vehicle and perform linear interpolation, or one can use an historical time-space diagram for a route to find where a vehicle will arrive at a certain time. The results would also be an approximation.

The transformation from a linear location referencing method to a temporal referencing method is valid primarily for transit vehicles on a fixed route. The transit route is referenced to a network using a linear referencing method. A location along a transit route can be tied relatively to a set of time periods through a schedule. In many situations, GPS or a radio frequency measurement is used to denote the location of a transit vehicle along a route. The location transmitted by radio frequency measurements also contains some error, which can affect prediction algorithms. Additionally, radio frequency measurements, including GPS, also transmit a time stamp with location. When using radio frequency measurements, the transformation needed is between a three-dimensional location referencing method and a linear location referencing method, not between a linear location referencing method and a temporal referencing method, because the time value is given. Finding a location (or time) given a time (or location) for a conveyance is and has historically been a matter of going through past radio frequency measurements of the conveyance. However, in the near future, finding a location (or time) given a time (or location) for that conveyance will be a matter of using current radio frequency measurements to find the conveyance's current location and time (i.e., tracking) and using a prediction algorithm.

The MDLRS data model satisfies Functional Specification III.d because the model supports a spatial datum through the datum object hierarchy (see Figure 2-11). The datum object hierarchy supports five types of spatial data (linear, cadastral, horizontal, geocentric, and vertical), their datum objects, and their associated reference objects.

3.2.5 Functional Requirement IV: Multiple Cartographic/Spatial Topological Representations

An object or event can be represented cartographically as a point, line, or area. The choice of cartographic representation is usually made to be consistent with the degree of generalization or scale of the map. For example, a bridge can be a point, a line, or an area, depending on the displayed scale. Or, when introduced into a one-dimensional system, that bridge can be a line regardless of scale.

Within current GIS models, an object or event has one topological representation: a node, a link, or a polygon. Generalization algorithms can change the object's cartographic representation, but the topological representation remains constant. To facilitate multidimensional spatial operations in transportation applications, the data model needs to support topological aliases of an object. Topological aliases for a bridge object may be a node, edge, or face, depending on the nature of the application accessing the bridge object.

A robust data model allows for multiple cartographic and topological representations of an object and provides linkages between representations so that changes in representations due to map scale or level of generalization lead to references to the appropriate cartographic or topological representation.

Functional Requirement IV is as follows: A comprehensive, multidimensional LRS data model must support multiple cartographic and topological representations at both the same level and varying levels of generalization of transportation objects.

The functional specifications for this requirement are as follows:

- IV.a: A model must support multiple alternative spatial topological representations for individual objects.
- IV.b: Each topological representation may have one or more associated cartographic representations of the same geometric object.
- IV.c: Each cartographic representation may have one or more associated topological representations.
- IV.d: Changes in cartographic representation (due to change in map scale) must lead to references to the appropriate topological representation to support analysis at that scale.
- IV.e: Changes in the topological representation (due to level of abstraction) must lead to references to the appropriate cartographic representation.
- IV.f: At interchanges and intersections, a model must support consistent turning movements and restrictions that apply for all topological representations.

The MDLRS data model satisfies Functional Specification IV.a through the one-to-many relationship between a transportation feature and a spatial object (see Figure 2-12). A transportation feature can have one or more spatial objects that can be topological objects.

The MDLRS data model satisfies Functional Specifications IV.b and IV.c through the many-to-many relationship between topological objects and geometric objects (see Figure 2-12). This many-to-many relationship allows transportation features, such as roadways, to be represented topologically as centerlines while cartographically displayed as two-dimensional lines.

The MDLRS data model satisfies Functional Specifications IV.d and IV.e through the scale applicability constraint and the dimensionality association on the relationship between topological objects and geometric objects (see Figure 2-12). In the MDLRS data model, each spatial object is assigned an attribute of scale applicability. Scale applicability indicates the scale range for which the object is valid. The scale applicability constraint allows scale-appropriate objects to be associated with each other. For example, a point (which is a geometric object) may have a scale applicability of 1:100,000 (i.e., the representation is valid for a scale of 1:100,000 and greater). Associated with that point can be several topological representations (from the many-to-many relationship). The scale applicability constraint allows only topological representations with a scale applicability of 1:100,000 or smaller (e.g., 1:1,000,000) to be associated with that point object. The scale applicability constraint works similarly for a topological object and its associated cartographic representations. The scale applicability constraint also provides for consistency in connections between objects. For example, a transportation system represented by a network would consist of transportation features with the same scale applicability.

An additional constraint on the relationship between topological and geometric objects is the dimensionality association. The dimensionality association is a set of business rules that further restricts the association of scale-related objects by dimensionality constraints. One example of these dimensionality constraints is shown in Figure 2-19. The dimensionality constraints are meant to provide dimensional consistency between geometric and topological representations to the user. For example, if a user is supplied a surface (i.e., area) representing the extent of a city, that user should be able to expect that a topological representation that is dimensionally consistent with the surface (i.e., a face) would be available to use for analysis. The dimensionality association and the scale applicability attributes and constraints are user defined. While the dimensionality association may be optional, the scale applicability constraint is not.

The MDLRS data model satisfies Functional Specification IV.f through the transportation complex object model of an interchange. In the MDLRS data model, the expression of an interchange, when given a full topology, is that of a transportation complex. The interchange transportation complex is made up of ramp and bridge transportation features (see Figure 3-2, Inset A). These ramp and bridge transportation features contain scale-appropriate topological representations. Viewing an interchange at different levels of abstraction requires that certain topological objects are used and others drop out because of a change in scale applicability. For example, if given the full topology of an interchange (see Figure 3-2, Inset A) and its associated data model (see Figure 3-3), to produce an interchange at a greater level of abstraction (see Figure 3-2, Inset B), certain topological objects drop out of the data model because of scale applicability and the result is a new aggregation of topological objects (see Figure 3-3). Reducing the level of detail in the interchange by further decreasing the scale applicability results in a bi-directional link representation (see Figure 3-2, Inset C) or a node representation with attributes indicating prohibited turns (see Figure 3-2, Inset D). Given a complete topology of an interchange, turning movements or restrictions are not necessary because the topology defines which movements are possible. With limited topologies (e.g., bi-directional links and node), prohibited turns may need to be recorded.

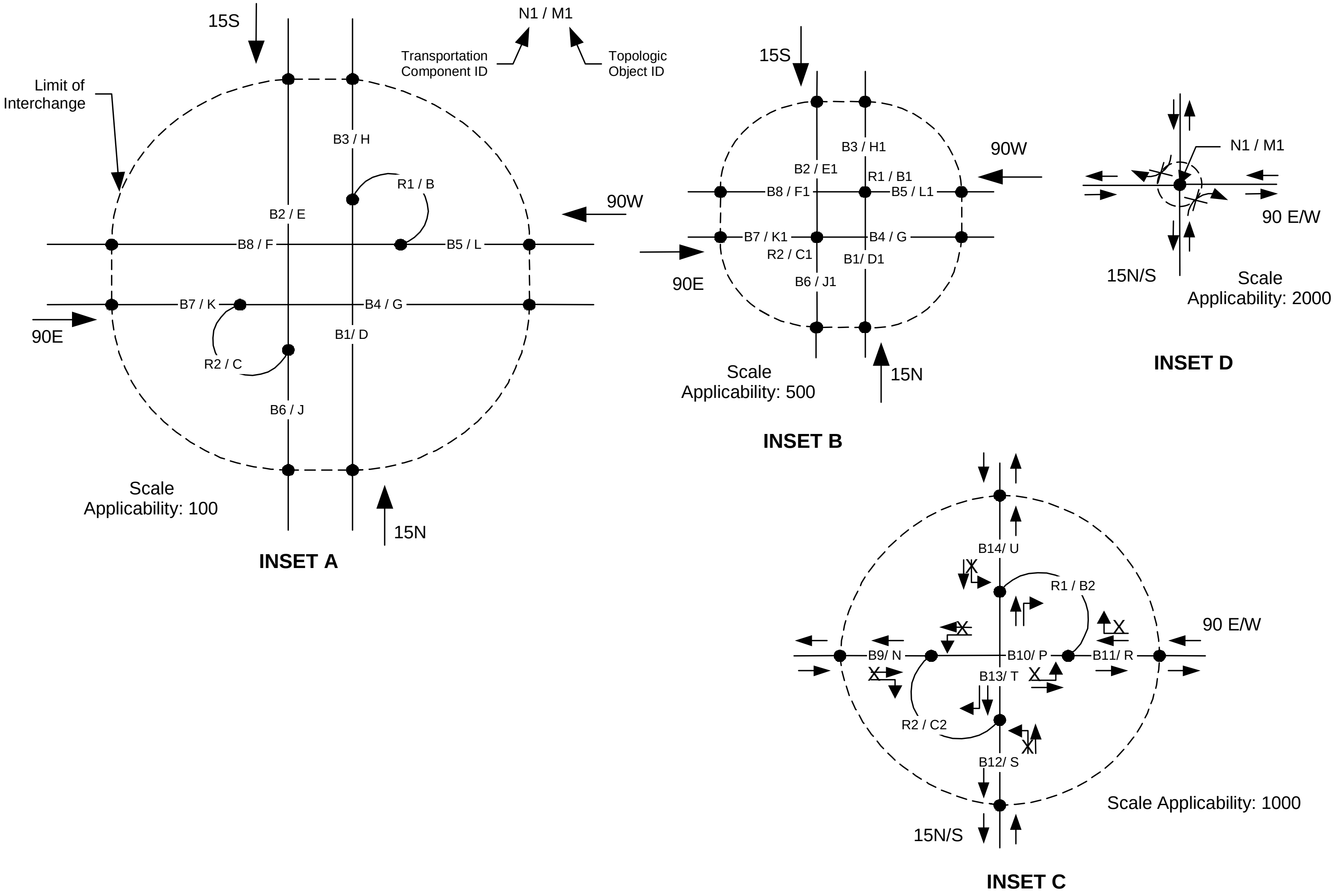
If the interchange model is initially given a limited topology, then each time a refined topology is given, the interchange needs to be remodeled. However, once the interchange is represented as a transportation complex, additions or alterations to the interchange are simply a matter of adding or altering transportation features. For example, if a node represents an interchange that has some turning restrictions (see Figure 3-2, Inset C), a transportation feature can be used to represent the interchange (see Figure 3-3). Later, when given a full topology of the interchange (see Figure 3-2, Inset A), the interchange model would need to be reassembled (see Figure 3-3) into a collection of transportation features. Adding a future ramp to the interchange entails adding a ramp transportation feature with suitable representations and altering bridge transportation features connected to the ramp.

Previously, it was noted that the topological objects that make up an interchange are intended for a certain level of abstraction or scale. Each topological representation of an interchange is meant to fit into a network consistent with the scale of the interchange so that an interchange represented as a node would fit into one roadway network at a certain scale and that same interchange represented as a topological complex would fit into another roadway network at a different scale. The modularity of topological representations of interchanges (i.e., a different topological representation of an interchange) would require a substantial amount of effort and would have to be weighed by the user against storing multiple versions of a roadway network.

3.2.6 Functional Requirement V: Resolution

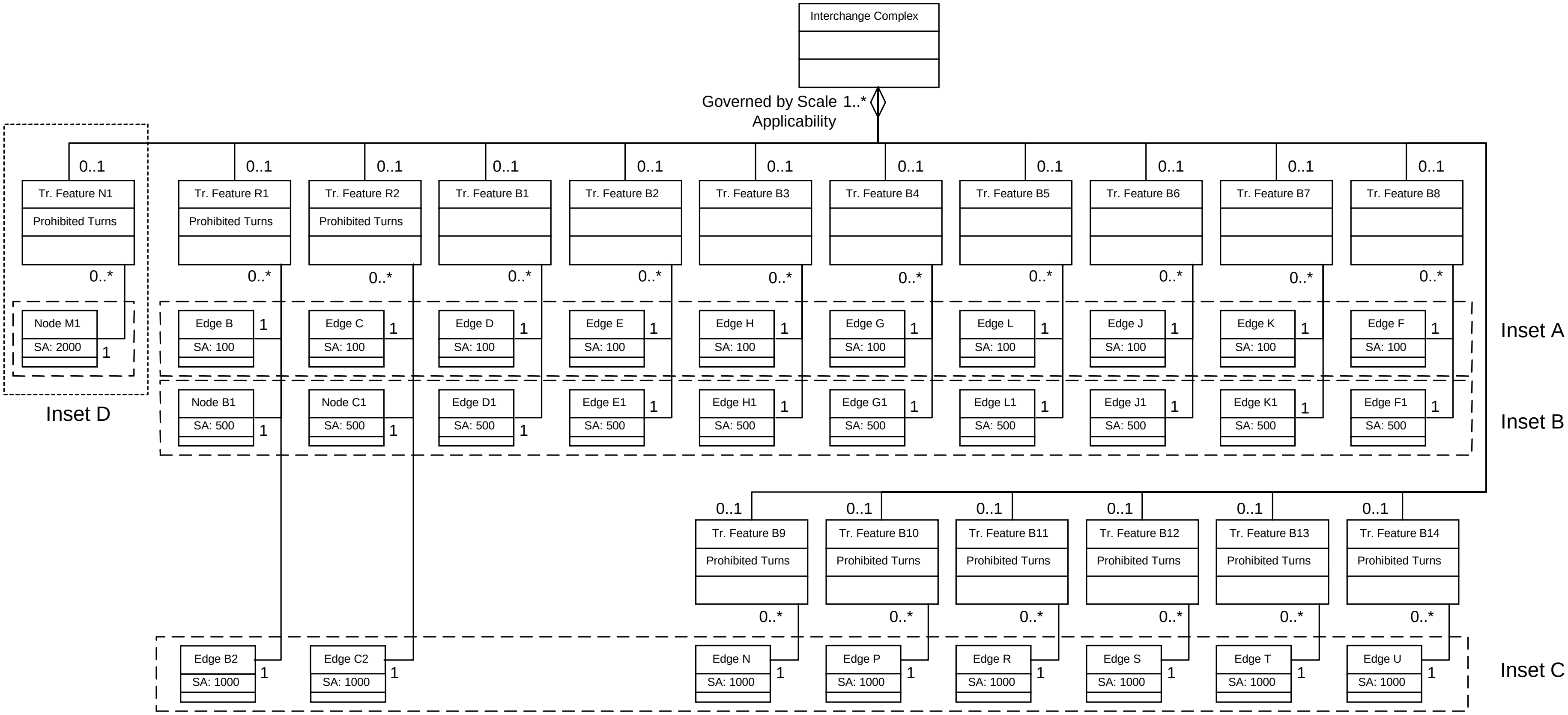
Resolution defines the granularity, or detail, of the data obtained and analyzed. Resolution can be expressed in terms of the number of significant digits for the source, display, and analysis of data. For example, mileposts can be recorded and displayed in 0.1, 0.01, 0.001 of a mile. The number of significant digits can decrease (but not increase unless warned) on the basis of the stakeholder's needs. The resolution of data displayed often depends on scale.

Level-of-detail requirements lead to thresholds not only of scale, but also of representation in higher dimensions. For example, representing crashes as spatial point events along a centerline is adequate for general analysis. In other cases, the



Note: Letters designate features and edges and correspond with the letters in Figure 3-3.

Figure 3-2. Topological representations of an interchange.



Note: Tr. = transportation. SA = scale applicability. All other letters designate features and edges and correspond with the letters in Figure 3-2.

Figure 3-3. Object model of interchange.

locations of crashes must be resolved to the lane level. For example, an incident may be recorded to a lane level (± 1 m) by GPS, which may be sufficient for incident management, but for safety management, the incident can be analyzed at a resolution of 0.01 km (± 10 m) or greater. Even further detail, in the form of two-dimensional representations of crash scenes, is sometimes needed. Finally, information on the third spatial dimension (e.g., bridge clearance or ditch depth) might be critical for analysis.

The considerations for spatial resolution also apply to temporal aspects of transportation data (*50*). For example, the time of occurrence of a crash measured to the nearest month might be adequate for seasonal analysis and to the nearest 12 h might be adequate for diurnal analysis, but to the nearest 15 min might be required for analysis of lighting conditions at dusk or dawn. Each of these three resolutions is associated with a need for determining temporal concurrency with other events.

Functional Requirement V is as follows: A comprehensive, multidimensional LRS data model must support the display and analysis of objects and events at multiple spatial and temporal resolutions.

The functional specification for this requirement is as follows:

- V.a: A model must not limit the user to a restricted resolution and dimensional specification for data collection and storage. Rather, a model must support the recording of objects and events at alternative spatial and temporal resolutions and alternative dimensional representations (e.g., point along centerline, lane level, areas, and vertical dimension).

Functional Specification V.a can be decomposed into two parts: (a) the recording of objects and events at alternative resolutions and (b) the recording of objects and events at alternative dimensional representations.

The MDLRS data model supports the recording of objects and events at alternative spatial and temporal resolutions through the use of measurement and time objects. As shown in Figure 2-13, measurement objects record the spatial measurements used to derive coordinates at unrestricted resolutions. Through the attribute “unit system” in the measurement object superclass, the user can specify which unit system (e.g., meters, feet, miles, or degrees) the measurement is in, but the resolution of the value entered for the measurement is unrestricted. As shown in Figure 2-14, the temporal measurement and duration objects record the temporal measurements of the time object. The temporal measurement and duration objects do not restrict the resolution of data values and allow various temporal constructs (e.g., interval and time aggregate objects) to be created.

The MDLRS data model also supports the recording of objects and events at alternative dimensional representations through the relationship between the transportation feature and the spatiotemporal object (see Figure 2-9). The transportation feature can have one or more spatiotemporal objects, each with a different dimensional geometric or topological representation.

3.2.7 Functional Requirement VI: Dynamics

Inherent to the design of the MDLRS data model is the functionality of movement within a system. The incorporation of time within the model provides for this functionality. Traversal guidance (e.g., being able to provide directions or navigation from an origin to one or more destinations as a function of select criteria) is a key function for many stakeholders.

Rather than merely providing the shortest path under ideal conditions, true traversal guidance incorporates infrastructure elements (e.g., clearances, crossings, and road closures), traffic-related elements (e.g., congestion during peak hours), demographic elements (e.g., schools and hospitals), and path restrictions (e.g., speed limits and HOV lanes), as well as pedestrian barriers (e.g., handicap access) based on the dynamics of time. Traversals should have the ability to be stored and modified in response to conditions that change during transit (i.e., they should be able to find the next best route en-route). The model also needs the ability to provide multiple alternative traversals to reach a location using various criteria (e.g., highest travel speed, shortest distance, lowest adjacent population, and fewest railroad grade crossings).

Therefore, there is a need for interoperability of data from different sources and the need for a robust set of guidance functions. Guidance must be demand responsive and provided either in real time (as for in-vehicle navigation) or within an accepted tolerance representing conditions at the time of the query. Inclusion of navigation requires an object to execute it. This object is referred to as a “conveyance” and is anything (usually a vehicle or a person) that moves in a spatiotemporal reference frame.

Functional Requirement VI is as follows: A comprehensive, multidimensional LRS data model must support the navigation of objects, in near real time and contingent on various criteria, along a traversal in a transportation network.

The functional specifications for this requirement are as follows:

- VI.a: A model must support conveyance objects with locations that are time dependent, a temporal referencing method for temporal reasoning, a path-finding algorithm for multimodal networks, time-dependent intersection movements and restrictions, time-dependent link attributes, and event objects having time-dependent attributes.
- VI.b: With regard to pathfinding in multimodal network topologies, a model must support proximity analysis for spatiotemporal disconnects among events and objects.
- VI.c With regard to link attributes that are time dependent, a model must support temporally based lane configurations, such as HOV lanes and reversible lanes.

The MDLRS data model satisfies Functional Specification VI.a through conveyance objects (see Figures 2-9 and 2-10). A conveyance is a moving object that contains the navigational functions "track" and "route." In the track function, the conveyance transmits to a dispatcher a sequence of time-dependent locations of the conveyance. The dispatcher then transforms the conveyance locations into a chain of positions (i.e., the dispatcher attaches the conveyance locations to the linear roadway network and obtains the traversal link the conveyance is on). From the track operator, the dispatcher creates a route by generating a path with linear tracks and a sequence of maneuvers, and transmits the routing instructions to the conveyance. The conveyance then follows the routing instructions and performs a tracking operation. The interaction between the conveyance and the dispatcher through the tracking and routing operations becomes cyclic. As the conveyance is navigating toward its destination, it is building a traversal, or path, consisting of links over which the conveyance has traveled. From the track operator, a time-space diagram can be generated, and along with the completed traversal, the locational history of the conveyance can be regenerated.

The MDLRS data model provides for temporal referencing methods through the temporal referencing method object. Time-dependent intersection movements and restrictions, general restrictions, and time-dependent link attributes are accommodated in the MDLRS data model through the attributes of transportation features. Attributes of transportation features and event objects can have a time dependency associated with them.

Because the MDLRS data model supports topological representations of transportation system networks (e.g., automotive, pedestrian, and public transit), support of various types of pathfinding algorithms is possible.

The MDLRS data model satisfies Functional Specification VI.b through the connectivity of transportation systems. Transportation systems (see Figure 2-10) are a collection of transportation features, transportation complexes, and other transportation systems that serve a transportation function in support of transportation objectives (adapted from Fletcher, Henderson, and Espinoza [*2*]). The MDLRS data model allows for the connectivity of modal transportation systems (e.g., a bus transportation system connected to a subway transportation system by a pedestrian walkway transportation system, with each system having its own operating characteristics). This connection supports spatio-temporal disconnects.

The MDLRS data model does not provide methods for pathfinding or proximity analysis, but does provide the data constructs to support the methods. In pathfinding, the user represents a "conveyance" and takes on the characteristics of the transportation system that the user interacts with. For example, when a user makes a trip using public transit, a user conveyance travels a walkway on a pedestrian transportation system with a defined method of movement to the bus stop. The user conveyance gets onto the bus transportation system and rides a bus conveyance, taking on the bus's movement characteristics. The user conveyance then gets onto the pedestrian transportation system walkway to the subway, gets onto the subway transportation system, and rides a subway conveyance. Finally, the user conveyance gets onto the pedestrian transportation system walkway to a destination.

The MDLRS data model satisfies Functional Specification VI.c through the attributes of transportation features (see Figure 2-9). In the MDLRS data model, special lane configurations are separate transportation features. Therefore, an HOV lane or a reversible lane would be a separate transportation feature. Transportation features have attributes that describe the aspatial characteristics of the transportation feature. An attribute can be quantitative, qualitative, or temporal. An essential attribute of a lane-based configuration such as an HOV lane is the time of operation, or operational period. The validity period for the HOV's operational schedule may also be important (e.g., winter schedule). In the MDLRS data model, the operational period can be modeled as a temporal attribute (i.e., an attribute represented as a time object). Additionally, the operational and validity periods can be modeled together as a temporal attribute and represented as a time aggregate object.

3.2.8 Functional Requirement VII: Historical Databases

Typically, within a GIS database, the element of time is categorized as an attribute of the topological feature being represented. Often because of the lack of temporal operators within a GIS and the lack of adequate and accurate temporal data, the time attribute is not fully used or included. The presence of this attribute may be questioned in very large databases (e.g., "I know the time element is important, but why should it take up valuable resources when I cannot perform time-related analysis, even though in the future maybe the operators will be there?"). In addition, many stakeholders duplicate the nonspatial data (e.g., accident reports) in relational databases (e.g., Oracle) that can perform temporal analyses (e.g., Oracle has more than thirty temporal operators).

All objects are defined by their state in time, and events change the states of objects. For example, an event might cause the creation of new objects or the retirement of existing objects. With the incorporation of time into a data model, various historical analyses can be performed, such as comparing the states of an object over time or displaying the system state (i.e., the map plus the attributes) that most closely matches the controlling record time. Rollback functions can be used to link old and new objects.

The ability for the MDLRS data model to create a history trail can be viewed in several ways. Under the existing relational GIS models (which are object- and event-driven), time, status, and state are modeled as attributes of the object and event. Users need a model that allows time attributes to be markers (or “bread crumbs”) so that conducting an historical query is analogous to following a trail of crumbs. Having a data model that supports historical queries (e.g., providing certain accidents from 1993 to 1995, given changes in the LRS) leads to the need for adequate maintenance of databases in an archival format, as well as the need for revised data collection guidelines.

Functional Requirement VII is as follows: A comprehensive, multidimensional LRS data model must support regeneration of object and network states over time and maintain the network event history.

The functional specification for this requirement is as follows:

- VII.a: A model must maintain state histories of objects and events.

The MDLRS data model satisfies Functional Specification VII.a through event objects and through the experience objects of transportation features (see Figure 2-9). An event is something that happens in an instant or over a period of time that changes the state of a transportation feature (*2*). Figure 2-9 shows the event object and its interaction with the transportation feature. The state of an object is “a condition of being defined by constant attributes and associations over some duration of time” (*2*). Events have no states. The MDLRS data model maintains the histories of events through a transaction log of event objects.

The registry in the transportation feature that indicates which event objects caused spatial, aspatial, or temporal changes in that feature is called an experience—that is, each event that the transportation feature participates in is called an experience (see Figure 2-9). Events are phenomena external to objects, whereas experiences are phenomena tightly coupled with objects. For example, a crash is an external event, and damage is the vehicle’s experience of that crash (*35*). For the transportation feature, the experience and its participatory event form the end or beginning of a new state, while states with no ending event are considered current. The analogy is that of links and nodes. Links are defined by their end nodes, whereas states are defined by their “end” participatory events.

Over time, the transportation feature participates in several events, producing additional experience objects. These experience objects form a time-ordered, or sorted linked, list and represent the event registry, or the “container of memories,” for the transportation feature. The life span of a transportation feature (i.e., the entire time that the feature is known to the database) is the time-ordered sequence of all its experiences (*2*). An example of the experiences that define the life span of a feature is the following: A highway is designed, constructed, maintained, and destroyed. Four experiences lead to at least four states: in design, under construction, in service, and abandoned. The transition from one state to another is marked by some event occurring at some time. For example, the event “authorize construction” marks the transition from in design to under construction, and the event “open to traffic” marks the transition from under construction to in service (*35*).

An analogy of the experience object collection is that of a stack whose experiences are piled on or taken off, depending on the time being considered. This collection of experience objects allows for the historical rollback of the transportation feature.

3.2.9 Functional Requirement VIII: Accuracy and Error Propagation

The locations of transportation features are typically collected, analyzed, operated on, transformed, and compared relative to other transportation feature locations without regard for positional accuracy and other quality aspects of the data. Positional and temporal errors, arising from imperfect measurements, are inherent in the data. Furthermore, certain operations on data, such as projection between dimensions, can introduce additional persistent spatial distortions. For example, to associate data collected by GPS with linearly referenced data, it is often first necessary to project two- or three-dimensional coordinates onto two-dimensional coordinate strings that form the primary cartographic representation in a GIS database that is, in turn, associated with the linearly referenced data. These projections introduce distortions that vary with the density and accuracy of the vertices in the coordinate string. Moreover, the coordinates collected by GPS are, themselves, uncertain in two- and three-dimensional space.

Such errors propagate through spatiotemporal analytical processes that are imbedded in applications and that manipulate data in various ways to produce results used in decision making. The applications overlay, combine, and compare collections of data having various precisions, accuracies, and resolutions. Currently, characterization, propagation, and effective means of management and visualization of errors in transportation data are not well formulated, leaving decisionmakers to face unknown risks arising from uncertainty and lack of quality measures.

Moreover, without effective means for determining the impact of spatiotemporal error on analysis, no defensible statements can be made concerning the required accuracy of data to support applications. Thus, it is almost certainly true that there is under-investment in collection of some data (i.e., the data are not accurate enough to support their applications) and over-investment in collection of other data (i.e., the data are more accurate than needed). Furthermore, without reliable estimates of the uncertainty in data and without knowledge of the uncertainty’s effects on decision making, users risk reaching flawed conclusions and making costly erroneous decisions. As Goodchild (*51*) states, “If we know there is uncertainty in the input to GIS analysis, but fail to identify the impact of that uncertainty on the outputs and instead present them as correct, then surely we can and should be held liable for the consequences.”

Functional Requirement VIII is as follows: A comprehensive, multidimensional LRS data model must support association of error measures with spatiotemporal data at the object level and support propagation of those errors through analytical processes.

The functional specifications for this requirement are as follows:

- VIII.a: A model must support measures of spatiotemporal error (i.e., bias and precision) within objects and events. A model must support spatiotemporal correlation of error among objects and events.
- VIII.b: A model may satisfy this requirement with a measure of spatiotemporal error that merely indicates error with a confidence level (i.e., positional accuracy). To satisfy the requirement in this way, it is assumed that there is no bias in the spatiotemporal (i.e., position) measure, that the error is random, and that the confidence level is the probability that the true value of objects' spatiotemporal attributes fall within the stated error bound. Also, it is assumed that, in such a model, there is no spatiotemporal correlation of error (i.e., that the errors in objects and events are independent).

The MDLRS data model satisfies Functional Specification VIII.a through the variance/covariance matrix object, the lineage metadata object, the uncertainty attribute in the measurement object superclass, and the temporal error measures object. The spatial correlation of error among objects is presented through a variance/covariance matrix. For a two-dimensional data object (e.g., a point with x,y), a simple variance/covariance matrix is made up of four elements: the variance in the x-coordinate of Location A, the variance in the y-coordinate of Location A, and the two covariances between x and y. If this point was used to derive other geometric objects, the resulting variance/covariance matrix for the new object could become immense. A three-dimensional data object (x,y,z) would require a 3×3 variance/covariance matrix containing nine elements. The MDLRS data model uses a final variance/covariance matrix (see Figure 2-13) for spatial objects, along with a familiar functional lineage (see Figure 2-12), instead of carrying a full variance/covariance matrix of each spatial object to model error propagation.

The temporal correlation of error among objects is through the temporal error measures object and the lineage metadata object (see Figure 2-14). Because time is one-dimensional, there is no need for covariance measures. The temporal error measures object records the tolerance of a temporal measurement, while the lineage metadata object shows how the time object was derived, or its parentage.

Spatiotemporal correlation of error among objects and events primarily concerns moving vehicles or conveyances. Because the vehicle is moving, the spatial positional error of the vehicle depends on the error associated with the positioning device, the error in the timing device, and the error associated in transmitting instructions and data. An example of spatiotemporal error is the positional error resulting from tracking snowplows using a GPS receiver. In such a case, there was a positional error resulting from the GPS receiver and a positional error resulting from the difference between the GPS clock and an atomic clock. The spatiotemporal error could be divided into a spatial positional error due to the measurement instrument and a temporal bias due to clocks not being synchronized.

Usually, the uncertainty associated with a measurement is at least equal to the uncertainty or resolution of the measurement device. In the snowplow example, the uncertainty of a GPS signal is stored as an "uncertainty" attribute in the radio frequency measurement object (see Figure 2-13); the uncertainty associated with the time of a GPS signal is stored in the error measures object in the time object in the radio frequency measurement object.

The MDLRS data model satisfies Functional Specification VIII.b through the lineage metadata object. The lineage metadata object (see Figure 2-12) contains the positional accuracy of spatial objects derived from the variance/covariance matrix or provided elsewhere. Additionally, the MDLRS data model assumes that measurements are corrected for biases such as calibration errors.

3.2.10 Functional Requirement IX: Object-Level Metadata

In GIS models, metadata (i.e., "data about data") functionality provides information on the origin of the data within a classification level (e.g., coverages, themes, layers, and tables). The accuracy or error of the data can be indirectly derived from the origin of the data source (e.g., if the data source is TIGER DLG, then errors in the data could be ±100 m). Problems often arise when there are multiple sources for the data in a level, each with an error at a confidence level. Therefore, users need metadata regarding a specific feature or object, including an error measurement. The incorporation of feature-level metadata into the LRS data model is beneficial in that it provides guidance on the general use and representation of features and objects.

Functional Requirement IX is as follows: A comprehensive, multidimensional LRS data model must store and express object-level metadata to guide general data use.

The functional specification for this requirement is as follows:

- IX.a: A model must support data lineage and other metadata (e.g., attribute and feature quality) at the object level.

The MDLRS data model satisfies Functional Specification IX.a through the metadata object hierarchy. Metadata objects are used to describe the characteristics of data at the object level in transportation features, events, spatiotemporal objects, and time objects (see Figures 2-9 and 2-14). There are two types of metadata objects: source metadata objects and lineage metadata objects. The source metadata object identifies the administrative aspects of where the data come from, possible restrictions on the use of the data, and when the data were entered into the database. The lineage metadata object indicates the history, or parentage, of the data, including the data's compilation and processing history. For spatial objects, the lineage metadata object and the variance/covariance matrix object describe the quality of the data and are used to model the propagation of spatial error.

3.2.11 Functional Requirement X: Temporal Topology/Latency

Because all objects are defined by their state in time, because events are actions that happen instantaneously in a point of time, and because change is the state of objects (*28*), temporal relationships exist among objects and events, producing a temporal topology. Topological relationships can include disjoint, overlap, during, and simultaneous. The temporal topological relationships may be explicit or derivable from temporal coordinates. Temporal topology allows for the following operations:

- Spatiotemporal proximity (e.g., prevent road striping before paving),
- Temporal within (e.g., identify all projects being let in the third quarter of the year),
- Spatiotemporal within (e.g., find all accidents during a construction project within a construction boundary), and
- Temporal after (e.g., find all accidents that occurred after a project completion).

The concept of latency is associated with the interaction of at least two dependent components of a system, one of which is delaying its next activity until the other completes its own current activity. In transportation applications, latency is often associated with the difference in time between scheduled and actual events occurring at a particular location in space. Such latencies can be thought of as spatiotemporal disconnects arising from unfulfilled expectancies.

Figure 3-4 shows an example of latency. If a bus arrives at a stop before its scheduled time (i.e., if it arrives at Actual 1), the bus must wait for riders who might be arriving at the scheduled time. If the bus arrives at the stop after its scheduled time (i.e., if it arrives at Actual 2), riders must wait during the delay. The bus being somewhere other than its expected place in space at a particular moment in time causes these effects. Latency of this sort is often referred to as "on-time performance" and involves comparing schedules with arrivals (i.e., comparing actual time of arrival with estimated time of arrival).

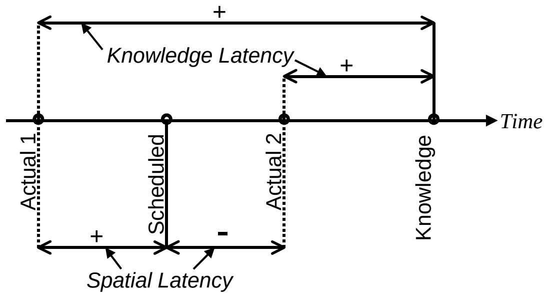


Figure 3-4. Latency between scheduled and actual arrivals at a bus stop.

The concept of latency can also be applied to the problem of database updates. Figure 3-4 illustrates that a database update, or knowledge of an event, always occurs after the event has taken place. Latency can cause things to happen at the wrong time in a particular place and causes database users to have the wrong (i.e., delayed) view of the real world.

Functional Requirement X is as follows: A comprehensive, multidimensional LRS data model must support temporal relationships among objects and events and must support the latency of events.

The functional specifications for this requirement are as follows:

- X.a: A model must support a temporal referencing method for temporal reasoning among objects and events.
- X.b: A model must support basic temporal topological relationships among objects and events. Topological relationships include disjoint, overlap, during, and simultaneous. The relationships may be explicit or derivable from temporal attributes.
- X.c: To evaluate on-time performance, a model must provide for recording and distinguishing between the actual and expected occurrence of an event and between the actual and expected duration of the event.
- X.d: To manage database concurrency and delayed knowledge of the event occurrences and object existence, a model must maintain a record of when object and event data were entered.

The MDLRS data model satisfies Functional Specification X.a through the use of the temporal referencing method object (see Figure 2-9). The temporal referencing method object allows users to transform disparate temporal data into a unified temporal data set. This unified temporal data set becomes the prerequisite for temporal reasoning. In other words, before temporal relationships can be modeled, the temporal data set of interest must be in the same temporal referencing method. In the MDLRS data model, this consistency is accomplished through temporal referencing method objects.

The MDLRS data model satisfies Functional Specification X.b through the use of the temporal relationship hierarchy (see Figure 2-9). The temporal relationship objects allow for basic temporal topological relationships among transportation features and events. There are two types of temporal relationship objects used in the MDLRS data model (see Figure 2-9): temporal topology and temporal proximity. The temporal topology relationship object models temporal topological relationships, such as follows, during, and simultaneous. The temporal proximity relationship object is analogous to a temporal buffer operation. Section 2.3.5.4 describes the details of the temporal relationship hierarchy.

The MDLRS data model satisfies Functional Specification X.c through the attributes of the event object. The event object (see Figure 2-9) has the attributes "scheduled time" and "actual time," each of which is associated with one time object. The attribute "scheduled time" indicates the expected occurrence or duration of an event, while the attribute "actual time" indicates the actual occurrence or duration of an event. Because the time object can be expressed as a point in time, a duration of time, or an aggregate of time, the time object alone can be used to represent occurrences as well as durations.

The MDLRS data model satisfies Functional Specification X.d through the time object and its associated source metadata object (see Figure 2-14). The time object primitives and aggregates record when an activity actually occurred. Associated with a time object is, at most, one source metadata object. The source metadata object records when the time object, or data, was recorded or entered into the database.

In temporal GIS research, the time at which an activity occurred is called "valid," or "world," time (*39*). The time at which the activity was recorded in the database is called "transaction," or "system," time (*39*). Most temporal GIS models assume that the difference between world and transaction time is negligible and, therefore, use "world" time. In the MDLRS data model, transaction time is recorded in the source metadata object. The time object represents a bi-temporal model because both world and transaction times are maintained. A bi-temporal model is key for the development of a temporal database, identified as the best method of temporal data organization (*39*).

3.3 MDLRS MODEL TRADE-OFFS

This section discusses some of the basic assumptions that underlie the MDLRS model. Associated with each assumption is a discussion regarding the trade-off between potential benefits and limitations of the assumption.

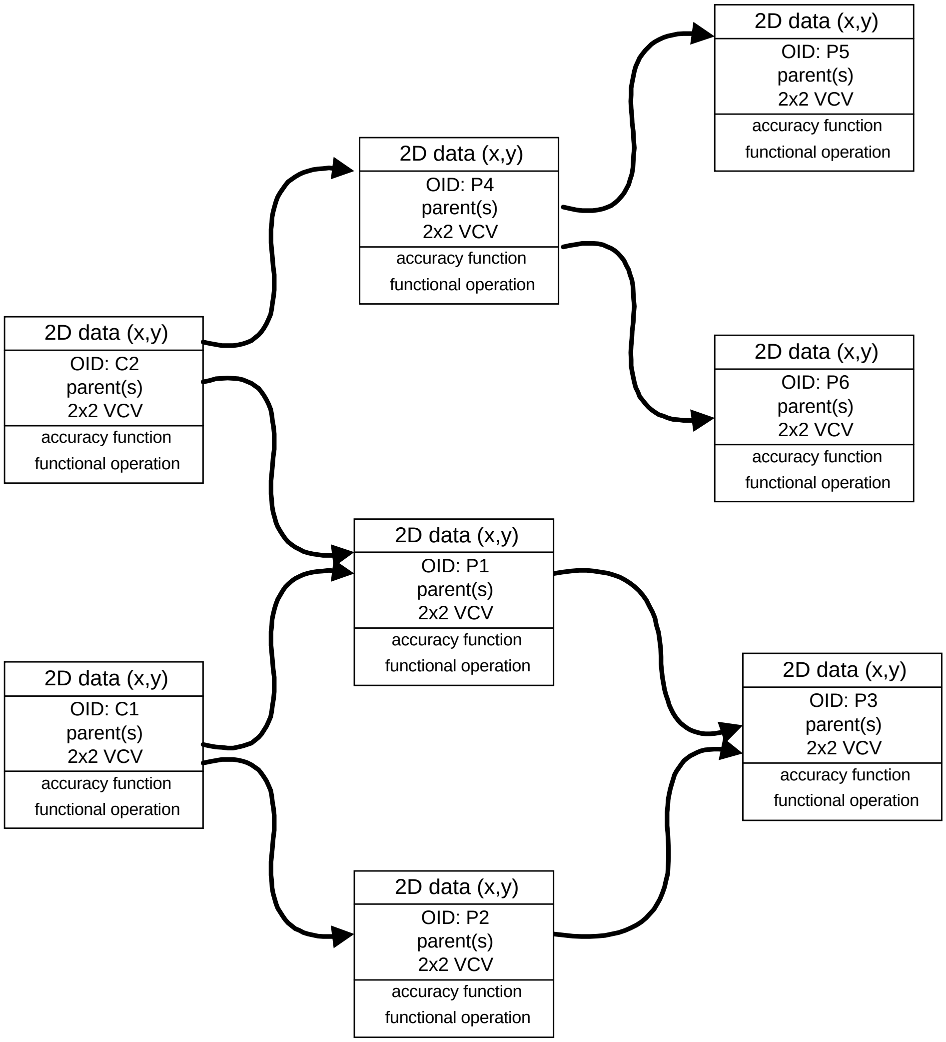
Some of the trade-offs in the MDLRS data model are the following:

- **The MDLRS data model assumes UTC and the Gregorian calendar as the temporal datum.** Although the MDLRS data model supports ordinal and interval TRSs, as well as various calendars and temporal metrics, the data model assumes UTC and the Gregorian calendar as the temporal datum. The MDLRS data model assumes that most data in this model use these temporal metrics and calendar. Additionally, the data model concentrates on temporal referencing methods that have the same metrics as the datum.
- **The MDLRS data model distinguishes between the spatial and temporal elements of objects.** The MDLRS data model represents phenomena as spatial objects that are valid for a certain period. In the MDLRS data model, the spatiotemporal object is an abstract data class consisting of a spatial object associated with zero or one time object. The separation of the spatial and temporal elements is primarily due to concerns about integrating data sets that have no temporal information. Therefore, the MDLRS data model allows integration of data sets without temporal data.
- **The MDLRS data model assumes one temporal reality of phenomena along a timeline.** The MDLRS data model stores the phenomenon's past histories through experience objects that can be rolled back along one timeline. Although the MDLRS data model does not provide the methods to create alternative spatial realities on different timelines (resulting from simulations), the data model does not prevent the use of such methods. Transportation features, complexes, and systems can be used to model alternative futures and pasts through extension of the data model.
- **In the MDLRS data model, geometric objects carry a parental lineage.** Three ways of dealing with the propagation of error identified in Section 3.2.11 were the following:
  - Carry an $N \times N$ variance/covariance matrix that carries all variables from prior operations (i.e., accuracy trace).
  - Carry a functional lineage (full ancestry) of the object from its initial source and a final 2×2 variance/covariance matrix for two-dimensional data objects. In this case, a functional lineage could tell that a point was created by the intersection of objects. Carrying a functional lineage is analogous to carrying the source code and allows for generation of the error matrix identified in the previous case.
  - Store the immediate or familiar functional lineage of the object and a final 2×2 variance/covariance matrix for two-dimensional data objects, require all data sources to do the same, and let the user find the sources of data or go back as the user's needs require. In this case, objects refer to their parents and the parents refer to their parents, as in a family tree.

  The MDLRS data model uses this third case to model the propagation of error. The use of a familiar functional lineage would require the user to find the physical source of parental data to recompute accuracies when parents of a child object become more accurate. However, for most users, having a reference to parental data is sufficient and outweighs the drawbacks of managing potentially immense variance/covariance matrices or managing functional lineages for each spatial object merely to recompute accuracies.

Figure 3-5 illustrates this third case. Each two-dimensional data object (x,y) has a 2×2 variance/covariance matrix. A three-dimensional data object (x,y,z) would have a 3×3 matrix. Each object stores its immediate parents and two functions: one that calculates accuracy (i.e., variance/covariance) and another that allows the object to compute itself (or a method that knows how to operate on itself—e.g., intersection). To determine whether two points are correlated (or siblings), one would have to check for a common parent.

- **In the MDLRS data model, complex events do not have their own time stamp.** In the MDLRS data model, each event has two temporal attributes: actual time and scheduled time. Complex events are aggregates of events and can represent activities, such as the projects in a yearly construction program. In the MDLRS data model, the collection of temporal objects of the individual events indicates the temporal characteristics of the complex event. A complex event does not have a time coordinate or time stamp because having such could cause inconsistencies between the complex event and individual events.
- **The MDLRS data model uses temporal relationships to derive temporal topology.** Temporal topological constructs primarily deal with the relative temporal position of events (e.g., whether Event A occurred before Event B). Temporal geometric constructs indicate the absolute temporal position of features and events on a timeline (e.g., Event A occurred at 9:15 p.m., January 1, 2000). An



Note:
2D = two-dimensional.
OID = object ID.
VCV = variance/covariance matrix.
C1, C2, and P1 … PS designate features and edges.

Figure 3-5. Illustration of a familiar functional lineage.

example of when temporal topological constructs would be used is in the creation of a construction schedule, when the critical path method would be used to find the time of completion (analogous to pathfinding on a topological network). Whereas one of the reviewed geospatial standards (ISO 15046) divides temporal constructs into topological and geometric, the MDLRS data model uses temporal geometric constructs (e.g., time object) and uses temporal relationship objects to derive a temporal topology. Additionally, temporal topology can be derived from temporal metrics. For example, if Event A occurred at 6:15 a.m., January 1, 2000, and Event B occurred at 10:15 a.m., January 1, 2000, it can be shown that Event A occurred before Event B. Also, temporal topological constructs are not needed for events or spatial objects, though they can be used with attributes. Therefore, although dividing temporal constructs into separate geometric and topological constructs seems novel, it is not necessary.

- **The MDLRS data model stores the current version of events.** The data model assumes that the event of relevance is always the current event, so that only the current event version is stored. However, the MDLRS data model can be extended to accommodate versions of events as they evolve (e.g., refining a schedule as time passes).
- **The MDLRS data model does not manage measurement biases that are due to instrument calibration errors.** These biases affect the computation of coordinates from measurements. Management of these biases would require an association between each measurement and an object that indicates the instrument used to make the measurement. The MDLRS data model does not account for these biases and assumes that the measurements are corrected before being entered into the data model.
- **The MDLRS data model does not represent an authority that is responsible for managing a transportation system.** This absence of an authority object is evident in modeling a conveyance and its interaction with its associated transportation system. In Section 2.3.5.1.2, the term “dispatcher” was used to denote an outside source that does the routing and tracking operations. These operations are too broad to be performed in a conveyance alone. The MDLRS data model can be extended to represent authorities by incorporating the concept of an “agency,” as described by Fletcher, Henderson, and Espinoza (*2*).
- **In the MDLRS data model, a method is required to maintain multiple geometric and topological representations of a single transportation feature.** In the data model, a transportation feature can have one or more geometric or topological object representations, each at the same or different scale applicability. Each geometric and topological representation is considered independent of the others associated with the transportation feature. Having multiple spatial objects can present duplication concerns (i.e., one spatial instance of a surface representation decomposed into points and another spatial instance of a point exists for a transportation feature, both at the same scale applicability).

  A limitation in having independent geometric and topological objects is that potential inconsistencies in spatial representations can be produced. If a change is made in one representation, it is not automatically reflected by other representations. The management of consistency in spatial objects of a transportation feature, especially in the context of transportation complexes and transportation systems, is challenging but possible through the use of a user-supplied method. The issue of consistency in spatial objects is important in topological objects, changes to which can affect connectivity with other topological objects, affecting operations such as pathfinding. Although independent geometric and topological objects can produce inconsistencies that can be overcome, these objects provide the MDLRS data model with flexibility in associations because of change in scale or change in level of detail. This flexibility is not possible with combined geometry/topology data models.
- **The MDLRS data model requires maintenance of multiple topological networks.** In the MDLRS data model, spatial objects have an attribute called “scale applicability,” which indicates at which scale the object is valid. Section 3.2.6 mentioned that interchanges are transportation complexes consisting of transportation features with topological objects at different scale applicabilities. Viewing an interchange at a certain level of detail implies that only topological objects with similar scale applicabilities would be displayed. Also implied is that the topological objects connecting intersections/interchanges would be at the same scale applicability as the intersection, thereby producing a topological network at a certain scale applicability. As a result, there could be several topological networks at different scale applicabilities for a transportation system (e.g., lane-level topologies and divided highway topologies). Having to support several topological representations presents difficulties in maintaining topology in addition to maintaining consistency. For example, if a more detailed version of the topology of an interchange were added to an existing topology at a certain scale applicability, all connections to that new interchange’s topology would need to be updated.

  An alternative to having several topological network representations would be to make the interchange topological representations more modular where alternate interchange topologies would fit into one existing network topology without changes. A problem with this approach is that one would need to reconcile the connections of the interchange with the network at each topological representation of the interchange (i.e., the connecting nodes would have to be at the exact position for all interchange representations). Additionally, having modular topological representations would be valid for unidirectional or bi-directional links only (i.e., a divided interchange representation with separate directional links would not work on a bi-directional link network). Therefore, making interchange representations more modular also presents difficulties in maintaining topology.

In addition to difficulties in maintaining network topologies, having multiple topological networks presents difficulties in maintaining consistency. If a ramp is constructed in an interchange, a new ramp transportation feature has to be added to the interchange transportation complex, with compatible scale-applicable topological objects. Each topological representation of the interchange would have to be modified to accommodate the new ramp. Changes made in a scale-applicable topological representation have to be made in all topological representations to maintain consistency.

The potential benefits of allowing multiple topological networks exceed the limitations of these networks. The issues of maintenance and consistency are present for any topological network, regardless of which data model is being used. Providing for multiple topological networks allows for consistent turning movements and pathfinding at varying levels of detail (i.e., a user does not have to program turning movements for each level of detail).

3.4 MODEL IMPLEMENTATION

3.4.1 Implementation Approach

To identify the functional requirements for a particular agency's implementation of the MDLRS, a high-level view of user needs and their linkages to the functional requirements are provided. The entire range of applications and user needs were not represented at the stakeholder's workshop that identified the functional requirements because some stakeholders were not represented (e.g., traffic simulation/modeling). A comprehensive transportation business model is needed to represent the scope of applications.

The NCHRP 20-27(2) business model (*52*) identifies transportation business areas that are mapped to business systems and business functions. This business model provides a high-level view of user needs within the transportation community. Where the 20-27(2) business model is too abstract, the National ITS Architecture (*14*) user services supplement the business model.

Figure 3-6 shows the schematic of the implementation approach. The ITS user services and 20-27(2) business systems are mapped to the functional requirements of the MDLRS model. This mapping indicates the specific functional requirements that support specific business systems and user services bundles (e.g., the identification of functional requirements necessary for facilities management). Each functional requirement of the MDLRS model and its specifications are mapped to the MDLRS data model (e.g., the identification of objects needed to measure object-level accuracy and error propagation). The mappings are used to identify the necessary components of the MDLRS for a business system or user services bundle. This method of identifying components of the model does not result in a disconnected model because certain basic elements (e.g., transportation features) are necessary for all requirements.

As expected, the 20-27(2) business systems require most of the functional requirements. However, there are notable exceptions. For example, to support asset management, Functional Requirement VI and conveyance objects are not needed.

Agencies can use Tables 3-2 and 3-3 to create procurement documents that specify only the parts of the MDLRS model that are of interest. Section 3.4.3 provides examples of the approach.

3.4.2 Mapping of 20-27(2) Business Systems to Functional Requirements

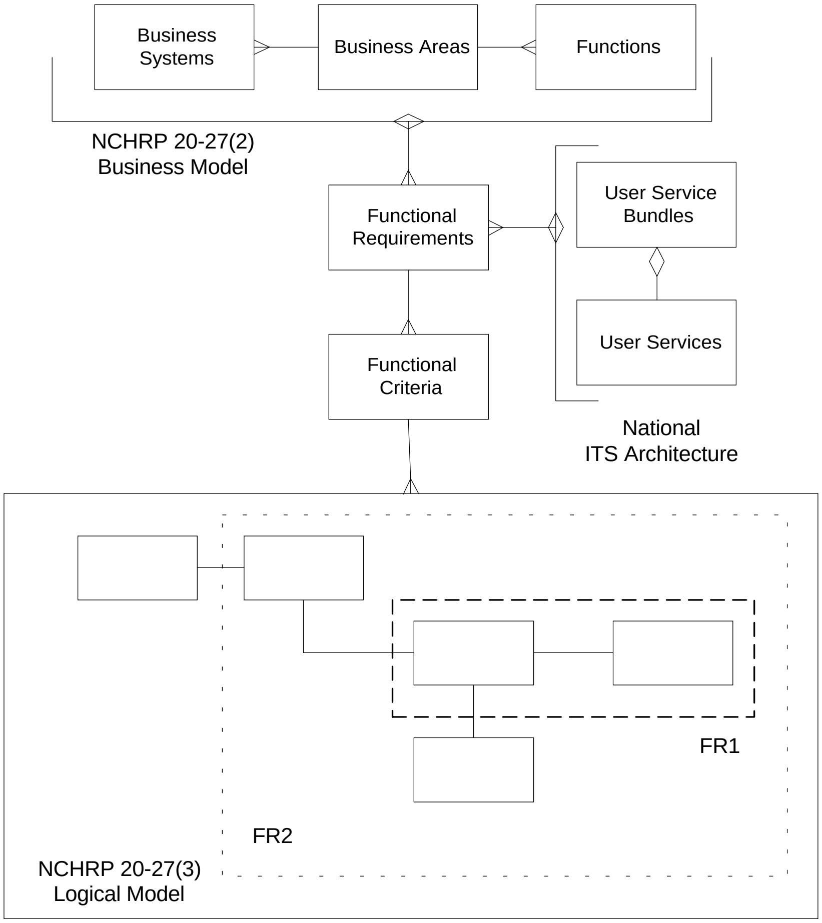
This section provides a mapping of the transportation agency business systems, as identified by NCHRP Project 20-27(2) (*52*), and provides the ITS user services bundles (*14*) to the MDLRS functional requirements. The section also maps these functional requirements to the MDLRS data model.

Table 3-2 shows the mapping of transportation agency business systems to the MDLRS functional requirements. An "X" in a cell indicates that, for a specific business system or ITS user services bundle, the corresponding functional requirement is needed. For example, to do location control, one needs the functional requirements for spatiotemporal referencing methods, TRS/temporal datum, transformation of data sets, and accuracy and error propagation.

Three NCHRP 20-27(2) business systems—Advanced Traveler Information, Advanced Traffic Management, and Incident Management—were deleted because of overlapping scope when the six ITS user services bundles were added.

A description of each of the NCHRP 20-27(2) business systems follows.

- **Location control** supports development and maintenance of LRS, including linear, geodetic, and cadastral control, as well as support for photogrammetric engineering and real property surveying and mapping. Location control is fundamental for infrastructure management systems.
- **Transportation monitoring and performance assessment** determines the value of each transportation component state and compares actual performance with desired levels of performance. This business system is fundamental for traffic management and control.



Note:
FR1 = Functional Requirement I.
FR2 = Functional Requirement II.

Figure 3-6. Schematic of implementation approach.

- **Functionally integrated transportation system** maintains the inventory of transportation components and the functional transportation systems set up to monitor policy objectives. This business system generates and allocates system- and component-level travel demands (*53*) and is fundamental for transportation planning and programming.
- **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. This business system allows for statewide intermodal transportation planning.
- **Real property management** supports inventory and management of title to real property and improvements controlled by the agency. An example of this business system is a land information system.
- **Facilities management** supports space allocation, design, construction, and maintenance of the agency's buildings and grounds facilities. An example of this business system is a facilities management system.
- **Contractor selection** supports pre-qualification of vendors; preparation, issuance, and evaluation of bids; and preparation of contracts.
- **Estimating and scheduling** integrates cost estimation and scheduling of materials, equipment, and workforce for a transportation improvement project.
- **Computer-aided design** supports development of plans and specifications for transportation improvement projects.
- **Socioenvironmental evaluation** supports GIS applications for evaluating socioeconomic and environmental impacts of a transportation improvement project. Examples of this business system are environmental impact and assessment studies.
- **Program development and management** evaluates the effectiveness of each project concept on the basis of performance and environmental, social, and economic effects. The business system then incorporates projects into regional and statewide plans and improvement programs (*53*). An example of this business

TABLE 3-2 Mapping of functional requirements to transportation agency business systems and ITS user services

Functional Requirements for a multimodal, multidimensional location referencing system data model	NCHRP 20-27(2) Business Systems													ITS User Services Bundles					
	Location Control	Transportation Monitoring and Performance Assessment	Functionally Integrated Transportation System	Data Sharing	Real Property Management	Facilities Management	Contractor Selection	Estimating and Scheduling	Computer-Aided Design	Socio-Environmental Evaluation	Program Development and Management	Treatment Development	Weather Operations	ITS Travel and Traffic Management	ITS Public Transportation Management	ITS Electronic Payment	ITS Commercial Vehicle Operations	ITS Emergency Management	ITS Advanced Vehicle Safety Systems
Spatiotemporal Referencing Methods: The model supports the *locate*, *place*, and *position* processes for objects and events in three dimensions and time relative to the roadway.	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Temporal Referencing System/Temporal Datum: The model accommodates a temporal datum that relates the database representation to the real world and provides a domain for transformations among temporal referencing methods.	X	X	X	X	X	X	X	X		X			X	X	X	X	X	X	X
Transformation of Data Sets: The model supports transformation between linear, nonlinear, and temporal referencing methods without loss of spatial / temporal accuracy, precision, or resolution.	X	X	X	X	X	X			X	X	X	X	X		X	X	X	X	X
Multiple Cartographic/Spatial Topological Representations: The model supports multiple cartographic and spatial topological representations at both the same and varying levels of generalization of transportation objects.			X	X		X			X	X		X	X		X	X	X	X	X
Resolution: The model supports the display and analysis of objects and events at multiple spatial and temporal resolutions.			X	X		X			X	X		X	X		X	X	X	X	X
Dynamics: The model supports the navigation of objects, in near real time and contingent upon various criteria, along a traversal in a transportation network.													X		X	X	X	X	X
Historical Database: The model supports generation of object and network states over time and maintains the network event history.		X	X		X		X			X		X	X			X	X		X
Accuracy and Error Propagation: The model supports association of error measures with spatiotemporal data at the object level and propagation of those errors through analytical processes.	X			X					X	X		X	X	X		X	X		X
Object-Level Metadata: The model stores and expresses object-level metadata to guide general data use.		X	X	X		X			X	X		X	X	X		X	X		X
Temporal Topology/Latency: The model supports temporal relationships among objects and events and latency of events.		X			X			X	X	X		X	X	X		X	X		X

Note: ITS = intelligent transportation systems.

system is the use of cost-benefit studies in transportation planning.

- **Treatment development** associates performance needs with underlying causes, thereby identifying appropriate system- and component-level treatments. The business system develops effective treatment strategies, using an evaluation of past treatments plus life cycle costs and benefits, and then synthesizes treatment strategies into project concepts, reconciling all treatment alternatives (*53*). An example of this business system is the use of a pavement management system in the context of a pavement improvement program.
- **Weather operations** supports mitigation of unsafe road conditions due to meteorological changes. An example of this business system is the real-time monitoring of snowplows.

A description of each of the NCHRP 20-27(2) ITS user services bundles follows:

- **ITS travel and traffic management** includes services such as pre-trip travel information, route guidance, traveler services information, traffic control, incident management, and emissions testing and mitigation.
- **ITS public transportation management** includes services such as public transportation management, en-route transit information, and public travel security.
- **ITS electronic payment** includes only the electronic payment user service.

TABLE 3-3 Mapping of functional requirements to MDLRS data model objects

	Spatio-temporal Referencing Methods FR 1				Temporal Referencing System/ Temporal Datum FR 2			Transformation of Data Sets FR 3						Multiple Cartographic/ Spatial Topological Representations FR 4						Resol-ution FR 5	Dynamics FR 6						Historical Databases FR 7	Accuracy & Error Propaga-tion FR 8		Object-Level Metadata FR9	Temporal Topology/ Latency FR 10			
MDLRS Object	a	b	c	d	a	b	c	a1	a2	a3	b	c	d	a	b	c	d	e	f	a	a	b	c	d	e	f	a	a	b	a	a	b	c	d
Transportation Feature	■	■	■	■				■	■	■	■	■		■	■	■	■	■	■	■			■	■	■		■	■	■			■		■
Conveyance	■			■				■	■	■	■	■		■	■	■	■	■	■	■	■		■				■	■	■			■		■
Transportation Complex								■	■	■	■	■		■	■	■	■	■	■	■			■	■	■		■	■	■			■		■
Transportation System								■	■	■	■	■		■	■	■	■	■	■	■			■	■	■		■	■	■			■		■
Attribute				■															■				■	■	■	■	■					■	■	■
Experience																											■							
Event	■																									■	■	■	■			■	■	■
Complex Event	■																									■	■	■	■			■	■	■
Spatial Datum																																		
Vertical Datum									■	■			■																					
Geoid									■	■			■																					
Local Datum									■	■			■																					
Benchmark		■	■						■	■			■														■							
Geocentric Datum									■	■			■																					
3D Cartesian Axes									■	■			■																					
GPS Satellite		■	■						■	■			■														■							
Horizontal Datum									■	■			■																					
Ellipsoid									■	■			■																					
Projection									■	■			■																					
Control Station		■	■						■	■			■														■							
Cadastral Datum									■	■			■																					
Corner									■	■			■																					
Corner Point		■	■						■	■			■														■							
Linear Datum								■	■		■	■	■																					
Linear Referencing Method								■	■		■	■	■																					
Anchor Point								■	■		■	■	■																					
Anchor Section								■	■		■	■	■														■							
Transport Node								■	■		■	■	■																					
Transport Link								■	■		■	■	■																					
Transport System Link								■	■		■	■	■																					
Traversal								■	■		■	■	■																					
Traversal Link								■	■		■	■	■																					
Traversal Reference Point								■	■		■	■	■														■							
Temporal Referencing System																																		
Temporal Datum							■					■	■									■				■	■				■			
Temporal Referencing Method					■	■						■	■									■				■	■				■			
Spatial Object																																		
Scale Applicability Constraint																	■	■																
Dimensionality Constraint																	■	■																
Geometric Object																																		
Geometric Primitive																																		
Point								■	■	■	■	■			■	■	■	■		■							■	■	■					
Reference Point								■	■	■	■	■			■	■	■	■		■							■	■	■					
Curve								■	■	■	■	■			■	■	■	■		■							■	■	■					
Surface								■	■	■	■	■			■	■	■	■		■							■	■	■					
Solid								■	■	■	■	■			■	■	■	■		■							■	■	■					
Geometric Complex								■	■	■	■	■			■	■	■	■		■							■	■	■					
Coordinate																																		
1D Coordinate	■	■																		■								■	■					
2D Coordinate	■	■																		■								■	■					
3D Coordinate	■	■																		■								■	■					
GPS Coordinate	■	■																		■								■	■					

(*table continued on next page*)

TABLE 3-3 (*Continued*)

	Spatio-temporal Referencing Methods FR 1				Temporal Referencing System/ Temporal Datum FR 2			Transformation of Data Sets FR 3						Multiple Cartographic/ Spatial Topological Representations FR 4						Resolution FR 5	Dynamics FR 6						Historical Databases FR 7	Accuracy & Error Propagation FR 8		Object-Level Metadata FR9	Temporal Topology/ Latency FR 10			
MDLRS Object	a	b	c	d	a	b	c	a1	a2	a3	b	c	d	a	b	c	d	e	f	a	a	b	c	d	e	f	a	a	b	a	a	b	c	d
Linear Coordinate	■	■																		■								■	■					
Measurement																																		
1D Gnd Measurement	■	■	■																									■	■					
2D Gnd Measurement	■	■	■																									■	■					
3D Gnd Measurement	■	■	■																									■	■					
Radio Frequency Measurement	■	■	■																									■	■					
Linear Measurement	■	■	■																									■	■					
Distance Measurement	■	■	■																									■	■					
Angle Measurement	■	■	■																									■	■					
Direction	■	■	■																									■	■					
Variance/Covarience Matrix	■	■																										■	■					
Topological Object																																		
Topological Primitive																																		
Node														■	■	■	■	■	■				■		■									
Edge														■	■	■	■	■	■				■		■									
Face														■	■	■	■	■	■				■		■									
Volume														■	■	■	■	■	■				■		■									
Topological Complex														■	■	■	■	■	■				■		■									
Network														■	■	■	■	■	■				■		■									
Time Object																																		
Date Time	■	■									■	■								■			■	■	■	■	■	■	■			■	■	■
Date	■	■									■	■								■			■	■	■	■	■	■	■			■	■	■
Time	■	■									■	■								■			■	■	■	■	■	■	■			■	■	■
Timestamp	■	■									■	■								■			■	■	■	■	■	■	■			■	■	■
Temporal Measure	■																											■	■					
Temporal Error Measures																												■	■					
Duration																																		
Year Month Duration	■										■	■								■			■	■	■	■	■					■	■	
Day Time Duration	■										■	■								■			■	■	■	■	■					■	■	
Interval	■										■	■								■			■	■	■	■	■	■	■			■	■	
Time Aggregate	■										■	■								■			■	■	■	■	■	■	■			■	■	
Cycle	■										■	■								■			■	■	■	■	■	■	■			■	■	
Break	■										■	■								■			■	■	■	■	■	■	■			■	■	
Stage	■										■	■								■			■	■	■	■	■	■	■			■	■	
Sequence	■										■	■								■			■	■	■	■	■	■	■			■	■	
Temporal Relationship																																		
Temporal Topology																																■		
Temporal Proximity																																■		
Metadata																																		
Source Metadata	■	■																									■			■				
Lineage Metadata																											■	■	■	■				■

Note:
1D = one-dimensional.
2D = two-dimensional.
3D = three-dimensional.
FR = functional requirement.
Gnd = ground.
GPS = global positioning systems.
MDLRS = multimodal, multidimensional transportation location referencing system.

- **ITS commercial vehicle operations** include services such as automated roadside safety inspection, on-board safety monitoring, hazardous material incident response, and commercial fleet management.
- **ITS emergency management** includes services such as emergency notification, personal security, and emergency vehicle management.
- **ITS advanced vehicle safety systems** includes services such as longitudinal/lateral/intersection collision avoidance, safety readiness, precrash restraint deployment, and automated vehicle operation.

Table 3-3 shows the mapping of MDLRS functional requirements to the MDLRS data model. Each row in the table represents an MDLRS object construct, and each column or set of columns represents an MDLRS functional requirement and its underlying specifications. A filled cell indicates that, for a specific functional requirement or specification, the corresponding object construct is needed. For example, to implement Functional Requirement II, the temporal datum and temporal referencing method objects are needed.

3.4.3 Example Use of Model Implementation in an RFP

Stakeholders who write RFPs for projects involving the MDLRS data model must include in their RFPs design specifications for the model. Because individual stakeholders and stakeholder needs vary on the basis of a project's scope, design specifications will also vary. The project scope and the resulting design specifications will affect how the MDLRS data model is implemented.

The scope of a project may be extensive and include several functions detailed in the design specifications of an RFP. For example, an RFP for a traffic management center conforming to the ITS Architecture may include in the design specifications a table defining the functions of that management center (shown in Table 3-4 and adapted from Malone [*54*]), along with a general statement such as "The design developed by the consultant for the project shall conform to the provisions of the NCHRP 20-27(3) MDLRS data model." In this example, the contractor chosen to conduct this project can successfully implement the MDLRS data model by using Tables 3-4 and 3-5. The first two columns of Table 3-4 list the RFP function categories and detailed function descriptions. The last column lists the related 20-27(2) business systems or ITS user services bundles. Table 3-4 indicates that the following 20-27(2) business systems and ITS user services bundles are supported by the data model: data sharing, ITS travel and traffic management, transportation monitoring and performance, ITS public transportation management, ITS emergency management, and ITS commercial vehicle operations. Table 3-5, using functional requirements from Table 3-2, lists the MDLRS functional requirements that relate to each of these 20-27(2) business systems and ITS user services bundles. As shown in Table 3-5, all MDLRS functional requirements must be supported for the traffic management center example. Therefore, the contractor can deduce from Tables 3-4 and 3-5 that the complete MDLRS data model is required for this particular traffic management center.

Alternatively, the scope of a project may be limited to one function, and the design specifications would reflect that limitation. For example, a project may require only public transportation management and may state in the RFP, "The design developed by the consultant for the project shall conform to the provisions of the ITS public transportation management business system of the NCHRP 20-27(3) MDLRS data model." In this case, the contractor chosen to conduct this project can successfully implement the MDLRS data model by using Tables 3-6 and 3-7. Table 3-6 uses the MDLRS functional requirements from Table 3-2 to show that the MDLRS functional requirements of historical database, accuracy and error propagation, object-level metadata, and temporal topology/latency are not needed in a data model for ITS public transportation management. Table 3-7 lists the data model objects that are needed for ITS public transportation management. Thus, the contractor can deduce from Tables 3-6 and 3-7 that the best data model to use for this particular traffic management center is the one illustrated in Figures 2-9 through 2-14, except for the following objects: experience, temporal error measures, temporal topology, temporal proximity, and lineage metadata.

3.5 SUPPORT FOR INTEROPERABILITY

The MDLRS data model achieves procedural interoperability in the following ways:

- **The MDLRS data model is based on existing geospatial standards and models.** The MDLRS data model relies on several current geospatial standards and transportation-based data models. Using existing accepted geospatial standards assists in the exchange of data in that these standards provide transfer formats. Additionally, because the MDLRS data model relies on the NCHRP 20-27(2) LRS data model for linear referencing, linear data based on the 20-27(2) data model format do not need to be reformatted for data exchange. The MDLRS data model is designed to accept and disseminate linearly based information with little or no modifications.
- **The MDLRS data model is application independent.** The MDLRS data model does not rely on the data constructs of vendor-based geospatial software solutions (e.g., Environmental Systems Research Institute [ESRI], Integraph, and Smallworld). As such, the MDLRS data model and its data constructs are primarily application independent. Being application independent affords various vendors flexibility in providing solutions while maintaining consistent data structures to allow for easier data exchange.

TABLE 3-4 Features of a proposed traffic management center and their related MDLRS business systems and ITS user services bundles

RFP Function Category	RFP Detail Function Description	Related MDLRS Business System or ITS User Services Bundle
Communications	Ability to share broad-band data, video feed, and reports with other agencies	Data Sharing
	Integration and shared use of communication infrastructure and right-of-way with a citywide communication network	
Traffic Signals	Centralized, remote signal monitoring with alarm functions, for coordinated, fixed time signal system	ITS Travel and Traffic Management
	Remotely change signal timing plan at central locations. Ability to upload or download signal timing plans from a central location	
	Computer-aided dispatching for traffic signal malfunctions and maintenance	
	Adaptive traffic signal control	
	Integration with cross-jurisdiction systems	
Traveler Information	Provide real-time travel information for city arterial streets to the public via the internet and to private information service providers	
	Remotely control variable message signs at various locations from a central operating station	
	Coordinate the operation of a Highway Advisory Radio service	
	Process and send selected travel information to the Traveler Information Center	
Special Event Traffic Operations	Provide a "command center" environment to enable effective management of special events, including remote changing of portable message boards as traffic conditions or parking availability changes during the course of the event	
Traffic Monitoring	Non-intrusive volume monitoring devices along selected arterial corridors	Transportation Monitoring & Performance
	Full-motion video monitoring at critical intersections	
Transit Integration	Exchange data with the transit authority control center	ITS Public Transportation Management
	Support technology for bus-traffic signal priority on selected corridors	
	Utilize information from the automatic-vehicle-location system on the transit authority’s bus fleet for travel conditions on major routes	
Incident Detection, Reporting, Response	For specified threshold real-time travel conditions on arterial streets, alert an operator to direct field-verification of possible incidents	ITS Emergency Management
Commercial Vehicle Operations Support	Provide electronic capability for on-demand routing and permitting for oversize loads, based on agreements for heavy-duty truck corridors being investigated by the state department of transportation	ITS Commercial Vehicle Operations

Note:
Table adapted from D. Malone, “Request for Proposal for Category T: Intelligent Transportation Systems: Traffic Management Center Project” (Chicago, Illinois: Department of Transportation, 2000).
ITS = intelligent transportation systems.
MDLRS = multimodal, multidimensional transportation location referencing system.
RFP = request for proposals.

TABLE 3-5 Mapping of functional requirements to transportation agency business systems and ITS user services bundles identified for a traffic management center

Functional Requirements for a multimodal, multidimensional transportation location referencing system data model	**NCHRP 20-27(2) Business Systems**		**ITS User Services Bundles**			
	Transportation Monitoring and Performance Assessment	Data Sharing	ITS Travel and Traffic Management	ITS Public Transportation Management	ITS Commercial Vehicle Operations	ITS Emergency Management
Spatiotemporal Referencing Methods: The model supports the *locate*, *place*, and *position* processes for objects and events in three dimensions and time relative to the roadway.	X	X	X	X	X	X
Temporal Referencing System/Temporal Datum: The model accommodates a temporal datum that relates the database representation to the real world and provides a domain for transformations among temporal referencing methods.	X	X	X	X	X	X
Transformation of Data Sets: The model supports transformation between linear, nonlinear, and temporal referencing methods without loss of spatiotemporal accuracy, precision, and resolution.	X	X		X	X	X
Multiple Cartographic/Spatial Topological Representations: The model supports multiple cartographic and spatial topological representations at both the same and varying levels of generalization of transportation objects.		X		X	X	X
Resolution: The model supports the display and analysis of objects and events at multiple spatial and temporal resolutions.		X		X	X	X
Dynamics: The model supports the navigation of objects, in near real time and contingent upon various criteria, along a traversal in a transportation network.				X	X	X
Historical Database: The model supports generation of object and network states over time and maintains the network event history.	X				X	
Accuracy and Error Propagation: The model supports association of error measures with spatiotemporal data at the object level and propagation of those errors through analytical processes.		X	X		X	
Object-Level Metadata: The model stores and expresses object-level metadata to guide general data use.	X	X	X		X	
Temporal Topology/Latency: The model supports temporal relationships among objects and events and latency of events.	X		X		X	

Note: ITS = intelligent transportation systems.

TABLE 3-6 Mapping of functional requirements to the ITS public transportation management bundle

Functional Requirements for a multimodal, multidimensional transportation location referencing system data model	**ITS User Services Bundles** ITS Public Transportation Management
Spatiotemporal Referencing Methods: The model supports the *locate*, *place*, and *position* processes for objects and events in three dimensions and time relative to the roadway.	**X**
Temporal Referencing System/Temporal Datum: The model accommodates a temporal datum that relates the database representation to the real world and provides a domain for transformations among temporal referencing methods.	**X**
Transformation of Data Sets: The model supports transformation between linear, nonlinear, and temporal referencing methods without loss of spatiotemporal accuracy, precision, or resolution.	**X**
Multiple Cartographic/Spatial Topological Representations: The model supports multiple cartographic and spatial topological representations at both the same and varying levels of generalization of transportation objects.	**X**
Resolution: The model supports the display and analysis of objects and events at multiple spatial and temporal resolutions.	**X**
Dynamics: The model supports the navigation of objects, in near real time and contingent upon various criteria, along a traversal in a transportation network.	**X**
Historical Database: The model supports generation of object and network states over time and maintains the network event history.	
Accuracy and Error Propagation: The model supports association of error measures with spatiotemporal data at the object level and propagation of those errors through analytical processes.	
Object-Level Metadata: The model stores and expresses object-level metadata to guide general data use.	
Temporal Topology/Latency: The model supports temporal relationships among objects and events and latency of events.	

Note: ITS = intelligent transportation systems.

TABLE 3-7 Mapping of functional requirements to MDLRS data model objects for the ITS public transportation management bundle

MDLRS Object	Spatio-temporal Referencing Methods FR 1				Temporal Referencing System/ Temporal Datum FR 2			Transformation of Data Sets FR 3						Multiple Cartographic/ Spatial Topological Representations FR 4						Resol-ution FR 5	Dynamics FR 6					
	a	b	c	d	a	b	c	a1	a2	a3	b	c	d	a	b	c	d	e	f	a	a	b	c	d	e	f
Transportation Feature	■	■	■	■				■	■	■	■	■		■	■	■	■	■	■	■			■	■	■	
Conveyance	■			■				■	■	■	■	■		■	■	■	■	■	■	■	■		■			
Transportation Complex								■	■	■	■	■		■	■	■	■	■	■	■			■	■	■	
Transportation System								■	■	■	■	■		■	■	■	■	■	■	■			■	■	■	
Attribute				■															■				■	■	■	■
Experience																										
Event	■																									■
Complex Event	■																									■
Spatial Datum																										
Vertical Datum									■	■			■													
Geoid									■	■			■													
Local Datum									■	■			■													
Benchmark		■	■						■	■			■													
Geocentric Datum									■	■			■													
3D Cartesian Axes									■	■			■													
GPS Satellite		■	■						■	■			■													
Horizontal Datum									■	■			■													
Ellipsoid									■	■			■													
Projection									■	■			■													
Control Station		■	■						■	■			■													
Cadastral Datum									■	■			■													
Corner									■	■			■													
Corner Point		■	■						■	■			■													
Linear Datum								■	■		■	■	■													
Linear Referencing Method								■	■		■	■	■													
Anchor Point								■	■		■	■	■													
Anchor Section								■	■		■	■	■													
Transport Node								■	■		■	■	■													
Transport Link								■	■		■	■	■													
Transport System Link								■	■		■	■	■													
Traversal								■	■		■	■	■													
Traversal Link								■	■		■	■	■													
Traversal Reference Point								■	■		■	■	■													
Temporal Referencing System																										
Temporal Datum							■					■	■									■				■
Temporal Referencing Method					■	■						■	■									■				■
Spatial Object																										
Scale Applicability Constraint																	■	■								
Dimensionality Constraint																	■	■								
Geometric Object **Geometric Primitive**																										
Point								■	■	■	■	■			■	■	■	■		■						
Reference Point								■	■	■	■	■			■	■	■	■		■						
Curve								■	■	■	■	■			■	■	■	■		■						
Surface								■	■	■	■	■			■	■	■	■		■						
Solid								■	■	■	■	■			■	■	■	■		■						
Geometric Complex								■	■	■	■	■			■	■	■	■		■						
Coordinate																										
1D Coordinate	■	■																		■						
2D Coordinate	■	■																		■						
3D Coordinate	■	■																		■						
GPS Coordinate	■	■																		■						
Linear Coordinate	■	■																		■						

(*table continued on next page*)

TABLE 3-7 (*Continued*)

	Spatio-temporal Referencing Methods FR 1				Temporal Referencing System/ Temporal Datum FR 2			Transformation of Data Sets FR 3						Multiple Cartographic/ Spatial Topological Representations FR 4						Resol-ution FR 5	Dynamics FR 6					
MDLRS Object	a	b	c	d	a	b	c	a1	a2	a3	b	c	d	a	b	c	d	e	f	a	a	b	c	d	e	f
Measurement																										
1D Gnd Measurement	▨	▨	▨																							
2D Gnd Measurement	▨	▨	▨																							
3D Gnd Measurement	▨	▨	▨																							
Radio Frequency Measurement	▨	▨	▨																							
Linear Measurement	▨	▨	▨																							
Distance Measurement	▨	▨	▨																							
Angle Measurement	▨	▨	▨																							
Direction	▨	▨	▨																							
Variance/Covarience Matrix	▨	▨																								
Topological Object																										
Topological Primitive																										
Node														▨	▨	▨	▨	▨	▨				▨		▨	
Edge														▨	▨	▨	▨	▨	▨				▨		▨	
Face														▨	▨	▨	▨	▨	▨				▨		▨	
Volume														▨	▨	▨	▨	▨	▨				▨		▨	
Topological Complex														▨	▨	▨	▨	▨	▨				▨		▨	
Network														▨	▨	▨	▨	▨	▨				▨		▨	
Time Object																										
Date Time	▨	▨									▨	▨								▨			▨	▨	▨	▨
Date	▨	▨									▨	▨								▨			▨	▨	▨	▨
Time	▨	▨									▨	▨								▨			▨	▨	▨	▨
Timestamp	▨	▨									▨	▨								▨			▨	▨	▨	▨
Temporal Measure	▨																									
Temporal Error Measures																										
Duration																										
Year Month Duration	▨										▨	▨								▨			▨	▨	▨	▨
Day Time Duration	▨										▨	▨								▨			▨	▨	▨	▨
Interval	▨										▨	▨								▨			▨	▨	▨	▨
Time Aggregate	▨										▨	▨								▨			▨	▨	▨	▨
Cycle	▨										▨	▨								▨			▨	▨	▨	▨
Break	▨										▨	▨								▨			▨	▨	▨	▨
Stage	▨										▨	▨								▨			▨	▨	▨	▨
Sequence	▨										▨	▨								▨			▨	▨	▨	▨
Temporal Relationship																										
Temporal Topology																										
Temporal Proximity																										
Metadata																										
Source Metadata	▨	▨																								
Lineage Metadata																										

Note:
1D = one-dimensional.
2D = two-dimensional.
3D = three-dimensional.
FR = functional requirement.
Gnd = ground.
GPS = global positioning systems.
ITS = intelligent transportation systems.
MDLRS = transportation multimodal, multidimensional location referencing system.

- **The MDLRS data model uses the lowest common denominator.** In the MDLRS data model, the transportation feature represents a non-decomposable object in the transportation domain. Examples of transportation features are signs, guard rail, pavement sections, intersections, anchor points, and abutments. The exchange of data is easier when stakeholders share the same definitions, but not necessarily the same composition, for transportation features. For example, when stakeholders designate signs as a transportation feature, though the attributes of the signs may differ, the exchange and integration of these signs is enhanced. Designating a class of phenomena as non-decomposable is based on a set of stakeholder business rules. For example, although signs can be decomposed (e.g., into the actual sign, a post, anchoring hardware, and a base, all of which are themselves transportation features), stakeholders may view a sign as a single unit.
- **The MDLRS data model uses object-level metadata.** The MDLRS data model uses metadata objects at various levels of the abstraction of a phenomenon (i.e., transportation feature). Metadata objects are associated with the spatial and temporal objects of the transportation feature, as well as with the feature itself. The metadata objects in the MDLRS data model contain information on the source, lineage, and quality of the data. Additionally, the MDLRS data model provides data constructs that identify spatial error and its propagation. By providing the source, lineage, quality, and error of a phenomenon, the MDLRS data model makes the exchange of data more intelligent, allowing the stakeholder to be better informed on his or her data, thereby making better decisions.

CHAPTER 4

CONCLUSIONS AND SUGGESTED RESEARCH

4.1 PROOF OF PROBLEM SOLUTION

A critical part of any data model that represents a geographic phenomenon and its interactions with other phenomena is the foundation or assumptions upon which it is based. The MDLRS data model was founded on the results of a workshop consisting of 34 participants representing various transportation stakeholder groups and considered to be experts in their respective groups.

The functional requirements for an MDLRS are tied to existing research. For example, the requirement of a multiscale or multirepresentational GIS has been the focus of much research (*55, 56, 57, 58, 59, 60, 61, 62, 63, 64*). Multiscale approaches allow one representation to be shown at one scale and a detailed representation to be shown at an enlarged scale.

The NCHRP 20-27(3) multidimensional LRS data model was developed to meet the emerging need of the transportation community to integrate multidimensional data. The 20-27(3) MDLRS data model includes multiple location referencing methods, multiple cartographic representations, and multiple topological representations. The MDLRS data model is a comprehensive model for location referencing that can accommodate and integrate data expressed in one to four dimensions. Data integration is supported through transformations among linear methods through a "linear datum" (as described in the 20-27[2] linear referencing system data model), among nonlinear methods through mathematical equations, and among linear and nonlinear methods through the association of cartographic objects with the linear datum. Time objects, which record when an activity occurred and when it was entered into the database, describe the temporal aspects of phenomena.

The MDLRS data model goes beyond the 20-27(2) LRS data model by providing a datum hierarchy and details on the associations between the linear datum and datums of higher dimensions. The MDLRS data model accounts for temporal referencing by adopting the concept of a "temporal datum" and provides the constructs needed for temporal referencing. The data structures of transportation features, of transportation complexes, and of transportation systems adopted from the GIS-T/ISTEA PFS Phase B architecture provide the MDLRS data model with flexibility for modeling multiple modes and modeling the intermodal relationships between modal networks.

NCHRP Project 20-27(3) resulted in tools to support consistent location referencing across the transportation community. These tools include a comprehensive data model and implementation guidelines. Implementation of the MDLRS data model will result in effective systems and allow organizations to implement improved transportation systems and advanced GIS-T technology, thereby assisting in the changing roles of DOTs, metropolitan planning organizations, and transit agencies.

4.2 FUTURE RESEARCH

NCHRP Project 20-27(3) furthers the development of LRS data models in transportation; however, more research can be done. Areas for future research and potential improvement to the MDLRS data model include the following:

- **Development of the measurement management system.** In the MDLRS data model, a framework for a system that manages different types of measurements was provided through the coordinate and measurement object hierarchies. The method "location derivation" was included in coordinate objects to derive coordinates from collections of measurements. Future research can fully develop the measurement management system, including all types of measurements (field based or in-house based); develop the algorithms for the location derivation methods; and develop guidelines for implementing the measurement management system to be used with the MDLRS data model.
- **Versioning and persistence of transportation features, complexes, and systems.** Versioning is defined as "the tracking of the evolution of an object's state through time" (*65*). Versions reflect multiple alternative values for characteristics of the single entity. Versioning allows multiple realizations of a model for a single entity, not the realization of multiple models of multiple entities. The MDLRS data model accommodates versioning by allowing an object to have one or more spatiotemporal representations and by keeping a history of attribute values. However, the MDLRS data model does not answer the question, What makes an entity a version of itself instead of a completely new entity? This issue has been called "persistence" (*66*). Persistence involves the essential user-defined property that defines an entity. Every geographical entity has

such a defining property (*67*), and if this defining property changes, then the entity is "destroyed," or becomes another entity, while other property changes merely result in new versions of the same entity. The essential property can be the entity's location or an attribute, but is identified by stakeholder business rules. In the MDLRS data model, the event list is rolled forward or backward to trace an entity and its replacements. Additionally, the MDLRS data model does not address business rules for object persistence. Future research can develop business rules for object persistence and provide guidelines for their use.

- **Business rules for scale applicability and dimensional constraints.** The MDLRS data model allows individual topological entities to be associated with many cartographic entities and vice versa. This association between topological and cartographic entities is constrained by the applicable scale of the entities, primarily because of cartographic representation. This association is also constrained optionally by dimensional business rules. The MDLRS data model does not provide guidelines on the appropriate scales to use with each spatial entity, nor does the model provide guidelines for the use of the dimensionality constraint. Future research can develop guidelines and recommendations for the scale of spatial objects and for the dimensionality constraint.
- **Testing of the MDLRS data model.** Future research can involve rigorous implementing and testing of the MDLRS data model, including the following:
  - Test the implementation guidelines to determine whether they are accurate and complete and whether they produce the intended results.
  - Develop the physical design of the MDLRS data model, optimizing the physical design for spatiotemporal data using mathematical functions. Physical design involves database management system technology, architecture environment, performance requirements, security requirements, and constraints of the processing transactions, as well as decisions about which derived data to store and how to store volumes of data (*36*).

    A critical concern in the physical design of the MDLRS data model is how to efficiently store, reference, and perform transactions on the immense volume of data resulting from spatiotemporal processes. One process that produces volumes of data is that of tracking vehicles. Instead of storing individual sampled locational points, a mathematical or space-time function can be used to store data in compressed form and to allow transformation of data in continuous and discrete representations without loss of information. An example used in the communications field of this space-time function is the short-term Fourier transform.
  - Implement the physical design of the data model and test the code with data with various types of queries. Because the MDLRS data model is a data model, operations (e.g., transformation operators or event methods) on data constructs are not specified (i.e., algorithms are not given). Implementation of data operations is likely to bring about changes in the model.
- **Development of the conveyance object and its interaction with its environment.** The MDLRS data model specifies a moving object called a "conveyance." The conveyance object takes part in the track and route navigational functions. However, the MDLRS data model does not provide the algorithms for the track and route navigational functions. Additionally, the MDLRS data model does not provide the functions needed to perform pathfinding, route guidance, travel time prediction, stochastic processing (e.g., predictive traffic estimates), or dynamic programming. Future research can develop the track and route navigational functions in the context of implementing an advanced traveler information system or an advanced public transportation system and provide guidelines for the implementation.

4.3 LINKAGE TO PAST EFFORTS

The strategy for developing the MDLRS data model was to use the NCHRP 20-27(2) data model and selected components of other existing data models. Employing this strategy demonstrates continuity in that past efforts in modeling transportation-based phenomena are folded into the MDLRS model rather than being replaced. Replacing existing models of transportation-based phenomena creates additional confusion and reduced acceptability with stakeholders because of the unfamiliarity of new concepts in a completely new data model.

In keeping with this strategy, the MDLRS data model relies on the 20-27(2) data model, the GIS-T/ISTEA PFS data model, the National ITS Architecture, the CGIS-SAIF data model, and the ISO 15046 data model. The 20-27(2) LRS data model is used in the MDLRS data model as the framework for managing and transforming linearly referenced data. The GIS-T/ISTEA PFS model is used as the framework for modeling transportation-based geospatial data and their relationships. From the GIS-T/ISTEA PFS model, the MDLRS data model adopts the historical modeling of transportation-based phenomena. The National ITS Architecture is used in the MDLRS data model as the framework for identifying and mapping ITS business areas. The CGIS-SAIF model is used in the MDLRS data model as the framework for modeling the temporal attributes and relationships of transportation-based phenomena. From the ISO 15046 model, the MDLRS data model adopts the spatial representation of transportation-based phenomena.

GLOSSARY

abstraction. (a) Concentrating on a problem at some general level of detail and ignoring details that are not at that level of generalization (*2*). (b) A mental facility that permits humans to view real-wold problems with varying degrees of detail depending on the current context on the problem (*28*).

accuracy. (a) A measure of how closely a set of values (measured or calculated) agrees with the true value (*68*). (b) The degree to which a measured or calculated value conforms to its definition or to a standard reference (*69*). (c) How closely results of observations, computations, or estimates agree with the true values or the values accepted as being true (*70*). (d) How closely a test result agrees with the accepted reference value (*21*). (e) With regards to a digital base map, how closely observation or computational estimates of the position of mapped features agree with the true ground position (*71*).

aggregation. (a) An "a-part-of" relationship (*2*). (b) A special form of association, between a whole and its parts, in which the whole consists of the parts (*28*). (c) The operation of constructing more complex phenomena out of component phenomena. A lock is an aggregation of walls, gates, and a reservoir (*20*). (d) Concerned with objects as assemblies of components represented by other objects (*19*).

altitude. (a) Elevation above or below a reference datum, as defined in FIPSPUB 70-1. (b) The z-value in a spatial address (*20*).

anchor point. A known point or location along a transportation corridor, such as an intersection, bridge, monument, post, or travelway terminus (*2*).

anchor section. The explicit domain of valid linear locations. The direction of the section establishes the positive direction (*2*).

angle measurement. The observed two-dimensional angle located at a vertex, with a backsight at either a vertical plane through the instrument or at a point and a foresight at another point.

association. The assignment of phenomena to sets, using criteria different from those used for classification. For example, concrete roads may be associated with concrete sewers, concrete locks, and other phenomena constructed of concrete (*20*).

attribute. A quantitative or qualitative characteristic ascribed to an object from a stated domain (*19*).

attribute value. A specific quality or quantity assigned to an attribute (e.g., steel) for a specific entity instance (*70*).

benchmark. A relatively permanent material object, natural or artificial, bearing a marked point whose elevation above or below an adopted surface (i.e., datum) is known (*72*).

break. A time aggregate object consisting of the period of time represented by the difference in two disjoint, nonoverlapping intervals.

cadastral datum. A datum based on the set of rules and procedures for setting boundaries of public lands and parts, as established by the Bureau of Land Management and its predecessors (*72*).

calendar. Discrete temporal referencing system that provides a basis for defining temporal position to a precision of one day (*21*).

calendar era. The division of time into a sequence of calendar years counted from a specified date (*21*).

cartographic representation. A set of lines that can be mapped to a linear datum. The set of lines can be fully or partially linked. That is, the set can consist of disjoint groups with the lines in each group being internally linked. Cartographic representations have a "source" attribute that denotes the source (i.e., scale and lineage) of the object. Cartographic representations provide coordinate references; the basis for to-scale visualization of other components of the linear referencing system model; and linkages to extended, vector-based GIS data models (*1*).

CGIS-SAIF. Canadian Geomatics Interchange Standard–Spatial Archive and Interchange Format.

class. A software component comprising data structure descriptions (or templates) and procedures (called methods) for manipulating that structure (*21*).

classification. The assignment of similar phenomena to a common class. An individual phenomenon is an instance of its class—for example, Route 10 is an instance of the class "road" (*20*).

complex event. A collection of related events (e.g., a yearly construction schedule).

conceptual model. A model that defines concepts of a universe of discourse (*21*).

conceptual schema. Schema of a conceptual model (*21*).

control station. A point, on the ground, whose location is used as a basis for obtaining locations of other points (*72*).

conveyance. An object required to execute navigation. A conveyance object is anything (usually a vehicle or a person) that moves in a spatiotemporal reference frame (*43*).

coordinate. A specified or derived ordered set of *N* numbers that designate the location of a point in a space of *N* dimensions (*72*).

Coordinated Universal Time (UTC). A time scale maintained by the International Bureau of Weights and Measures and the International Earth Rotation Service (IERS) that forms the basis of a coordinated dissemination of standard frequencies and time signals (*21*).

coordinate referencing system. A coordinate system that relates to the Earth by a datum (*21*).

coordinate system. (a) A set of mathematical rules for specifying how coordinates are to be assigned to points (*21*).

(b) A referencing system for the unique definition of a point's location in *N*-dimensional space (*73*).

coordinate transformation. The computational process of converting a position from one coordinate system to another (*74*).

corner. A legal location that may mark the extremity of a parcel or a parcel legal area. A corner may have multiple corner points, which serve as measures or markers for the legal location of the corner (*75*).

corner point. A point that marks the ends of a record boundary or the extremities of a legal area. A corner point may or may not be monumented and is any representation of a corner (*75*).

curve. A bounded, connected, one-dimensional geometric primitive. A curve represents the continuous image of a line and, therefore, is realizable as a one-parameter set of points (the boundary of a curve is the set of points at either end of the curve: the first point is the start point, the last is the end point [*21*]).

cycle. A time aggregate object that consists of a beginning and optional ending date time object with a repeating duration object.

data quality. A category of measures of how well a given data set fits a given use. Quality measures include such things as information on data sources, accuracy, logical consistency, completeness, and positional and attribute accuracy (*74*).

data set. (a) An identifiable collection of data. A data set may be a smaller grouping of data that, though limited by some constraint (such as spatial extent or feature type), is located physically within a larger data set. Theoretically, a data set may be as small as a single feature or a feature attribute contained within a larger data set (*21*). (b) A collection of related data files (*17*). (c) An identifiable collection of data (*18*).

date. (a) A unique instant defined in a specific time scale (*69*). The date can be conventionally expressed in years, months, days, hours, minutes, seconds, and fractions. (b) A specified instant. The instant is specified by its time within the day and by its day (*68*). (c) The day, month, and year of a specified calendric system for an absolute point in time (adapted from the BC Ministry of Environment, Lands, and Parks [*19*]).

date time. (a) The zero-dimensional temporal geometric primitive, equivalent to a point in space. (b) An interval whose duration is less than the resolution of the time scale. A date time object is associated with a single temporal position in a given temporal referencing system. The date time can be conventionally expressed in years, months, days, hours, minutes, seconds, and fractions (modified from ISO Technical Committee 211, Working Group 1 [*21*]). (c) An abstract superclass dealing with date and time constructs (*19*).

datum. Any quantity or set of quantities that may serve as a reference or basis for the calculation of other quantities (*21*).

day time duration. A duration defined in terms of number of days, hours, minutes, and seconds (*19*).

DGIWG. Digital Geographic Information Working Group.

DIGEST. Digital Geographic Information Exchange Standard.

direction. The computed azimuth or bearing between two points.

direct positioning. A position expression, using coordinates defined in relation to a geodetic reference frame, sufficient to ascribe a coordinate position to a feature on the Earth (*21*).

distance measurement. The observed distance between two points.

DOT. Department of transportation.

duration. (a) A quantity of time, the temporal equivalent of length (*21*). (b) An abstract superclass with subclasses designating different types of time durations (*19*).

edge. A one-dimensional topological primitive (*21*).

EF. Entity-relationship.

ellipsoid. An ellipsoid whose dimensions and position have been selected to best fit the astronomical and geodetic coordinates of a particular geodetic network (*72*).

entity. A phenomenon that cannot be subdivided into like units (*18*).

epoch. (a) The beginning of an era or event or the reference data of a system of measurements (*69*). (b) A particular instant of time from which an event or a series of events is calculated; a starting point in time, to which events are referred; a date and instant, corresponding to the position of a coordinate system, to which all subsequent positions are referred. Whereas date is associated with a value of time and with the event that occurred then, epoch is associated with a point in time to which events are referred (*68*).

error. The difference between the measured value of a quantity and the theoretical or defined value of that quantity (*68*).

error measures. The uncertainties associated with measurements (bias is assumed to be removed by calibration).

ESRI. Environmental Systems Research Institute.

event. An instant or period in which something happens that changes the state of an object (adapted from Rumbaugh et al. [*28*]). An event that changes the state of a specific object results in a significant experience for that object.

experience. An event participated in—that is, an event that changes the state of an object (adapted from Fletcher, Henderson, and Espinoza [*2*]). The experience object holds the memory of events that have directly affected its existence.

face. (a) A two-dimensional topological primitive (*21*). (b) A two-dimensional element bounded by a closed set of edges and zero or more nonintersecting inner closed set of edges; the atomic two-dimensional element (*17*).

FHWA. Federal Highway Administration.

fleet. A collection of conveyances that represent a group of vehicles that supports fleet management applications.

FTA. Federal Transit Administration.

functional requirement. A functional-level capability or business rule that is identified by an organization and is necessary to solve a problem or achieve an objective (*48*).

generalization. (a) The gradual loss of resemblance between a symbol on a map and the object represented by that symbol, as the scale of the map becomes smaller (*68*). (b) An "a-kind-of" relationship (*2*). (c) The relationship between a class and one or more refined or specialized versions of it (*28*). (d) A process in which classes are assigned to other classes. The general class includes all the instances of the constituent classes. For example, sewers are included in the more general class of "utilities" (*20*). (e) Dealing with supertype and subtype relationships by use of an "is-a" hierarchy (*19*).

geocentric datum. A datum that uses the Earth's center of mass to specify the coordinate system (*72*).

geodetic coordinate system. A coordinate system in which position is specified by latitude, longitude, and ellipsoidal height (*21*).

geodetic datum. (a) A set of parameters describing the relationship of a coordinate system to the Earth (*21*). (b) A mathematical model of the Earth's shape (*73*). (c) A geometric set of five quantities that serves as a locational reference or base for other quantities. The five quantities are latitude and longitude of an initial point, the azimuth of a line from this point, and two constants necessary to define the terrestrial spheroid (*71*).

geodetic referencing system. A coordinate system, based on a geodetic datum, that defines the position of the origin and the orientation of the axes (*21*).

geographic coordinates. The quantities of latitude and longitude (and, sometimes, altitude) that define the position of a point on the Earth with respect to the reference spheroid or ellipsoid (*71*).

geographic data. Data with implicit or explicit reference to a location relative to the Earth (*21*).

geographic object. (a) An object representing a real or artificially defined phenomenon that has or potentially has some kind of spatial or spatiotemporal position (*2*). (b) An object representing a real-world phenomenon that exists in a spatial or spatiotemporal domain. An object is considered a geographic object if its position in space, or in both space and time, forms an integral part of the user's understanding of the object (*19*). (c) An object representing a real-world phenomenon that exists in a spatial or spatiotemporal domain. An object is considered a geographic object if its position in space, or in both space and time, forms an integral part of the user's understanding of the object (*19*).

geographic reference network. A set of spatial objects that represent the position of the reference network at some cartographic scale and resolution (*2*).

geoid. The equipotential surface of the Earth's gravity field that coincides with the surface that the oceans would have if they were motionless and were affected only by the Earth's gravity field (*72*).

geometric complex. A collection of geometric primitives, other geometric complexes, or both.

geometric object. The region in space occupied by a transportation feature (adapted from the BC Ministry of Environment, Lands, and Parks [*19*]). A geometric object provides the means for the quantitative description, through coordinates and mathematical functions, of the spatial characteristics of features, including dimension, position, size, shape, and orientation (*21*).

geometric primitive. A non-decomposable object representing a single, connected, homogeneous element of geometry. Geometric primitives present information about geometric configuration (*21*).

geometric/topological association. A relation that associates a single geometric object to a set of topological objects and imposes a restriction on the set of topological objects that is realized by the scale of the geometric object.

GIS. Geographic information systems.

GIS-T. Geographic Information System in Transportation.

GPS. Global positioning systems.

GPS coordinate. A specified or derived ordered set of three numbers that designate the location of a point in a space of three dimensions (adapted from DeLoach [*72*]). The derivation of this coordinate uses a radio measurement object.

GPS satellite. A geosynchronous, passive satellite that is part of the NAVSTAR constellation used to provide passive global positioning (*72*).

Gregorian calendar. The calendar in general use introduced in 1582 to correct an error in the Julian calendar (*21*).

ground control. A system of points with established horizontal and vertical positions that are used as fixed references in positioning and relating map features (*20*).

ground control point. A point of known location that can be recognized on an image or a map and that can be used to calculate the transformation needed for the registration of images or maps. Ground control points relate to a known projection for use in geometric transformation (*73*).

homomorphism. A relationship between two complexes such that there is a structure-preserving function from one complex to the other (*21*).

HOV. High-occupancy vehicle.

instant. (a) A specific time (*69*). (b) A zero-dimensional temporal geometric primitive; a point in time (*21*).

intelligent transportation systems (ITS). Systems that apply modern technology to transportation problems (another appropriate meaning of the ITS acronym is integrated transportation systems, which stresses that integrated transportation systems will often integrate components and users from many domains, both public and private [*74*]).

interoperability. The ability to share information between heterogeneous applications and systems (*74*).

interval. A one-dimensional temporal geometric primitive, equivalent to a curve in space. Like a curve, it has beginning and end points (each a date) and a length (its duration). Its temporal position is described in terms of the temporal positions of the dates at which the interval begins and ends (adapted from ISO Technical Committee

211, Working Group 1 [*21*]). An interval is defined in terms of either (a) a beginning and ending start date and time or (b) a start date and time and a duration beginning at that date and time (*19*).

interval time scale. A time-measuring scale that provides an origin and one or more standard time intervals. These intervals are used to describe the temporal position and duration of a temporal primitive (*21*).

ISO-GDF. International Standards Organization–Geographic Data Files.

isomorphism. A relationship between two complexes such that there is a one-to-one, structure-preserving function from one complex to the other. For example, a geometric complex is isomorphic to a topological complex if the elements of the two complexes are in a one-to-one, dimension- and boundary-preserving correspondence to one another (*21*).

ISTEA. Intermodal Surface Transportation Efficiency Act of 1991.

ITS. Intelligent transportation systems.

Julian day number. The integer number of days since the date 1 January 4712 B.C. in the Julian calendar (*21*).

latency. In general, the period of time in which one component in a system is idle while waiting for another component; wasted time.

lineage metadata. An object that indicates the history or parentage of the data, including their compilation and processing history (*19*).

linear coordinate. A specified or derived traversal measure that designates the location of a point in a linear space (adapted from DeLoach [*72*]). The derivation of this coordinate uses a linear measurement object.

linear datum. The complete set of anchor sections and anchor points, constituting a mutually exclusive, totally exhaustive, ordered set of linear locations (*1*).

linear measurement. An abstract data type representing either the observed distance or offset between two points (i.e., linear distance or offset distance).

linear reference method. The location of a site relative to a traversal in some system. A linear reference method object contains linear locations represented by traversals and their reference point sites (*2*).

linear referencing system. A means of identifying a location by reference to a segment of a linear geographic feature (such as a roadway) and distance from some point along that segment (*21*).

local vertical datum. A level surface taken as a surface of reference from which to reckon elevations (*72*).

locate. To establish the location in space and time of an unknown point in the field by reference to objects in the "real world" (adapted from Vonderohe et al. [*1*]).

location. (a) The numerical or other identification of a point or object, sufficiently precise that the object or event can be found from the identification (adapted from the American Society of Civil Engineers [*68*]). (b) A spatiotemporal expression that designates a unique place and time in space. (c) The name given to a specific point on a highway for which an identification of its linear position with respect to a known point is desired (*16, 41*). (d) Identifiable part, of a physical place, that may be identified by positional parameters (*21*). (e) A position on the Earth's surface (*74*).

location (or spatial) referencing method. A mechanism for finding and stating the location of an unknown point by referencing it to a known point (adapted from the Transportation Research Board [*41*]).

location (or spatial) referencing system (LRS). (a) Policies, records, objects, and procedures that relate the included location referencing methods in a way that the accuracy requirements for end users are met (adapted from ISO Technical Committee 211, Working Group 1 [*21*]). (b) A system of determining the position of an entity relative to other entities to some external frame of reference (*15*).

LRS. See "location referencing system."

MDLRS. Multimodal, multidimensional transportation location referencing system.

measurement. (a) The act of deliberately sensing an event or thing, noting the circumstances, and assigning a numerical value to the event or thing. (b) An observation, together with the act of associating a numerical value with the observation (*72*). A measurement object contains the identifiers associated with the observation, the value of the observation, and the uncertainty associated with the measurement.

metadata. Data about the content, quality, condition, and other characteristics of data (*75*).

motion. A change over time of coordinate values with respect to a particular reference frame (*21*).

NAD. North American Datum.

NATO. North Atlantic Treaty Organization.

NAVD. North American Vertical Datum.

navigate. To move within a spatiotemporal reference frame.

network. (a) A topological object, consisting of an aggregation of nodes and edges, that forms the basis for operations such as pathfinding and flow (*1*). (b) A set of nodes, some of which are joined by edges (*21*).

node. (a) A zero-dimensional element that is a topological junction of two or more edges or that is an end point of an edge (*17*). (b) A zero-dimensional topological primitive (*21*).

nongeodetic datum. A datum with a local reference (*21*).

nongeospatial dimensions. Dimensions used for giving data nongeographic location in space, such as the time dimension (*20*).

NSDI. National Spatial Data Infrastructure.

NSIF. NATO Secondary Imagery Format.

object. (a) A tangible or intangible phenomenon (e.g., road, sign, route, event, or conveyance) that the user wants to keep information (i.e., attributes) about. Objects can have attributes. Attributes have values that are valid for a time instant or interval (i.e., values that are time dependent). An object's state is the object's attributes' values at a time instant or interval. Any change in any object attribute value changes the object's state. (b) A unit of data that may be treated as indivisible at a higher level of abstraction. Objects often relate to real-world entities; however, they may also pertain to more abstract concepts (such as a mapping projection). Objects may be characterized by behavior (i.e., the set of operations that can be performed on them) and by state (i.e., the values for the attributes defining the objects [*19*]). (c) An inseparable package or capsule of data definitions and values and the procedures (often called methods) that act upon the data (*74*).

OMT. Object-modeling technique.

one-dimensional coordinate. A specified or derived elevation that designates the vertical location of a point in a space of one dimension (adapted from DeLoach [*72*]). The derivation of this coordinate uses a one-dimensional ground measurement object.

one-dimensional ground measurement. An abstract data type representing the observed signed difference in distance in the elevation of one point to the elevation of another point (i.e., vertical distance).

ordinal era. A named interval of time in an ordinal temporal referencing system. The duration of an ordinal era, and the point in time at which it begins and ends, may be unknown or indefinite (*21*).

ordinal temporal referencing system. A temporal referencing system consisting of a hierarchy of ordinal eras ordered in time (*21*).

ordinal time scale. A time-measuring scale that provides a basis for describing only the relative temporal position of a temporal geometric primitive (*21*).

path. A finite, alternating sequence of nodes and edges, such that every arc is immediately preceded and succeeded by the two vertices with which the arc is incident and in which no vertex is repeated, except possibly the first and last one (*17*).

period. A bounded, one-dimensional temporal geometric primitive (*21*).

PFS. Pooled fund study.

phenomenon. (a) A significant occurrence or event; the most general abstract superclass in the model. Every object is or represents a phenomenon (*2*). (b) A fact, occurrence, or circumstance. For example, Route 10, George Washington National Forest, and Chesterfield County are all phenomena (*20*).

place. To translate a database location in space and time into a real-world location in space and time (adapted from Vonderohe et al. [*1*]).

point. A zero-dimensional geometric primitive, representing a position, but not having extent (*21*).

point-of-interest. A geographic location, such as a transit stop, that is of interest to the transportation community (*74*).

polar coordinate system. A coordinate system in which position is specified by distance to the origin and by direction (*21*).

polymorphism. Assuming many forms; that property indicating that an operation may behave differently in different classes (*28*).

position. (a) To translate a real-world location in space and time into a database location in space and time (adapted from Vonderohe et al. [*1*]); to encode a real-world location and time metric in a database. (b) A numerical or other description of the location and orientation of an object (*68*). (c) A numerical or other description of the location of a point or object (*21*).

positional accuracy. (a) How closely the result of a position determination agrees with the true value of a position (*21*). (b) How closely the geographic position of an object agrees with its corresponding real-world entity (*74*).

positioning system. A system of measuring devices for determining the position of a point of interest (*21*).

precision. (a) A measure of the quality of the method by which measurements are made. Precision differs from accuracy in that the latter relates to the quality of the results of the measurements, not the quality of the method used (*68*). Precision is often expressed in terms of repeatability (i.e., the amount by which the measurements in a set differ from one another). (b) The degree of mutual agreement among a series of individual measurements. Precision is often, but not necessarily, expressed by the standard deviation of the measurements (*69*).

primitive. The smallest spatial component of which all features consist. There are three geometric primitives (nodes, edges, and faces) and one cartographic primitive (text [*18*]).

projected coordinate system. A two-dimensional Cartesian coordinate system resulting from a map projection (*21*).

projection. A set of functions, or the corresponding geometric constructions, relating points on one surface to points on another surface in such a manner that to every point on the first surface corresponds exactly one point on the second surface (*72*).

quality. (a) An essential or distinguishing characteristic necessary for cartographic data to be fit for use (*70*). (b) The totality of a product's characteristics that bear on the product's ability to satisfy stated and implied needs. Within the data quality model, quality indicates the totality of the following: feature representation types, feature representations, feature attributes, feature relationships, and operations of feature representation types. Quality is used to determine fitness for use (*21*).

radio frequency measurement. An abstract data type representing an observed radio signal and the time recorded at a location.

real time. (a) A time in which the occurrence of an event and the reporting or recording of that event are almost simultaneous (*46*). (b) A situation in which events are reported or recorded at the same time as they are happening (*68*). (c) The absence of delay in getting, sending, and receiving data (*68*).

real-time system. An interactive system in which time constraints on actions are particularly tight or in which the slightest timing failure cannot be tolerated (*28*).

real-world location. A description of the actual physical object. For example, a real-world location could be “the intersection of Main St. and Broad Ave” (*24*).

record. An implementation-dependent construct that consists of an identifiable collection of one or more related fields (*17*).

reference object. A physical, not readily movable object that is a component of a spatial referencing system and whose location is known and from which measurements are made in the real world to determine the unknown locations of other objects (adapted from DeLoach [*72*]).

reference point. A point representing the position of a reference object.

relationship. A meaningful connection between object classes or instances (*2*).

relative accuracy. How closely the positional relationships of features in a data set agree with true relationships or with the relationships accepted as true (*21*).

resolution. (a) A measure of the finest detail distinguishable in an object or phenomenon (*68*). (b) The smallest significant difference that can be measured with a given instrument (*69*). (c) The minimum difference, between two independently measured or computed values, that can be distinguished by the measurement or analytical method being considered or used (*70*). (d) A measure of the ability to distinguish detail or separation of objects under certain specific conditions. (e) The minimum distance between two adjacent objects, or the minimum size of an object, that can be distinguished under certain specific conditions (*18*).

RFP. Request for proposals.

rollback. To push back (*46*).

route. (a) To generate by direction and location, with linear tracks and a sequence of maneuvers, a traversal that may or may not be time dependent. (b) An aggregation of sequentially connected links in a network, typically denoting an intended or scheduled path of a transport resource (*74*).

schema. A formal description of a model (*21*).

SDTS. Spatial Data Transfer Standard.

sequence. A time aggregate object consisting of two or more intervals that meet.

solid. A bounded, connected, three-dimensional geometric primitive that represents the continuous image of a region of Euclidean 3 space and that is, therefore, fully realizable locally as a three-parameter set of points (*21*).

source metadata. An object that identifies the administrative aspects of where the data come from, where they are going, possible restrictions on the data, and when the data were entered into the database (*19*).

spaghetti. A digital storage format in which no lines or points relate to each other (*18*).

spatial attribute. A feature attribute describing the spatial characteristics of the feature in terms of spatial primitives and relationships between them (*21*).

spatial autocorrelation. The degree of correlation between a surface value and the values of its neighbors; the propensity of spatial data to vary smoothly with distance (*40*).

spatial data. Information about the location, shape, relationships, and attributes of geographic features (*74*).

spatial data sets. Collections of spatially referenced data that are grouped together for reasons of convenience—for example, watershed with subbasins (*19*).

spatial information system. An information system with the capability to manage spatially referenced information (*73*).

spatial object. An object that provides the spatial characteristics of a transportation feature and that is described by one or more geometric or topological objects. A spatial object can consist of a primitive or a complex that is geometric or topological of zero, one, two, or three dimensions, or a set of these (*21*).

spatial (or location) referencing method. A mechanism for finding and stating the location of an unknown point by referencing it to a known point (adapted from the Transportation Research Board [*41*]).

spatial (or location) referencing system (SRS). (a) Policies, records, objects, and procedures that relate the included location referencing methods in a way that the accuracy requirements for end users are met (adapted from ISO Technical Committee 211, Working Group 1 [*21*]). (b) A system of determining the position of an entity relative to other entities to some external frame of reference (*15*).

spatial reference. The geographic extent of the domain within which referenced features may be located (*21*).

spatiotemporal object. The region of space and time occupied by a transportation feature (adapted from the BC Ministry of Environment, Lands, and Parks [*19*]).

SPCS. State Plane Coordinate System.

SRS. See “spatial referencing system.”

stage. A time aggregate object consisting of two or more intervals that can meet, overlap, equal, start, end, or be disjoint.

state. (a) A condition that persists for a period (*21*). (b) A condition of being defined by constant attributes and link relationships. A state can be thought of as a portion of time between events. A state without an end state is current when valid time equals system time (*2*).

state plane coordinate system. A rectangular coordinate system used by particular states, typically for production of state transportation maps and resource management (*74*).

surface. A connected two-dimensional geometric primitive bounded by a set of oriented closed curves that delineate the limits of the surface (*21*).

system. An organized collection of components that interact (*28*).

TC211. Technical Committee 211 (of the International Standards Organization).

temporal attribute. A feature attribute describing the temporal characteristics of the feature (*21*).

temporal coordinate. The distance from the origin of the interval time scale to a point in time. This distance is used as the basis for a temporal referencing system (*21*).

temporal coordinate system. A temporal referencing system based on an interval time scale defined in terms of a single, standard, time interval (*21*).

temporal datum. An accepted time scale that has a definable epoch.

temporal error measures. The uncertainties associated with the measurement of time and dates.

temporal geometric primitive. A non-decomposable object used to describe position and magnitude within the temporal dimension (*21*).

temporal measurement. The point or interval of time recorded for an activity by one observer using a known temporal measuring device.

temporal position. The location of a temporal geometric primitive relative to a temporal referencing system (*21*).

temporal proximity. A temporal relationship, analogous to a temporal buffer, that answers the question of whether Object A occurred within a given time (i.e., a duration) of Object B (*19*).

temporal reference equation. A derivable equation that relates the temporal datum to the temporal referencing method. The temporal reference object equation consists of two parts: a reference offset (e.g., −3 h for eastern standard time [EST] to pacific standard time [PST]) and a metric scaling function that relates the metric of the method to the metric of the datum—for example, to create swatch time = ([{seconds/60 + minutes}/60 + hours]/24)*1000 swatch beats. The temporal reference object can accommodate various metrics and various temporal representations. The user must develop the appropriate offset and metric scaling functions to convert temporal addresses (e.g., 1/1/2000 Gregorian = 12/19/1999 Julian = 2451544.5 Julian date, or 10/5/3761 B.C. = 0/0/0 Jewish calendar, or 3:00 p.m. EST = 12:00 p.m. PST).

temporal referencing method. A mechanism for unambiguous ordering of events. A temporal reference is absolute or relative value or position on an interval or ordinal time scale that is stable and homogeneous, such as atomic time, Coordinated Universal Time (UTC), International Atomic Time (TAI), Terrestrial Time (TT), universal time (UT), and ephemeris time (adapted from “time scale” in the National Institute of Standards and Technology’s glossary [*69*]).

temporal referencing system (TRS). (a) Internal-based policies, records, objects, and procedures that relate the included temporal referencing methods (adapted from the Transportation Research Board [*41*]). (b) A referencing system against which time is measured (*21*).

temporal relationship. An abstract superclass under which a number of classes can be defined dealing with metric (i.e., involving measurements) and nonmetric (i.e., topological) temporal relationships (*19*).

temporal topology. A temporal relationship involving nonmetric temporal relationships between events. Nonmetric temporal relationships include temporal disjoint and temporal intersect. Two events may temporally intersect in multiple ways, including follows, overlap at start, overlap at end, during, during from start, during from end, and simultaneous (*19*).

three-dimensional Cartesian axes. A coordinate system consisting of three straight lines intersecting at a common point and perpendicular to each other (*72*).

three-dimensional coordinate. A specified or derived ordered set of three numbers that designate the location of a point in a space of three dimensions (adapted from DeLoach [*72*]). The derivation of this coordinate uses a three-dimensional ground measurement object.

three-dimensional ground measurement. An abstract data type representing either the observed slope distance or direction between two points or a zenith angle or a horizontal angle measured at a third point.

time. (a) A system for measuring duration (*46*). (b) The hour, minute, and second of a point in the time period of a day. (c) The instant when an event occurs. Time is one of the four coordinates that are necessary and sufficient to completely identify the location of a particle or event. Time is the only one of these four coordinates that always increases during a change, regardless of whether or how the other three coordinates change. In Newtonian mechanics, time is the temporal coordinate of an event and the other three coordinates are the spatial coordinates. The time associated with a particular event is determined by the location of the origin (i.e., the epoch); such time is usually the date of that event (*68*).

time aggregate. A time object that consists of date time, interval, and duration objects, as well as other time aggregate objects (*19*).

time object. An object that represents a specific or relative portion of the time line in which the spatial object, event, or attribute is valid. A time object provides the location of temporal primitives and aggregates relative to a temporal referencing system (adapted from ISO Technical Committee 211, Working Group 1 [*21*]). A time object is an abstract superclass with subclasses that address a variety of time-related concepts, including dates, time during a day, intervals, and durations (*19*).

time of day. A designation of a particular instant within a calendar day (*21*).

time scale. (a) A system of unambiguous ordering of events. A time scale is meant to be stable and homogenous (*69*). (b) The system of units into which the axis of a temporal coordinate system is divided. The location of the origin is immaterial. Time scales are unusually classified according to the method used for measuring time. The terms “time scale” and “time” are frequently used as synonyms, and there is, in fact, little difference in the meanings (*68*).

time stamp. A date-and-time object (*19*).

time standard. (a) A device used to realize the time unit—for example, a continuously operating device used to realize a time scale in accordance with the definition of "second" and with an appropriately chosen origin (*69*). (b) A branch of mathematics that investigates the properties of a geometric configuration that are unaltered if the configuration is subjected to any one-to-one transformation continuous in both directions (*18*).

topological complex. A collection of topological primitives that is closed under the boundary operations. A topological complex consists of collections of primitives of all kinds below the dimension of the largest primitive. Thus, a two-dimensional complex must contain faces, edges, and nodes (*21*).

topological/geometric association. A relation that associates a single topological object to a set of geometric objects and imposes a restriction on the set of geometric objects that is realized by the level of abstraction of the topological object.

topological object. An object that remains invariant if the space is deformed elastically and continuously—for example, when geographic data are transformed from one coordinate system to another (*21*).

topological primitive. An object representing a single, connected element of topology that remains invariant if space is deformed (*21*).

topological representation. The representation of topology within a digital database; the conceptual structure by which topology is represented (*74*).

topology. (a) Spatial relationships and connectivity among graphic GIS features, such as points, lines, and polygons. These relationships allow for display and analysis of "intelligent" data in GIS. Many topological structures incorporate "begin" and "end" relationships, direction, and right and left identification (*16*). (b) A branch of mathematics that investigates the properties of a geometric configuration that are unaltered if the configuration is subjected to any one-to-one transformation continuous in both directions (*18*). (c) Properties of spatial configuration invariant under continuous transformation (*21*). (d) The logical relationships among map features in a digital base map. Topology can be used to characterize spatial relationships, such as connectivity and adjacency (*74*).

track. To generate a chain of a conveyance's locations through a sequence of locate and position operations. (b) The actual path of a conveyance on the surface of the Earth. The course is the path that is planned; the track is the path actually taken (*68*).

transform. (a) To convert between various spatiotemporal referencing methods, between various cartographic representations, and between location referencing methods and cartographic representations (adapted from Vonderohe et al. [*1*]). (b) A function relating coordinates in one coordinate system to coordinates in another coordinate system (*68*).

transformation. (a) A change of coordinates that is based on a one-to-one relationship, from one coordinate referencing system to another based on a different datum. A transformation uses parameters that may have to be derived empirically by a set of points common to both coordinate referencing systems (*21*). (b) A computational process of converting a position from one coordinate system to another (*20*).

transportation complex. A collection of interconnected transportation features (adapted from Fletcher, Henderson, and Espinoza [*2*]).

transportation feature. An object representing a real-world or virtual phenomenon that exists in a spatial or spatiotemporal transportation domain. An object is considered a transportation feature if its position in space, or in both space and time, forms an integral part of the user's understanding of the object in the transportation domain (adapted from the BC Ministry of Environment, Lands, and Parks [*19*]). A transportation feature is regarded as part of a transportation system (adapted from Fletcher, Henderson, and Espinoza [*2*]).

transportation system. An ordered set of transportation features serving a transportation function in support of transportation objectives (adapted from Fletcher, Henderson, and Espinoza [*2*]).

transport link. An historical, existing, or anticipated travelway used to transport passengers or goods. The direction of the links establishes the primary direction in which the traversal is said to "run" (*2*).

transport node. (a) A place where travel originates or ends. (b) A facility allowing for a change in transportation mode or travel route (*2*).

transport system link. An object responsible for maintaining the assemblies of transport systems and their links (*2*).

traversal. The geographical route, path, or course designated for travel or followed by a vehicle or traveler. Traversals also may be names of designated paths through a transportation system. Examples include mainline routes, business routes, spurs, county routes, scenic, and hazmat (*2*).

traversal link. An object responsible for maintaining the history of traversal and link assemblies (*2*).

traversal reference point. A point on a traversal that can be easily identified and whose identity and location are known (*2*).

TRS. See "temporal referencing system."

two-dimensional coordinate. A specified or derived ordered set of two numbers that designate the location of a point in a space of two dimensions (adapted from DeLoach [*72*]). The derivation of this coordinate uses a two-dimensional ground measurement object.

two-dimensional ground measurement. An abstract data type representing either the observed horizontal distance or direction between two points or the horizontal angle measured at a third point.

UML. Unified modeling language.

uncertainty. A parameter, associated with the result of a measurement, that characterizes the dispersion of the values and thereby indicates the measurement's precision or accuracy in terms of dispersion (*21*).

UPS. Universal Polar Stereographic.

UTC. See "Coordinated Universal Time."

UTM. Universal Transverse Mercator.

variance/covariance matrix. An $N \times N$ dimensional matrix that quantifies the spatial uncertainty of objects in each dimension, as well as between dimensions.

vertical datum. (a) The set of constants specifying the coordinate system to which elevations are referred (*72*). (b) A set of parameters describing the relation of gravity-related heights to the Earth (*21*).

volume. A three-dimensional topological primitive (*21*).

year month duration. A duration defined in terms of a number of years and months (*19*)

REFERENCES

1. Vonderohe, A. P., C. L. Chou, F. Sun, and T. M. Adams, "A Generic Data Model for Linear Referencing Systems." *NCHRP Research Results Digest 218.* Transportation Research Board, National Research Council, Washington, D.C. (1997).
2. Fletcher, D., T. Henderson, and J. Espinoza, "Geographic Information Systems–Transportation ISTEA Management Systems Server—Net Prototype Pooled Fund Study Phase B Summary." Sandia National Laboratory, Albuquerque, New Mexico (1995).
3. Armstrong, M., "Temporality in Spatial Databases." *Proceedings of GIS/LIS '88,* San Antonio, Texas (1988) pp. 880–889.
4. Langran, G., "A Review of Temporal Database Research and Its Use in GIS Applications." *International Journal of Geographical Information Systems,* Vol. 3, No. 3 (1989) pp. 215–232.
5. Langran, G., *Time in Geographic Information Systems.* Taylor and Francis, London, England (1992).
6. Egenhofer, M. J., and R. G. Golledge, "Time in Geographic Space: Report on the Specialist Meeting of Research Initiative 10." *NCGIA Report 94-9,* National Center for Geographic Information and Analysis, University of California, Santa Barbara (1994).
7. Al-Taha, K., and M. Abbas, "The Transportation Challenge for Temporal GIS." *Proceedings, AASHTO Symposium on Geographic Information Systems in Transportation,* Norfolk, Virginia (1994) pp. 90–108.
8. Ganter, J., and J. Cashwell, "Display Techniques for Dynamic Network Data in Transportation GIS." *Proceedings, AASHTO Symposium on Geographic Information Systems in Transportation,* Norfolk, Virginia (1994) pp. 42–53.
9. Sutton, J., "Geochronography: The Mapping and Representation of Real-Time Data." *Proceedings, AASHTO Symposium on Geographic Information Systems in Transportation,* Norfolk, Virginia (1994) pp. 109–120.
10. Xiong, D., and D. Marble, "Towards Real-Time GIS-T: Traffic Flow Modeling Using a Massive Parallel SIMD Computer." *Proceedings, AASHTO Symposium on Geographic Information Systems in Transportation,* Norfolk, Virginia (1994) pp. 54–71.
11. Zhao, F., L. Wang, H. Elbadrawi, and D. Shen, "Temporal Geographic Information System and Its Application to Transportation." *Transportation Research Record 1593,* Transportation Research Board, National Research Council, Washington, D.C. (1997) pp. 47–63.
12. Fletcher, D., "Moving Toward Interoperability." Session 479. 1999 Annual Meeting of the Transportation Research Board. Washington, D.C. (1999).
13. Buehler, K., and L. McKee, "The Open GIS Guide: Introduction to Interoperable Geoprocessing." *OGIS TC Document 96-001,* Open GIS Consortium, www.opengis.org/guide/guide1.htm (1996).
14. Intelligent Transportation Society of America, "The National ITS Architecture, Version 2.0." Washington, D.C. (1999).
15. Goodwin, C. W. H., F. E. Latham, D. Siegel, and S. R. Gordon, "Intelligent Transportation Systems Datum Public Sector Requirements Workshop Report." *Spatial Data Interoperability Protocol for ITS Project,* Oak Ridge National Laboratory, Oak Ridge, Tennessee (1998).
16. Federal Geographic Data Committee (Ground Transportation Subcommittee), "NSDI Framework Transportation Identification Standard." Washington, D.C. (1999).
17. ISO Technical Committee 204, Working Group 3, "Geographic Data Files Standard, Version 5.0." *ISO/WD 19990722-2* (1999).
18. Digital Geographic Information Working Group, "The Digital Geographic Information Exchange Standard, Edition 2.0." Directorate of Geomatics, Department of National Defense, Canada (1997).
19. BC Ministry of Environment, Lands, and Parks, "CGIS-SAIF Canadian Geomatics Interchange Standard—Spatial Archive and Interchange Format: Formal Definition, Release 3.2." *CAN/CGSB-171.1-95,* Canadian General Standards Board, Ottawa, Canada (1995).
20. American National Standard for Information Systems, "Spatial Data Transfer Standard (SDTS)—Part 2, Spatial Features." U.S. Geological Survey, Washington, D.C. (1997).
21. ISO Technical Committee 211, Working Group 1, "CD 15046-1.2: Geographic Information—Part 1: Reference Model," *ISO/TC 211 N 623* (1998).
22. Siegel, D., C. Goodwin, and S. Gordon, "ITS Datum Prototype Final Design Report." *Task C: Spatial Data Interoperability Protocol for ITS Project*, Federal Highway Administration, IVHS Research Division, U.S. Department of Transportation, McLean, Virginia (1996).
23. Fletcher, D., T. Henderson, and J. Espinoza, "The GIS-T/ISTEA Pooled Fund Study: An Integrated Approach to Transportation Planning." *Proceedings, AASHTO Symposium on Geographic Information Systems in Transportation,* Washington, D.C. (1995) pp. 252–260.
24. Dueker, K. J., and J. A. Butler, "GIS-T Enterprise Data Model with Suggested Implementation Choices." *Journal of the Urban and Regional Information Systems Association,* Vol. 10, No. 1, Spring (1998) pp. 12–36.
25. Chen, P., "The Entity-Relationship Model—Toward a Unified View of Data." *ACM Transactions on Database Systems,* Vol. 1, No. 1 (1974).
26. Kafer, W., N. Ritter, and H. Schoning, "Support for Temporal Data by Complex Objects." *Proceedings, 16th Conference on Very Large Databases (VLDB '90),* Brisbane, Australia (1990) pp. 24–35.
27. Martin, J., and J. Odell, *Object-Oriented Analysis and Design.* Prentice-Hall, Inc., Englewood Cliffs, New Jersey (1992).
28. Rumbaugh, J., M. Blaha, W. Premerlani, F. Eddy, and W. Lorensen, *Object-Oriented Modeling and Design.* Prentice-Hall, Inc., Englewood Cliffs, New Jersey (1991).
29. Lewis, J., and W. Loftus, *Java Software Solutions: Foundations of Program Design.* Addison-Wesley, Reading, Massachusetts (1998).
30. Booch, G., J. Rumbaugh, and I. Jacobson, *The Unified Modeling Language Users Guide.* Addison-Wesley, Reading, Massachusetts (1999).

31. Renolen, A., "Modelling the Real World: Conceptual Modelling in Spatiotemporal Information System Design." *Transactions in GIS,* Vol. 4. No. 1 (2000) pp. 23–42.
32. Heo, J., *A Spatio-Temporal Data Model for Parcel-Based Land Information Systems.* Preliminary Ph.D. Dissertation, University of Wisconsin, Madison (1999).
33. Tryfona, N., and C. Jensen, "A Component-Based Conceptual Model for Spatiotemporal Design." *CHOROCHRONOS Technical Report CH-98-10,* National Technical University of Athens, Greece (1998).
34. Hull, R., and R. King, "Semantic Data Modeling: Survey, Applications and Research Issues." *ACM Computing Survey,* Vol. 19, No. 3 (1987).
35. Fletcher, D., Electronic mail to T. Adams and A. Vonderohe, Subject: Questions in regards to the Pooled Fund Study Model, April 6, 2000.
36. Smith, W., "Logical and Physical Data Modeling." Barnett Data Systems, www.barnettdata.com/logical/logical.html (1999).
37. Worboys, M. F., *GIS: A Computing Perspective.* Taylor and Francis, London (1995).
38. Saab, D., and T. Haythomthwaite, "Application of Spatio-Temporal Database Models to Street Network Files." *Proceedings, GIS for the 1990s Conference,* Ottawa, Canada (1990) pp. 1,072–1,085.
39. Snodgrass, R., and I. Ahn, "A Taxonomy of Time in Databases." *Database Management Tutorial,* IEEE Computer Society Press, Washington, D.C. (1987) pp. 398–408.
40. Chrisman, N., *Exploring Geographic Information Systems.* John Wiley and Sons, New York, New York (1997).
41. The Transportation Research Board, "Highway Location Reference Methods." *Synthesis of Highway Practice 21,* National Research Council, Washington, D.C. (1974).
42. Adams, T., A. Vonderohe, and N. Koncz, "Functional Requirements for a Multimodal Multidimensional Location Referencing System Data Model." *Workshop Synthesis Document 20-27(3),* National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C. (1999).
43. Vonderohe, A., and T. Hepworth, "A Methodology for Design of a Linear Referencing System for Surface Transportation," *SAND97-0637,* Sandia National Laboratories, Albuquerque, New Mexico (1997).
44. Hintz, R., and H. Onsrud, "Upgrading Real Property Boundary Information in a GIS." *Journal of the Urban and Regional Information Systems Association,* Vol. 2, No. 1 (1990) pp. 2–10.
45. Jeffress, G., R. Hintz, and H. Onsrud, "An Automated Measurement Management System: A Useful Tool for Surveyors and Digital Cadastral Database Managers." *The Australian Surveyor,* Vol. 35 (1990) pp. 19–28.
46. Webster, M., *Webster's New World Dictionary, Second College Edition.* William Collins + World Publishing Co., Inc., New York, New York (1974).
47. Ensor, D., and I. Stevenson, *Oracle Design.* O'Reilly and Assoc., Inc., Cambridge, Massachusetts (1997).
48. Martin, J., *Information Engineering, Book II: Planning and Analysis.* Prentice-Hall, Inc., Englewood Cliffs, New Jersey (1990).
49. Date, C., *An Introduction to Database Systems, 6th edition.* Addison-Wesley, Reading, Massachusetts (1995).
50. O'Neill, W., "Space and Time from an ITS Perspective." Presentation at *AASHTO Symposium on Geographic Information Systems in Transportation,* Albuquerque, New Mexico (1998).
51. Goodchild, M. F., "Uncertainty: The Achilles Heel of GIS?" *Geo Info Systems,* Vol. 8, No. 11 (1998) pp. 50–52.
52. Vonderhoe, A., T. Adams, C. Chou, M. Bacon, F. Sun, and R. Smith, "Development of System and Application Architectures for Geographic Information Systems in Transportation." *NCHRP Research Results Digest 221,* Transportation Research Board, National Research Council, Washington, D.C. (1998).
53. Alliance for Transportation Research, "Geographic Information Systems–Transportation ISTEA Management Systems Server—Net Prototype Pooled Fund Study Phase A Summary." Albuquerque, New Mexico (1994).
54. Malone, D., "Request for Proposal for Category 7: Intelligent Transportation Systems: Traffic Management Center Project." City of Chicago Department of Transportation (2000).
55. Jones, C., "Database Architecture for Multi-Scale GIS." *Proceedings, ACSM-ASPRS Annual Convention,* Baltimore, Maryland, Vol. 6 (1991) pp. 1–14.
56. Newell, R., and M. Doe, "Discrete Geometry with Seamless Topology in a GIS." *EGIS '94, Fifth European Conference and Exhibition on Geographical Information Systems,* Paris (1994).
57. Egenhofer, M., E. Clementini, and P. DiFelice, "Evaluating Inconsistencies Among Multiple Representations." *Advances in GIS: Proceedings of the Sixth International Symposium on Spatial Data Handling,* Taylor and Francis, London (1994) pp. 901–920.
58. Kidner, D., and C. Jones, "A Deductive Object-Oriented GIS for Handling Multiple Representations." *Advances in GIS: Proceedings of the Sixth International Symposium on Spatial Data Handling,* Taylor and Francis, London (1994) pp. 882–900.
59. Merrett, T., and H. Shang, "Zoom Tries: A File Structure to Support Spatial Zooming." *Advances in GIS: Proceedings of the Sixth International Symposium on Spatial Data Handling,* Taylor and Francis, London (1994) pp. 792–804.
60. Frank, A., and S. Timpf, "Multiple Representations for Cartographic Objects in a Multi-Scale Tree—An Intelligent Graphical Zoom." *Computers and Graphics,* Vol. 18, No. 6 (1994) pp. 823–829.
61. Oosterom, P., and V. Schenkelaars, "The Development of an Interactive Multi-Scale GIS." *International Journal of Geographical Information Systems,* Vol. 9, No. 5 (1995) pp. 489–507.
62. Jones, C., D. Kidner, L. Luo, L. Bundy, and J. Ware, "Database Design for a Multi-Scale Spatial Information System." *International Journal of Geographical Information Systems,* Vol. 10, No. 8 (1996) pp. 901–920.
63. De Floriani, L., P. Marzano, and E. Puppo, "Multiresolution Modeling in Geographical Information Systems." *Spatial Analytical Perspectives on GIS, GISDATA Series 4,* Taylor and Frances, London (1996) pp. 9–19.
64. Loon, E., and K. Keesman, "Identifying Scale-Dependent Models: The Case of Overland Flow at the Hillslope Scale." *Water Resources Research,* Vol., 36, No. 1 (2000) pp. 243–254.
65. Loomis, M., "Object Versioning." *Journal of Object-Oriented Programming,* No. 1 (1992) pp. 40–43.
66. Lowell, K., and G. Edwards, "Modeling Heterogeneity and Change in Natural Forests." *Geomatica,* Vol. 50, No. 4 (1996) pp. 425–440.

67. Raafat, H., Z. Yang, and D. Gautheir, “Relational Spatial Topologies for Historical Geographical Information.” *International Journal of Geographical Information Systems,* Vol. 8, No. 2 (1994) pp. 163–173.
68. The American Society of Civil Engineers, “Glossary of the Mapping Sciences.” American Congress on Surveying and Mapping/American Society for Photogrammetry and Remote Sensing, New York, New York (1994).
69. The National Institute of Standards and Technology, “Glossary of Time and Frequency Terms.” Time and Frequency Division, NIST Boulder Laboratories, www.bldrdoc.gov/timefreq/glossary.htm (1999).
70. Federal Geographic Data Committee, “Content Standard for Digital Geospatial Metadata.” *FGDC-STD-001-1998,* Washington, D.C. (1998).
71. Minnesota Department of Transportation, “Mn/DOT’s GIS Statewide Base Map.” Report of the GIS Base Map Task Force to the Minnesota Department of Transportation Council for Geographic Information (1993).
72. DeLoach, S. R., “The Glossary of the Mapping Sciences.” American Society for Photogrammetry and Remote Sensing/American Congress on Surveying and Mapping, Bethesda, Maryland (1994).
73. Krzanowski, C., L. Palylyk, and P. H. Crown, “Lexicon of Terms for Users of Geographic Information Systems, Version 1.01.” University of Alberta, Edmonton (1993).
74. Goodwin, C., S. Gordon, R. Haas, J. Lau, and D. Siegel, “Location Referencing Message Specification, Revision C.” Federal Highway Administration, U.S. Department of Transportation, Washington, D.C. (1999).
75. Cadastral Subcommittee, “Cadastral Data Content Standard for the National Spatial Data Infrastructure.” Federal Geographic Data Committee, Washington, D.C. (1996).

APPENDIX

WORKSHOP PARTICIPANTS AND AGENDA

This appendix contains the list of participants and the agenda for the workshop on functional specifications for multimodal, multidimensional transportation location referencing systems held December 3–5, 1998, in Washington, D.C. Participant names and affiliations are as of the time of the workshop.

Breakout Group 1: Transportation Planning, Highway Construction, and Asset Management
- Ron Cihon, Washington DOT, **Coordinator**
- Teresa M. Adams, University of Wisconsin-Madison, **Recorder**
- Frederick Aubry, ESRI
- Stephen J. Bespalko, Sandia National Laboratories
- Charles Fleming, Georgia DOT
- John Hudson, Connecticut DOT
- Karl Olmstead, Minnesota DOT
- Thomas Palmerlee, Transportation Research Board
- Roger Petzold, FHWA, **Project Panel**
- Thomas Ries, Wisconsin DOT, **Project Panel**
- Paul Scarponcini, Bentley Systems, Inc.
- Frank Winters, New York State DOT

Breakout Group 2: Highway Safety and Incident Management
- Nancy Armentrout, Maine DOT, **Coordinator**
- Al Butler, Hamilton County, Tennessee, **Recorder**
- Bobby Harris, GIS/Trans, Ltd.
- Charley Hickman, U.S. Geological Survey
- Tim Neuman, CH2M Hill
- Wende O'Neill, U.S.DOT
- Kenneth S. Opiela, Transportation Research Board, **NCHRP Program Officer**

Breakout Group 3: Traffic Management and Highway Operation
- Val Noronha, NCGIA, **Coordinator**
- Tim Nyerges, University of Washington, **Recorder**
- Bill Cairns, Mitretek Systems
- Kenneth J. Dueker, Portland State University, **Project Panel**
- Steve Gordon, Oak Ridge National Laboratory
- Manny Insignares, TransCore
- Fang Zhao, Florida International University

Breakout Group 4: Transit Facilities and Operation; and Commercial Vehicles and Fleet Management
- Jeff Orton, Utah Transit Authority, **Coordinator**
- Alan P. Vonderohe, University of Wisconsin-Madison, **Recorder**
- Zahir Balaporia, Schneider National, Inc.
- Michael Berman, King County, Washington State
- David R. Fletcher, ATR Institute, **Project Panel**
- Simon Lewis, GIS/Trans, Ltd.
- Bruce Spear, U.S.DOT, **Project Panel**
- David Vessel, Twin Cities Metropolitan Council

Day 1 December 3, 1998

8:30–9:00 AM Continental Breakfast Green 118
9:00 AM–2:00 PM Session 1 Plenary Green 118
  9:00–9:10 AM Introductions (Adams)
  9:10–9:15 AM Welcome from NCHRP (Opiela)

9:15–9:20 AM Opening Remarks from Project Panel (Fletcher)
9:20–9:35 AM Objectives of the Workshop (Adams)
9:35–10:05 AM 20-27(2) Linear LRS Data Model and Terminology (Vonderohe)
10:05–10:20 AM Coffee Break Green 118
10:20–10:30 AM Participatory Process and Instructions (Nyerges)
10:30–11:45 AM Issues in Developing a Multi-modal, Multi-Dimensional LRS Presentations by Breakout Group Coordinators (15 min. each)
Summary of Pre-workshop Issues Paper (Adams)
Group 1 (Cihon) Planning, Highway Construction, and Asset Management
Group 2 (Armentrout) Highway Safety and Incident Management
Group 3 (Noronha) Traffic Management and Highway Operation
Group 4 (Orton) Transit Facilities and Operation; and Com. Vehicles and Fleet Mgmt
11:45 AM-Noon Group Discussion/Synthesis (Nyerges)
Noon-1:00 PM Lunch (tickets provided)
1:00–1:50 PM Continue Group Discussion/Synthesis (Nyerges)
1:50–2:00 PM Instructions for Breakout Groups (Nyerges)

2:00–6:00 PM Session 2 Breakout Groups
Group 1 Planning, Highway Construction, and Asset Management Green 122
Group 2 Highway Safety and Incident Management Green 128
Group 3 Traffic Management and Highway Operation Green 132
Group 4 Transit Fac. and Operation; and Com. Vehicles and Fleet Mgmt Green 134
2:00–3:30 PM Identify Functional Needs
3:30–4:00 PM Break Green 118
4:00–6:00 PM Identify Functional Specifications (Data Flow Diagrams)

Day 2 December 4, 1998
8:00–8:30 AM Continental Breakfast Green 118
8:30 AM–10:30 AM Session 3 Plenary Green 118
8:30–9:30 AM Reports on Session 2 from Breakout Group Coordinators
9:30–10:00 AM Group Discussion/Synthesis (Nyerges)
10:00–10:30 AM Coffee Break

10:30–5:30 PM Session 4 Breakout Groups
Group 1 Planning, Highway Construction, and Asset Management Green 122
Group 2 Highway Safety and Incident Management Green 128
Group 3 Traffic Management and Highway Operation Green 132
Group 4 Transit Fac. and Operation; and Com. Vehicles and Fleet Mgmt Green 127

10:30 AM–Noon Preparation of Functional Specification Statements
Noon–1:00 PM Lunch (tickets provided)
1:00–3:00 PM Continue Preparation of Functional Specification Statements
3:00–3:30 PM Break Green 118
3:30–5:30 PM Implementation: What will make the specs work?

Day 3 December 5, 1998
8:00–8:30 AM Continental Breakfast Green 118

8:30 AM–Noon Session 5 Plenary Green 118
8:30–9:30 AM Reports on Session 4 from Breakout Group Coordinators
9:30–10:00 AM Group Discussion/Synthesis (Nyerges)
10:00–10:30 AM Coffee Break Green 118
10:30–11:30 AM Group Discussion/Synthesis (Nyerges)
11:30–11:40 AM Closing Remarks from Project Panel (Fletcher)
11:40–11:45 AM Closing Remarks from NCHRP (Opiela)
11:45 AM–Noon Dissemination of Results and Continuation of Research (Adams)

Noon Adjourn

The **Transportation Research Board** is a unit of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. The Board's mission is to promote innovation and progress in transportation by stimulating and conducting research, facilitating the dissemination of information, and encouraging the implementation of research results. The Board's varied activities annually draw on approximately 4,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

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Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation

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