A Data Model for Multi-dimensional Transportation Location Referencing Systems

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Abstract: *Multi-dimensional data (i.e., data referenced in one, two, three, and four dimensions) are often managed by transportation agencies with databases and technologies that cannot be integrated due in part to the lack of a comprehensive model for location referencing of the data. This lack of a comprehensive location referencing system data model limits organizations in implementing improved solutions for stakeholders. In this article, a Multi-Dimensional Multi-Modal Transportation Location Referencing System data model is presented that builds on existing data models, allowing multi-dimensional location referencing, multi-scale representation, navigation, feature-level metadata, temporal geographic information system, measurement management, and error propagation. Semantics of data constructs and relationships in the data model are described.*

Introduction

National Cooperative Highway Research Program (NCHRP) Project 20-27(3) was initiated to develop a comprehensive transportation location referencing system (LRS) data model. The goals of this project were to establish consensus-based functional requirements for a transportation-based multi-dimensional LRS data model, to develop an improved LRS data model that met the functional requirements, and to develop guidelines to implement this improved LRS data model in transportation agencies.

This article describes the development of a Multi-Dimensional Multi-Modal Transportation Location Referencing System (MDLRS) data model for geographic information systems used by transportation agencies (GIS-T). The intended scope of the data model is all modes of roadway transportation in four dimensions (three spatial and one temporal). However, the data model can be extended for maritime and air transportation. The foundation for the MDLRS data model is provided by describing its core functional requirements and providing background on the approaches used by other GIS-T data models. The article then shows how the MDLRS data model builds on these data model approaches and satisfies the core functional requirements established by transportation stakeholders. Domain-specific data constructs of the MDLRS data model are then described.

MDLRS Functional Requirements

One of the first steps in developing a comprehensive transportation LRS is to identify the system's functional requirements (i.e., what it is intended to do). A workshop of 40 invited participants who contributed expertise in the areas of transportation planning, highway construction, asset management, highway, safety and incident management, traffic management, highway operations, transit facilities and operation and commercial vehicles, and fleet management was conducted in Washington, DC in December 1998. The objective of the workshop was to identify and define functional requirements that must be supported by a comprehensive transportation LRS data model.

Ten core functional requirements were synthesized from the results of the stakeholders' workshop. These requirements form the essence of a data model required to accommodate a comprehensive transportation LRS. Adams et al. (2000) provided a review of each of the requirements. The 10 core functional requirements of a comprehensive transportation LRS data model are as follows:

- Spatial/Temporal Referencing Methods: Supports the locate, place, and position processes for objects and events in three dimensions and time.
- Temporal Referencing System/Temporal Datum: Accommodates a temporal datum that relates the database representation to the real world and provides the domain for transformations among temporal referencing methods.
- Temporal Topology/Latency: Supports temporal relationships among objects and events and the latency of events (i.e., difference in time between scheduled and actual events occurring at a particular location).
- Historical Databases: Supports regeneration of object and network states over time, and maintains the network event history.
- Dynamics: Supports the navigation of objects, in near real-time and contingent on various criteria, along a traversal in a transportation network.
- Transformation of Data Sets: Supports transformation between linear, nonlinear, and temporal referencing methods without loss of spatial/temporal accuracy, precision, and resolution.
- Multiple Cartographic/Spatial Topological Representations: Supports multiple cartographic and topological representations at both the same and varying levels of generalization of transportation objects.
- Resolution: Supports the display and analysis of objects and events at multiple spatial and temporal resolutions.

- Object-Level Metadata: Stores and expresses object-level metadata to guide general data use.
- Accuracy and Error Propagation: Supports association of error measures with spatial/temporal data at the object-level and propagation of those errors through analytical processes.

Development of the MDLRS Data Model

Several strategies for development of the MDLRS data model were considered. These strategies included:

- extension of the NCHRP 20-27(2) data model;
- synthesis of the NCHRP 20-27(2) data model and selected components of existing data models; and
- derivation of an MDLRS data model directly from the functional requirements.

The approach adopted was a combination of the three strategies. The MDLRS data model was built on the strengths of each of the existing transportation location referencing system data models. Concepts from existing models were adapted when there was a clear correlation between the functional requirement and the model concept. The following paragraphs show the relationship of the MDLRS data model to existing transportation LRS data models.

Building on Existing Transportation LRS Data Models

In developing a comprehensive transportation LRS, the approaches used by existing transportation-based LRS data models were reviewed. These data models have been employed by database developers and information systems managers in transportation agencies, geographic information system (GIS) software vendors interested in transportation and network applications, and researchers involved in the application of geospatial technology in transportation.

NCHRP 20-27(2). The NCHRP 20-27(2) LRS data model (Vonderohe et al. 1997) provides the framework to manage and transform 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.

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 (Vonderohe et al. 1997). Cartographic representations 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-dimensional (2-D) and three-dimensional (3-D) references by associating the linear datum with the geometric objects that compose the cartographic representation. This association to 2-D and 3-D GIS databases provides the framework for transformations between linear and nonlinear datums.

Geographic Information Systems - Transportation Enterprise. The Geographic Information Systems - Transportation (GIS-T) Enterprise data model was developed to address sharing of digital road map databases within and among transportation organizations by supporting spatial and spatially referenced data, which include both linearly referenced data and nonlinearly referenced data (Dueker and Butler 1998).

This data model is a data-centric relational model based on the independence of a geographic datum, the business data that occur on a transportation system, the geometry to represent the system, and the topology that comprises transportation systems (Dueker and Butler 1998). As a result, the GIS-T Enterprise model has separate cartographic and topologic entities and allows multiple spatial representations for a transportation feature. Additionally, this model provides for the representation and integration of linear and nonlinear spatial data using the framework of NCHRP 20-27(2) (Vonderohe et al. 1997). The GIS-T Enterprise data model accommodates the basic forms of a GIS (point, line, and area) and focuses on the attributes of transportation-based facilities and services. This data model also includes a broad set of business rules for a wide range of applications and for various modes of transportation, such as the navigation of vehicles.

National Spatial Data Infrastructure. The Draft National Spatial Data Infrastructure (NSDI) Framework Transportation Identification Standard was prepared by the Federal Geographic Data Committee (FGDC) Ground Transportation Subcommittee as a component of the NSDI to provide a national standard for the exchange of spatially based transportation data (Federal Geographic Data Committee 2001).

The NSDI Framework Transportation Identification Standard presents a way to maintain the topological integrity of existing network segments when new segments are introduced. The maintenance of the topologic integrity of a network is a primary contribution of the NSDI standard and is critical in dealing with transactional updating and temporal versioning of network databases. This standard is based on the conceptual road data model developed under NCHRP 20-27(2) (Vonderohe et al. 1997). Additionally, NSDI framework data are documented in accordance with established metadata standards (Federal Geographic Data Committee 2001). Other notable features of the NSDI standard include the separation of geometry and topology and alternative representations of the same transportation feature (e.g., interchanges or divided highways)

GIS-T/ISTEA PFS. The Geographic Information Systems - Transportation/ISTEA Management Systems Server Net Prototype Pooled Fund Study (GIS-T/ISTEA PFS) was sponsored by Federal Highway Administration (FHWA), Federal Transit Administration (FTA), Sandia National Laboratories, several state Departments of Transportation, and several companies in the private sector to address management and monitoring systems as well as transportation planning requirements of the Intermodal Surface Transportation Efficiency Act of 1991 (Fletcher et al. 1995).

The GIS-T/ISTEA PFS model represents the history of transportation-based phenomena through Event and Experience objects. In the Pooled Fund Study model, Events change the state or attributes of objects (i.e., Transportation Components). Events represent action while Transportation Components are acted on (Fletcher et al. 1995). 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. This event registry or "container of memories" for the Transportation Component allows for the regeneration of object and network states over time.

Linkage of MDLRS Data Model to Existing Transportation LRS Data Models

Although each data model has significant strengths, what is lacking from these data models is a framework for the use and integration of multi-dimensional data in all its forms, including the temporal dimension and their interaction. These existing models satisfy some but not all of the functional requirements. The MDLRS data model is designed to satisfy the functional requirements and builds on the strengths of these models as described below:

- NCHRP 20-27(3): The MDLRS data model builds on the linear referencing framework employed by the NCHRP 20-27(2) data model and extends the association between linear and 2-D and 3-D references, necessary for the transformation of multi-dimensional data.
- GIS-T Enterprise: The MDLRS data model builds on the separation of cartographic and topologic entities and the multiplicity of the spatial representation of transportation features employed by the GIS-T Enterprise data model. The MDLRS data model uses these concepts and extends them through scale and dimensionality constraints on spatial representations, necessary for a multiscale GIS used for zooming and navigational display.
- NSDI: The MDLRS data model builds on the feature level metadata employed by the NSDI standard and extends these attributes into separate objects with lineage and error modeling capabilities, necessary for accuracy assessment and general guidance.
- GIS-T/ISTEA PFS: The MDLRS data model builds on the Event and Experience objects employed by the Pooled Fund Study for the causal domain of phenomena and extends their definitions and components, thereby allowing the historical regeneration of entity states.

Description of Model

The MDLRS data model is described in this article using the Unified Modeling Language (UML) specification (Booch et al. 1999). Figure 1 provides an overview of the UML notation. Rumbaugh et al. (1991) provided additional background on object-oriented modeling and design. Object modeling was selected for the MDLRS data model, given the benefits of an object model such as natural description, flexibility, and reuse of other work (Fletcher et al. 1995) and the availability of existing geospatial object models, such as the NCHRP 20-27(2) linear reference model (Vonderohe et al. 1997), the GIS-T Pooled Fund Study model (Fletcher et al. 1995), the Canadian Geomatics Interchange Standard - Spatial Archive and Interchange Format (CGIS-SAIF) model (SAIF, 1995), and the draft International Organization for Standardization (ISO) models (ISO 15046, 1998).

The MDLRS data model adopts and extends concepts of three-domain spatiotemporal data models (e.g., the TRIAD model by Peuquet and Qian 1997 and the Three-Domain Model by Yuan 1997). The aspatial domain ("what") is stored in the Transportation Feature object, the spatial domain ("where") is stored in the SpatialObject, and the temporal domain ("when") is stored in the TimeObject (Figure 2). The separate domains eliminate redundancy because spatial objects that have the same geographic meaning can be linked to a single semantic description (Yuan 1997). Additionally, this approach allows for modeling of dynamics (e.g., movement of storms and the spread of fires) not possible in other spatiotemporal models (Yuan 1997).

The MDLRS extends the three-domain data model by adopting a causal domain ("why"/"how"). The causal domain provides an explanation of the changes that occur in and among phenomena (Langran 1992) and is represented in the MDLRS data model as Experience and Event objects. The combination of Events and Experiences show, for example, what roads have been in a region, what changes have occurred to those roads, and how those changes occurred.

The complete MDLRS model is described through the submodels for each domain of phenomena: aspatial, spatial, temporal, and causal. The following subsections describe the domain-specific constructs of the MDLRS data model.

Aspatial Data Constructs

Aspatial-specific data constructs describe the nonspatial attributes of phenomena and help to answer the question, "what is at a location?" Transportation Features, their aggregations (e.g., Transportation Complexes), and their subclasses (e.g., Conveyances) provide storage for aspatial data (Figure 3).

Transportation Features. In the MDLRS data model, the Transportation Feature is the central object. Transportation Features represent a nondecomposable real world or virtual phenomenon in the transportation domain, such as anchor points, anchor

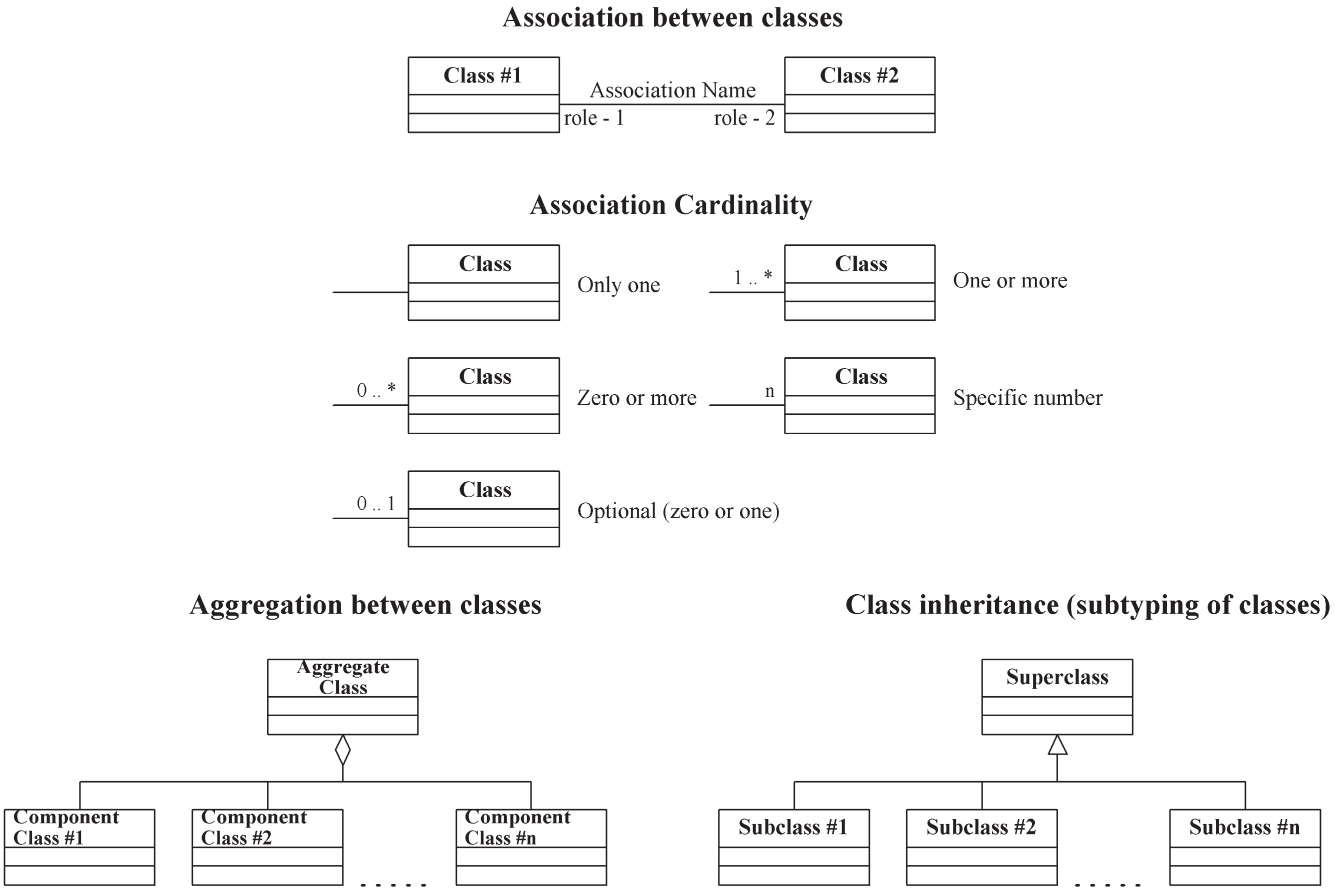

Figure 1: UML Notation (after ISO 15046, 1998).

sections, signs, pavements, highways, airports, interchanges, roadways, bridge elements, reference objects, and vehicles.

The Transportation Feature contains attributes that describe its aspatial characteristics. These attributes can be quantitative (e.g., pavement index or vehicular volume), qualitative (e.g., the color of a sign), or temporal (e.g., operating conditions of an high occupancy vehicle (HOV) lane or a signal timing sequence). The attributes of a Transportation Feature can also have a validity period (e.g., the time period of a roadway volume count). Previous 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 SourceMetadata object.

Transportation Complexes and Systems. Transportation Features are considered nondecomposable objects. Transportation Features may be aggregated to form Transportation Complexes and Transportation Systems (Figure 3). Transportation Complexes are collections of interconnected transportation features and other Transportation Complexes (adapted from Fletcher et al. 1995). For example, an interchange may be a Transportation Complex composed of bridges and ramps where the bridges and ramps are individual Transportation Features.

A Transportation System is a collection of Transportation Features, Transportation Complexes, and other Transportation Systems (adapted from Fletcher et al. 1995). A Transportation System can be functionally based (e.g., a highway system or a public transportation system) or physically based (e.g., a bridge system).

Conveyances. In the MDLRS data model, a Conveyance is a type of Transportation Feature that moves or navigates (Figure 4). A Conveyance can be a vehicle, a person, or a group of people. A collection of Conveyances is called a Fleet and represents a group of vehicles with fleet management capabilities. In addition to vehicles, the MDLRS data model can track people for activity-based travel demand analysis and personal guidance systems (Golledge et al. 1998). Conveyances can be concurrent. For example, a person (i.e., Conveyance) can walk from an origin to a station, ride a transit vehicle (also a Conveyance), then exit the vehicle and walk to a destination. The attributes of the person (e.g., location, time, and velocity) are concurrent with the transit vehicle when the person is on the vehicle.

There are two primary navigational activities for a Conveyance: tracking and routing. A Conveyance moves along a Transport Link for a duration. During that time one or more "track" operations are performed. Tracking involves retrieving the real-

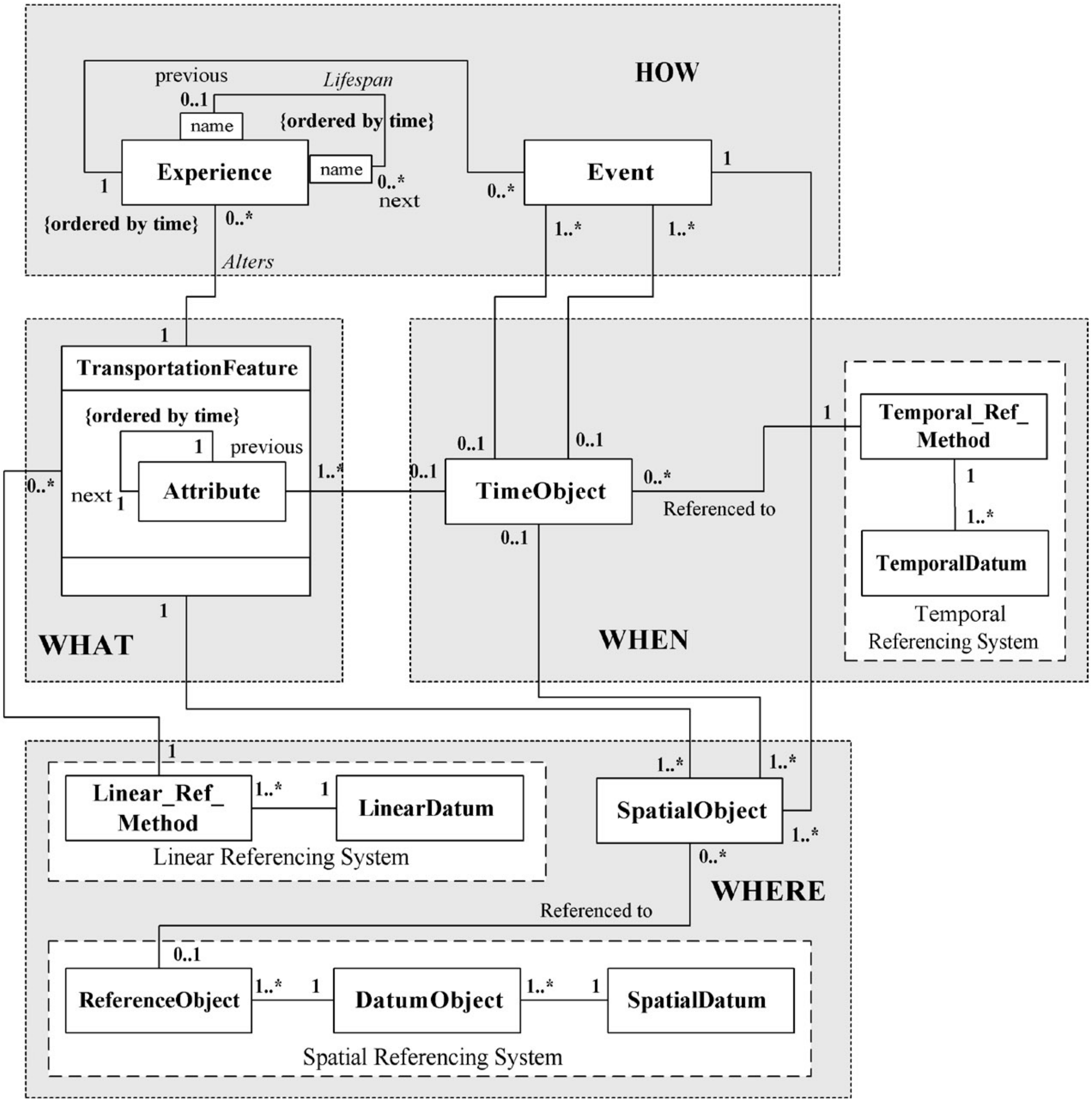

Figure 2: UML Conceptual View of the MDLRS Data Model.

time location of the Conveyance from a variety of sensors (e.g., global positioning system, radar, laser, microwave, loop detectors, gyroscopes, and accelerometers) and translation of the "real world" location into a database location indicating the Transport Link on which the Conveyance is moving. From the "track" operation the Transport Link on which the Conveyance is moving is identified and a path can be generated ("route" operation) indicating what links and turning movements the Conveyance should take. 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, participating in repeating cycles of tracking and routing, those links are being registered in the Traversal of the Conveyance (i.e., the Traversal is being built). The result after a trip is complete is a Traversal made up of a collection of Transport Links the Conveyance has navigated for a duration. Both the Traversal and Transport Links are valid for a certain time. The semantics of the term "Traversal" used in this context is that of a generated path. In other contexts (e.g., linear referencing), the term "Traversal" can mean a named route.

The MDLRS data model provides data to support location prediction/route guidance algorithms. As a Conveyance is navigating along a traversal, the Conveyance is transmitting locational coordinates through its tracking method. These coordinates can be discarded or used to retrace the movement of the Conveyance with a traversal and a space-time function. The space-time function represents the location as a function of time for the Conveyance and can be derived by connecting the dots of locational coordinates. In a Transportation System once a link is traversed, tracked locational points do not need to be stored because they can be replaced efficiently by a smoothed space-time function or

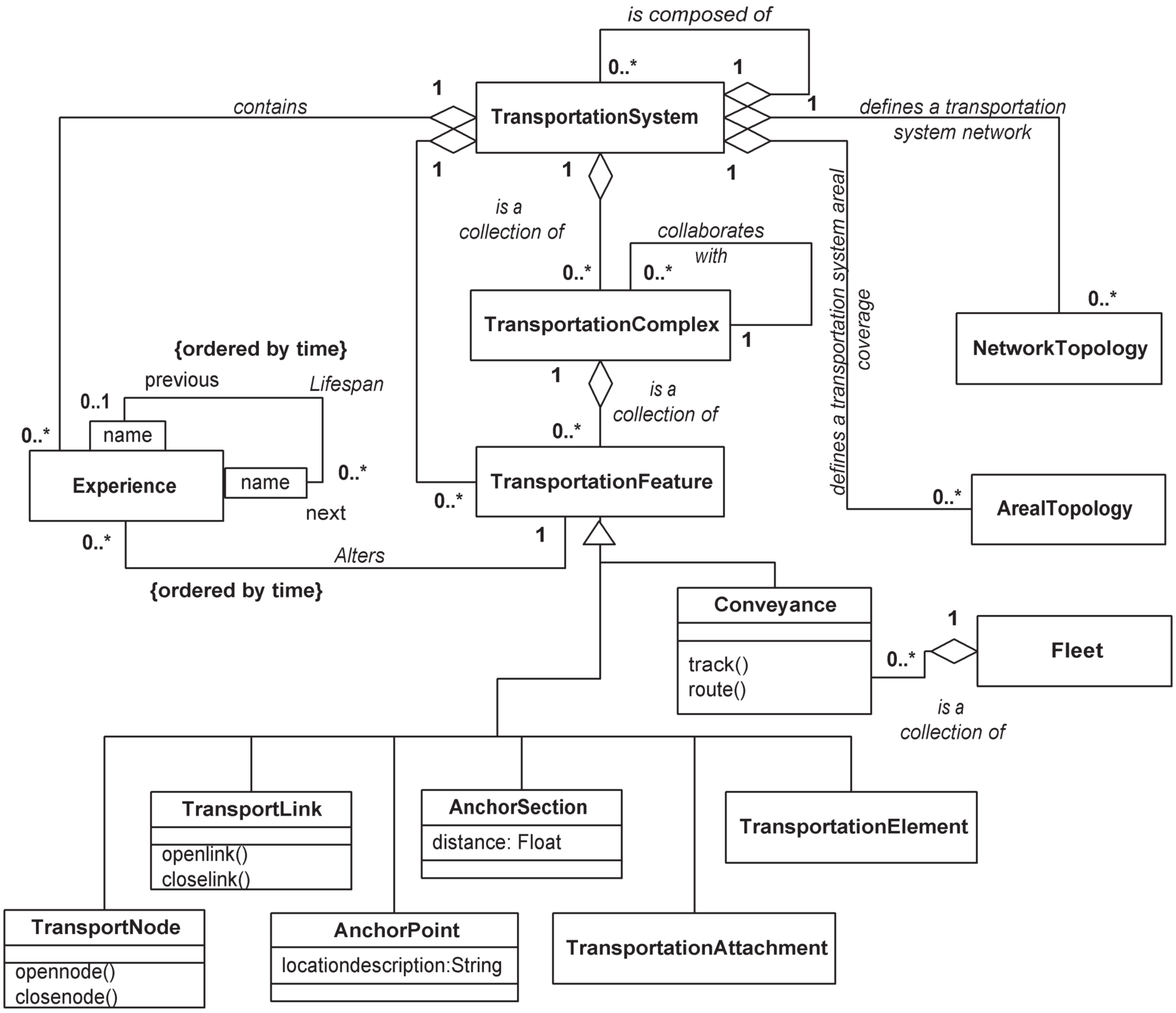

Figure 3: Transportation Feature Hierarchy.

a traversal step-function. In cases where there are no Transport Links (e.g., parking lots, private roads, and off-roads), locational coordinates are saved and used to replay Conveyance movement by connecting coordinates. An example of a simplified space-time function for a public transit vehicle is shown in Figure 5. 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 (t + xo, where x is the distance, v is the velocity, and t is the time. The slope of each segment represents the velocity of the length. Sections where the slope is zero indicate that the vehicle is stopped (due to delays or boarding/alighting passengers).

Spatial Data Constructs

The incorporation of the spatial dimension in a GIS requires data constructs for spatial referencing, spatial representation, spatial storage, and the propagation of spatial error. Spatial data constructs describe the spatial nature of phenomena and help answer the question, "where is an object?" A review of spatial data representation aspects applicable to transportation stakeholders can be found in Miller and Shaw (2001).

Spatial Referencing Systems. In the MDLRS data model, there are five categories of spatial referencing systems (SRSs): vertical, geocentric, horizontal, cadastral, and linear (Figure 6). Each SRS has a Datum Object(s) and an associated Reference Object (Table 1). Reference Objects are Transportation Features, can lie on other features, and are spatially represented as a Reference Point (Figure 6).

A Transportation Feature's GeometricObject must refer to a Reference Object to determine the location of a Transportation

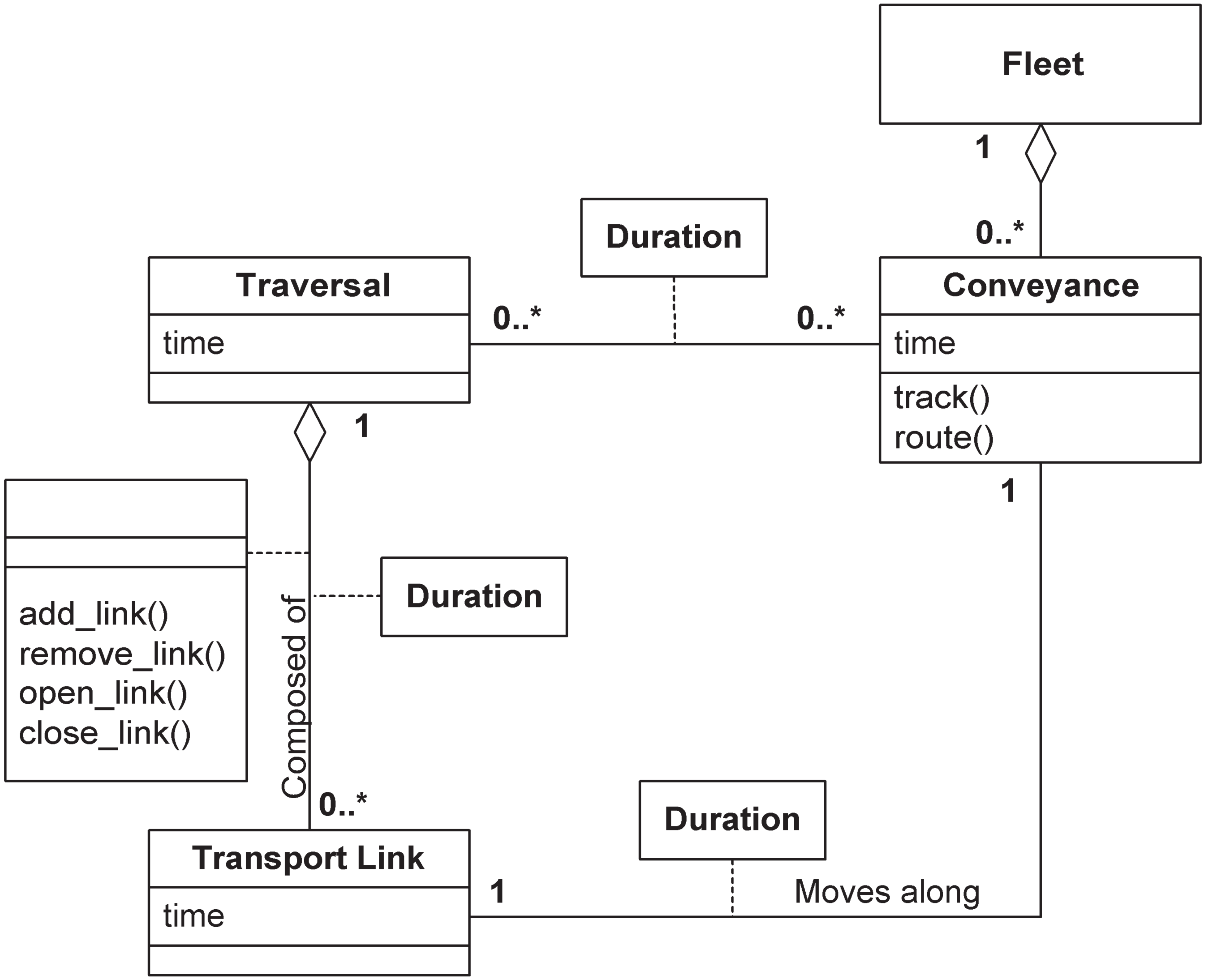

Figure 4: UML Object Model to Support Implementation of "Navigate.

Feature in a nonlinear SRS (Figure 6). To determine a Transportation Feature's linear location in a linear SRS, the Transportation Feature refers to the LinearReferenceMethod object. Constructs for a linear SRS are based on the NCHRP 20-27(2) linear referencing system data model (Vonderohe et al. 1997). A LinearReferenceMethod object is composed of a collection of TraversalReferencePoint and Traversal objects. Traversal objects are composed of TransportLink object defined by TransportNode objects, which are located on AnchorSection objects defined by AnchorPoint objects (Figure 6).

To transform data between linear and nonlinear systems, the "Represents" relationship between the AnchorSection object and the GeometricObject exists (Figure 6), requiring that an AnchorSection object know what GeometricObject it represents. This relationship has an association that provides the missing

Name	Dimension	Datum Object	Reference Object
Geocentric	3-D	3-D cartesian axes	global positioning system 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

Table 1 Characteristics of Spatial Referencing Systems (after Vonderohe and Hepworth, 1998)

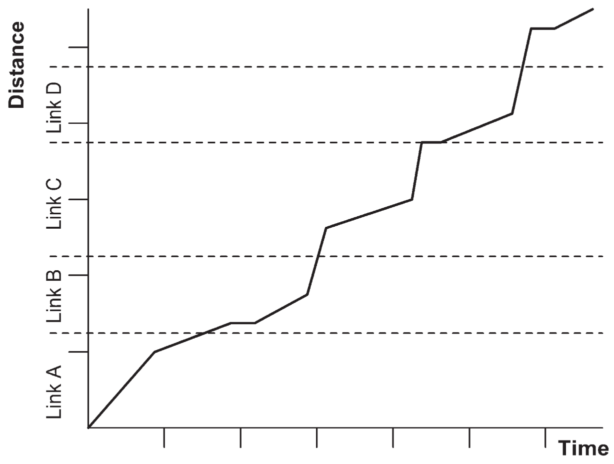

Figure 5: Example of a Space-Time Diagram for a Public Transit Vehicle.

coordinates (linear or nonlinear) to allow the transformation to occur. The AnchorSectionSnap method, in the "Represents" relation, generalizes a 2-D or 3-D GeographicObject to a 1-D GeometricObject compatible with the associated AnchorSection object. The AnchorSectionSnap method can also map an AnchorSection object to the centerline or centroidal axes of a Surface or Solid to obtain a 2-D or 3-D location, respectively.

Spatial Objects. The SpatialObject provides the spatial characteristics of a Transportation Feature and is described by one or more Geometric and/or TopologicObjects (Figure 7). Each instance of a SpatialObject has one coordinate representation according to its spatial referencing system.

A Transportation Feature can be associated with multiple Spatio-TemporalObjects. The Spatio-Temporal object is an abstract class representing the region of space and time occupied by a Transportation Feature. Spatio-Temporal Objects consist of a SpatialObject and an associated TimeObject. The TimeObject indicates the period of time (i.e., time of creation to time of retirement) in which the SpatialObject is valid.

Topological/Geometric Relationship. The MDLRS data model supports many-to-many relationships between Geometric and TopologicObjects (Figure 7). A Transportation Feature's geometric (i.e., cartographic) representation may have zero or more associated topological representations, and the converse is true. The representation of separate geometric and topological constructs allows multiple spatial cartographic (i.e., geometric) and topological representations for a single feature. This relationship allows Transportation Features such as roadways to be represented topologically as centerlines and cartographically displayed as 2-D lines.

The associations between Geometric and TopologicObjects are constrained by scale applicability and optionally, by dimensionality (Figure 7). The Scale Applicability attribute of the SpatialObject is user-defined and indicates the appropriate map scale for displaying the SpatialObject. The Dimensionality constraint guides the user in potential representational choices.

The Scale Applicability constraint associates Topologic and GeometricObjects with compatible representation scales. The topological representation of an entity (i.e., TopologicObject) is constrained to be associated with a cartographic representation (i.e., GeometricObject) of the same or greater detail. This constraint is due to cartographic generalization. For example, displaying a complete street network at a scale of 1:1,000,000 is not a useful representation because the streets would be displayed on top of each other).

The Dimensionality constraint is a set of user-defined business rules that helps maintain dimensional compatibility between Geometric and TopologicObjects based on user expectations. For example, if a bridge has a GeometricObject representation as a Point, then a user can expect to be able to perform topological analyses consistent with a Point.

Geometric Object. In the MDLRS data model, the GeometricObject (Figure 7) is the region in space occupied by a Transportation Feature. GeometricObjects have known positions. The constructs for the GeometricObject were adapted from the CGIS-SAIF (SAIF 1995) and ISO models (ISO 15046 1998). 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 (ISO 15046 1998).

GeometricObjects can be GeometricPrimitives or GeometricComplexes. GeometricPrimitives are nondecomposable objects representing a single, homogeneous element of geometry (ISO 15046 1998) and include Points (0-D), which bound Curves (1-D), which bound Surfaces (2-D), and which bound Solids (3-D). Reference Points are a subclass of the Point object and represent the position of a Reference Object. GeometricComplexes are collections of GeometricPrimitives and/or other GeometricComplexes.

Coordinate Object. In the MDLRS data model, a Coordinate object is associated with each Point object (Figure 8). The Coordinate object is an abstract data type containing attributes that indicate whether the coordinate was derived or specified, the unit system of the coordinate, the time interval (i.e., TimeObject) that the coordinate object is valid, and the method associated with the coordinate type (e.g., the projection method or the linear referencing method). There are five types of Coordinate objects, each with different attributes indicating the coordinates' position value: 1DCoordinate, 2DCoordinate, 3DCoordinate, LinearCoordinate, and GPSCoordinate.

The MDLRS data model provides the framework for a measurement management system where spatial measurements are stored and coordinates are recomputed from those measurements (Figure 8). Most coordinates are artifacts, that is, they are derived from measurements to reference objects. Associated with each coordinate in the MDLRS model is an optional set of

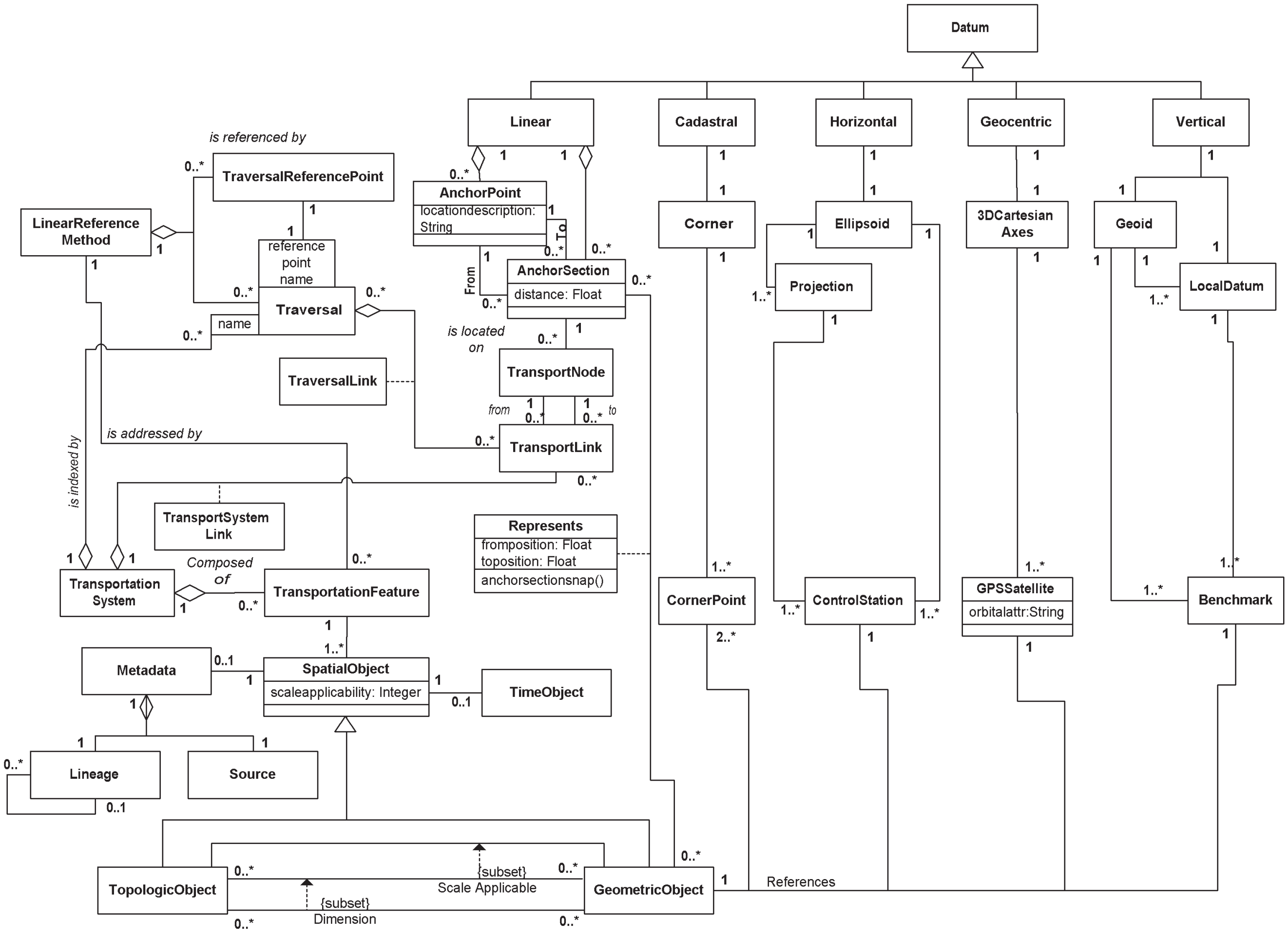

Figure 6: Spatial Referencing System Constructs.

ground measurements consistent with the type of the coordinate (e.g., a 3-D Ground Measurement with a 3-D Coordinate). The measurements are optional to accommodate cases where coordinates are not generated by ground measurements (e.g., digitizing and coordinate geometry (COGO). Each measurement can be associated with several Coordinate objects of the same type. Each dimensional measurement abstract class (1DGroundMeasurement, 2DGroundMeasurement, 3DGroundMeasurement, and LinearMeasurement) can be represented as an instance of a Measurement object subclass. For example, a 3DGroundMeasurement can be a SlopeDistance, a HorizontalAngle, a ZenithAngle, or a Direction.

The Measurement abstract object class (Figure 8) contains attributes that indicate its unit system, identifiers, value, and uncertainty associated with its value. The subclasses of the Measurement object are the DistanceMeasurement object, the AngleMeasurement object, the Direction object, and the RadioFrequencyMeasurement object.

The purpose of storing measurements along with the coordinates is to have the ability to recompute coordinates when there is a change in the datum. Each Coordinate object contains a method called LocationDerivation (Figure 8). The LocationDerivation method derives new coordinates values from the associated measurements. For example, given a set of 2DGroundMeasurements from a traverse, the LocationDerivation method under the 2DCoordinate would reduce the traverse, make adjustments to the traverse and compute coordinates from the traverse and associated surveyed points. If additional measurements are added, the LocationDerivation method derives a new set of coordinates with improved precision.

Error Propagation. When coordinates are the result of measurements, errors are introduced. All measurements have associated uncertainty. Each new measurement added to a database introduces new uncertainty in the database. That uncertainty is passed along to applications that use the data. Errors propagate from use of measurements in spatial/temporal analytical processes such as overlay, combine, and compare. Errors also propagate when coordinates are translated between spatial referencing systems.

Measurement errors and their interdependencies are represented as variances and covariances. The variances and covariances for each derived coordinate can be represented as a matrix. A 2x2 variance/covariance matrix is needed for each 2-D coordinate, and a 3x3 variance/covariance matrix is needed for each 3-D coordinate. A 2x2 variance/covariance matrix for 2-D coordinates consists of the X-coordinate variance, the Y-coordinate variance,

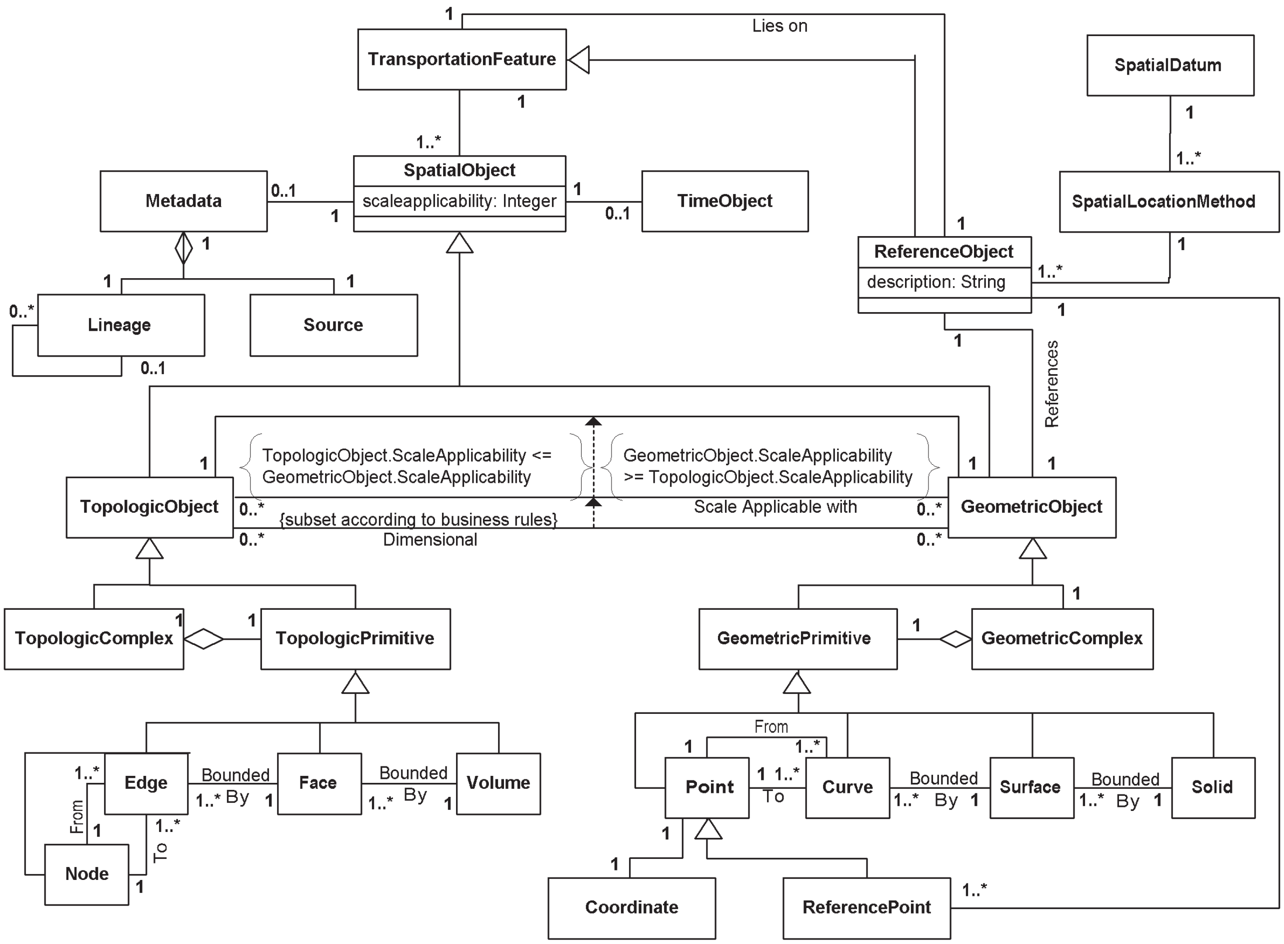

Figure 7: Spatial Object Constructs.

and the covariances between X and Y.

The variance/covariance matrix for a resultant set of 2-D points derived from the spatial overlay of two sets of arcs, with each set containing 2x2 matrices for each point, is at least of order 4x4. For example, the intersecting points of a roadway network with a railroad network would result in a 4x4 order variance/covariance matrix. If these new points were used to derive another set of points, the resultant points would result in at least an 8x8 variance/covariance matrix. After several spatial operations, the variance/covariance matrix could be very large and unmanageable.

An alternative to maintaining an NxN variance/covariance matrix is to store the immediate or familiar functional lineage of a spatial entity and the final variance/covariance matrix (order 2x2 for 2-D coordinates). In this alternative, the spatial entity points to its parent spatial entities as in a family tree structure. The data user can follow the sources of data to go back as their needs require. The MDLRS data model uses this alternative to model the propagation of error. Error propagation is represented using DxD VarianceCovarianceMatrix objects (Figure 8) (where D is the dimension of the spatial object) for each derived Coordinate object along with a LineageMetadata object. The VarianceCovarianceMatrix object contains variances and covariances for a derived 2-D or 3-D coordinate. The LineageMetadata object (Figure 7) indicates the history or parentage of the data including its compilation and processing history. Using this approach for error propagation eliminates the need to maintain potentially immense variance/covariance matrices and eliminates the need to maintain the full ancestry of each spatial entity.

Topologic Objects. Spatial topology allows various types of transportation-based network analyses to occur from optimal path analysis (e.g., directing a fire truck to a fire) to allocation of resources (e.g., defining the boundaries of a fire station's response time). The MDLRS data model separates topology from geometry so that multiple topologic representations are available to accommodate various applications.

If space is deformed elastically and continuously, the spatial topology among objects does not change; for example, when geographic data are transformed from one coordinate system to another (ISO 15046 1998). Accordingly, in the MDLRS data model, TopologicObjects can be derived by removing the metrics from GeometricObjects.

TopologicObjects can be TopologicPrimitives or TopologicComplexes (Figure 7). TopologicPrimitives include Nodes (0-

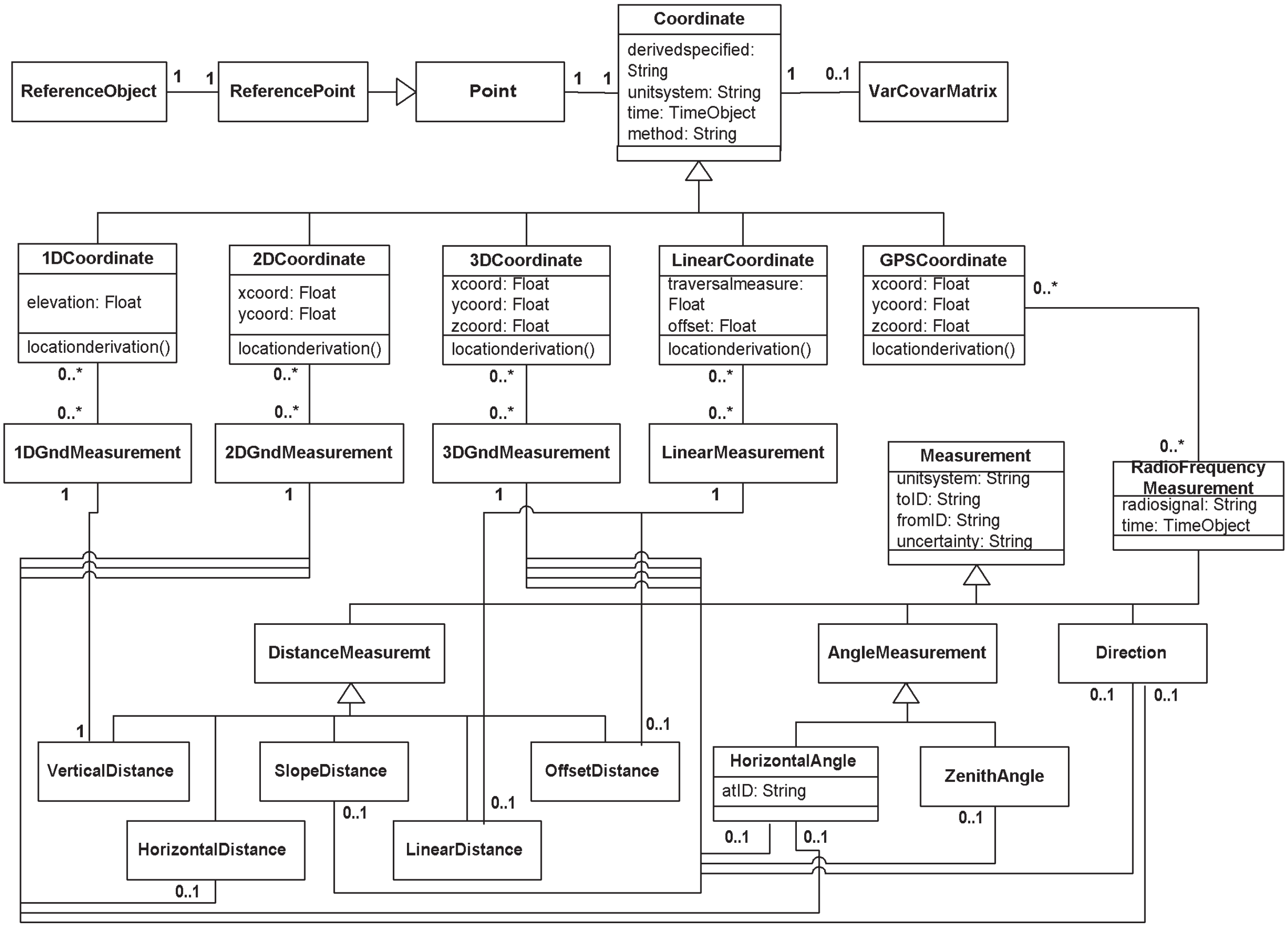

Figure 8: Coordinate and Measurement Constructs.

D), connected to Edges (1-D), which bound Faces (2-D), which bound Volumes (3-D). TopologicComplexes are aggregations of TopologicPrimitives.

Temporal Data Constructs

Temporal data constructs describe the temporal nature of phenomena and help answer the question, "when did an object exist at a location?" The temporal dimension has several analogies to the spatial dimension and its use in a GIS requires data constructs for representation, referencing, and relationships (i.e., topology) of the temporal dimension of phenomena.

Temporal Representation. The temporal dimension of phenomena is represented in the MDLRS data model as a TimeObject. The TimeObject provides the metric description of the temporal characteristics of Transportation Features and Events. TimeObjects represent a specific or relative portion of a time line, and its' associated temporal reference system (TRS) for which an object is valid (adapted from ISO 15046 1998).

The TimeObject can be a temporal primitive or aggregate object. The TimeObject can be represented as a time stamp or a point on a time line (DateTime object). The TimeObject can also be represented as a Duration object, where only temporal length (not position) is given (e.g., 5 hours, Monday, January, etc). An Interval object can also represent a TimeObject, where a segment of time is defined by two DateTime objects (e.g., the date of creation and date of retirement) or one DateTime object and a Duration. Also, the TimeObject can be represented as a TimeAggregate object, the temporal equivalent of a geometric complex. The TimeAggregate object can represent temporal structures such as cycles, breaks, stages, and sequences. Each type of TimeAggregate object can be decomposed into DateTime, Interval, and Duration objects.

Similar to spatial data, temporal measurements can contain uncertainty and these uncertainties lead to errors in derived data. These temporal uncertainties can be due to the resolution of a temporal measuring device (e.g., from an analog clock) or from temporal approximations when a measuring device is unavailable (e.g., "road closure occurred before noon"). In the same way, the MDLRS data model addresses spatial uncertainty in measurements through the Measurement object, and temporal uncertainties are modeled as temporal tolerances in the TemporalMeasurement object.

Associated with each TimeObject are Source and LineageMetadata objects (Figure 9). The LineageMetadata object provides the parentage of the TimeObject and allows for temporal correlation with other objects. In addition to providing the administrative aspects of the TimeObject, the SourceMetadata object indicates when the TimeObject was recorded in the database (called "transaction" time (Snodgrass and Ahn 1987)). This "transaction" time may be different from the time an activity actually occurred (called "valid" time). The TimeObject represents a bi-temporal model since both valid and transaction times are maintained.

Temporal Referencing Systems. The measurement and representation of time invoke the concept of a TRS, or an agreed-on measurement scheme. An explicit temporal reference system allows for transformation of temporal data between multiple clocks, zones, and calendar systems.

The MDLRS data model uses a TemporalDatum object and one or more TemporalReferencingMethod (TRM) objects to represent the TRS (Figure 9). The TemporalReferencingMethod object contains a TemporalReferenceEquation method, which is a derivable equation that relates the TemporalDatum to the TemporalReferencingMethod. The equation consists of two parts: a reference offset (e.g., -3 hrs 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). While the MDLRS data model can accommodate various metrics and various temporal representations through the temporal reference equation, the data model concentrates on those TRMs whose metrics are the same as the datum and assumes Coordinated Universal Time or UTC and the Gregorian calendar as the TemporalDatum.

Temporal Relationship Operators. To perform spatiotemporal queries, temporal relationships need to be established. There are two types of TemporalRelationship operators used in the MDLRS data model: TemporalTopology and TemporalProximity. These operators compute relationships on-the-fly, as needed.

TemporalTopology is a TemporalRelationship association involving nonmetric temporal relationships between two Transportation Features. TemporalTopology operators are based on Allen's interval operators (Allen 1984) and include: follows, overlaps, during, simultaneous, and disjoint. Adams et al. (2001) provided an overview of the temporal topologic operators and the pseudo-code for their generation. The TemporalProximity operator is a TemporalRelationship that functions as a temporal buffer. It answers the question: "has Transportation Feature A occurred within a given time of Transportation Feature B" (SAIF 1995)?

Causal Data Constructs

Causal data constructs provide an explanation of the changes in phenomena and help answer the question, "how has an object changed and what caused the changes to occur?" Event, Experience, and Metadata objects provide an explanation of data and their changes.

Event and Experience Objects. An Event (Figure 2) is a planned or unscheduled occurrence that happens in an instant or over a period of time that changes the state of a Transportation Feature (Fletcher et al. 1995). All Events have a spatial component, which allows the Events to be displayed graphically, and analyzed, and allows for the identification of the Transportation Features affected by the Events. An Event is essentially temporal (i.e., an Event is valid for a time period or instant), with a location. The TimeObject associated with an Event stores its temporal representation. Collections of related Events are called ComplexEvents and allow for modeling of multiple activities such as a construction schedule for a certain year, the parade schedule for a major city, or the transit schedule for a week day. Associated with each Event is a SourceMetadata object, which describes the administrative aspects of the Event.

An Event produces "changes" in a Transportation Feature. An Event can add or modify attributes of a Transportation Feature. For example, an Event can update the attribute "traffic volume" of a Transportation Feature. An event can add or modify a Spatio-Temporal Object of a Transportation Feature. An Event can retire or instantiate Transportation Features (e.g., the installation of guard rail).

While 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 what 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 (Figure 2) (Fletcher et al. 1995). Events are phenomena external to objects, while experiences are phenomena tightly coupled with objects. For example, a crash is an external event; damage is the vehicle's experience of that crash (Fletcher 2000). One Event can cause many Experiences, but each Experience is related to one Event.

While 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. By restricting the Experience object to contain only references, historical queries can be performed by tracing an Event to the affected objects of a feature. Rollback of an entire Transportation System is possible through the Experience objects of its Transportation Features.

Over time, the Transportation Feature participates in several Events producing additional Experience objects. These Experience objects 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 (Fletcher et al. 1995). An example of experiences that define the life span of a feature is a highway that is designed, constructed, maintained, and then 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

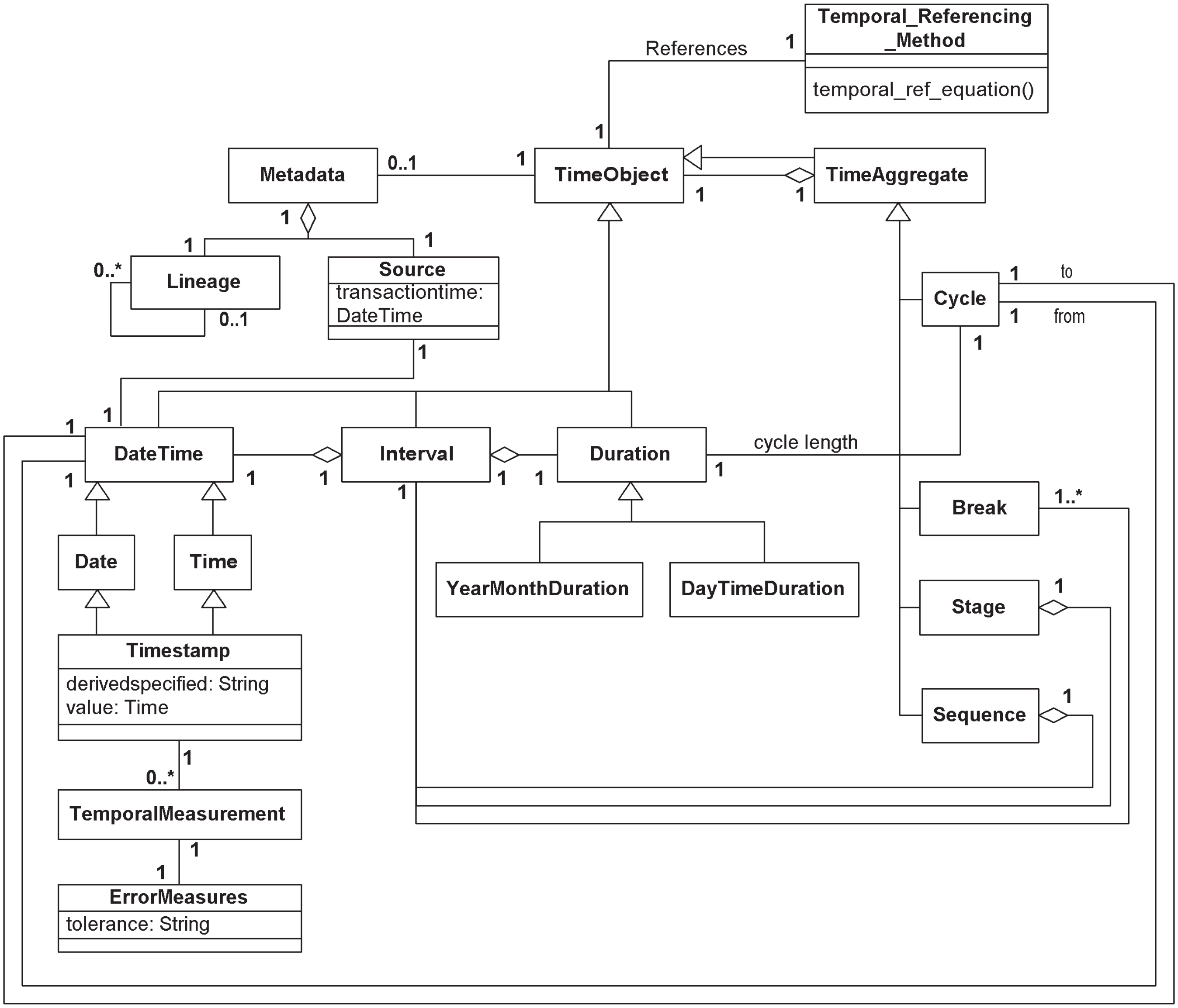

Figure 9: Time Object Constructs.

from "in design" to "under construction" and the event "open to traffic" marks the transition from "under construction" to "in service" (Fletcher 2000).

Metadata. Metadata objects are used to describe the characteristics of data in Transportation Features, Events, Spatio-TemporalObjects, and TimeObjects. There are two types of Metadata objects: SourceMetadata objects and LineageMetadata objects. The SourceMetadata object identifies the administrative aspects of where the data comes from, possible restrictions on the use of the data, and when the data were entered into the database ("transaction" time). The LineageMetadata object indicates the history or parentage of the data, including its compilation and processing history. The LineageMetadata object contains pointers or references to its' parent objects. For spatial objects, the LineageMetadata object also contains the positional accuracy of spatial objects derived from the VarianceCovarianceMatrix or provided elsewhere.

Conclusion

The MDLRS data model provides a framework for satisfying the need of the transportation community to integrate multi-dimensional data. The strategy for developing the data model was to use components of existing data models. The 20-27(2) LRS data model is used in the MDLRS data model as the framework to manage and transform linearly referenced data. From the GIS-T/ISTEA PFS model, the MDLRS data model adopts the historical modeling of transportation-based phenomena. The MDLRS data model employs the concepts of multi-scale representation of phenomena from the GIS-T Enterprise model. From the NSDI standard, the MDLRS data model adopts the framework for feature-level metadata. The MDLRS data model builds on the strengths of these data models and complements them with increased functionality by incorporating frameworks for measurement management, error propagation, temporal referencing, navigation, and the integration of linear and nonlinear referencing systems.

Employing the development strategy of the MDLRS data model demonstrates continuity, in that past efforts in modeling transportation-based phenomena are folded into the MDLRS model rather than being replaced. Since the MDLRS data model relies on existing transportation location referencing system data models, data from these models require nominal modifications for data exchange.

While the MDLRS data model represents the "next step" in providing a framework for location-based data management software development for the transportation community, it does not represent the final step. Implementation issues (e.g., data integration and application design) and testing are left to future efforts. These future efforts will help determine the MDLRS data model's success. Along with the MDLRS data model framework, these efforts will allow transportation organizations to share data between agencies and across business applications (e.g., incident and safety management). The result is improved performance of transportation systems as well as more efficient and effective planning, operation, and security decisions.

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