Report No. K-TRAN: KU-05-7
FINAL REPORT

ONTOLOGY ENGINEERING FOR MANAGEMENT OF DATA IN THE TRANSPORTATION DOMAIN

Gustavo Sudre
William Kritikos
Adolfo B. Matamoros, Ph.D.
Steve Graham
The University of Kansas
Lawrence, Kansas

November 2008

A COOPERATIVE TRANSPORTATION RESEARCH PROGRAM BETWEEN:

KANSAS DEPARTMENT OF TRANSPORTATION
KANSAS STATE UNIVERSITY
UNIVERSITY OF KANSAS

KANSAS
DEPARTMENT OF TRANSPORTATION

<table>
<tr><td>1 Report No.
K-TRAN: KU-05-7</td><td>2 Government Accession No.</td><td>3 Recipient Catalog No.</td></tr>
<tr><td colspan="2">4 Title and Subtitle
Ontology Engineering for Management of Data in the Transportation Domain</td><td>5 Report Date
November 2008
6 Performing Organization Code</td></tr>
<tr><td colspan="2">7 Author(s)
Gustavo Sudre, William Kritikos, Adolfo B. Matamoros, Ph.D., Steve Graham</td><td>8 Performing Organization Report No.</td></tr>
<tr><td colspan="2">9 Performing Organization Name and Address
The University of Kansas Center for Research, Inc.
2385 Irving Hill Road - Campus West
Lawrence, Kansas 66045</td><td>10 Work Unit No. (TRAIS)
11 Contract or Grant No.
C1512</td></tr>
<tr><td colspan="2">12 Sponsoring Agency Name and Address
Kansas Department of Transportation
Bureau of Materials and Research
700 SW Harrison Street
Topeka, Kansas 66603-3745</td><td>13 Type of Report and Period Covered
Final Report
Summer 2005 - June 2008
14 Sponsoring Agency Code
RE-0380-01</td></tr>
<tr><td colspan="3">15 Supplementary Notes
For more information write to address in block 9.</td></tr>
</table>

16 Abstract

This report discusses work done as a collaboration between the Kansas Department of Transportation, the University of Kansas Civil Engineering Department, and the Dakota State University School of Business and Information Systems. The work was an examination of the technologies, potential applications, and appropriate processes for applying semantic information in the service of knowledge management in the transportation domain. In particular, this research group examined taxonomies and ontologies, along with supporting technological infrastructure which have been or could be applied to matters related to DOT knowledge management. Since ontologies provide an overarching framework for expressing and embedding information, sufficient ontological foundations are essential. Since the entirety of transportation knowledge exceeded the scope of this project, two aspects were pursued: a broad, shallow portion ontology which would provide a context for other work, along with a narrow, deep ontology which would support examining knowledge representation issues in more detail.

During the project, the importance of re-using ontologies became apparent, along with the value of combining multiple ontologies to cover a domain. This was particularly true of the broader (upper level) ontologies and of those which are more generally applicable (e.g. ontologies for time, location, or documents). In examining a narrow, deep ontology, focused on a transportation topic, this research focused on bridges. First, we worked to identify the information structures necessary to describe bridges, in sufficient detail to represent those facets of most interest to DOTs. A key aspect of such work is determining a sufficiently fine representation. Since a key aspect of DOTs' operations involve interacting with transportation resources throughout their life-cycle, our group then developed an ontological model for the information involved in the long-term management and maintenance of bridges. In the course of this work, we adapted methodologies borrowed from software engineering to apply to ontology development.

The key results of this work are identifying the proximity of semantic tools such as ontologies to practical applications in the transportation domain, the importance of combining and re-using ontologies (along with the identification of a variety of such resources applicable for DOTs), and the value of developing and applying engineering processes to manage the development of ontologies.

<table>
<tr><td colspan="2">17 Key Words
ontology, transportation knowledge management</td><td colspan="2">18 Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161</td></tr>
<tr><td>19 Security Classification (of this report)
Unclassified</td><td>20 Security Classification (of this page)
Unclassified</td><td>21 No. of pages
208</td><td>22 Price</td></tr>
</table>

Form DOT F 1700.7 (8-72)

ONTOLOGY ENGINEERING FOR MANAGEMENT OF DATA IN THE TRANSPORTATION DOMAIN

Final Report

Prepared by

Gustavo Sudre
William Kritikos
Adolfo B. Matamoros, Ph.D.
Steve Graham

The University of Kansas
Lawrence, Kansas

A Report on Research Sponsored By

THE KANSAS DEPARTMENT OF TRANSPORTATION
TOPEKA, KANSAS

November 2008

PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

NOTICE

The authors and the state of Kansas do not endorse products or manufacturers. Trade and manufacturers' names appear herein solely because they are considered essential to the object of this report.

This information is available in alternative accessible formats. To obtain an alternative format, contact the Office of Transportation Information, Kansas Department of Transportation, 700 SW Harrison, Topeka, Kansas 66603-3745 or phone (785) 296-3585 (Voice) (TDD).

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the views or the policies of the state of Kansas. This report does not constitute a standard, specification or regulation.

ABSTRACT

This report discusses work done as a collaboration between the Kansas Department of Transportation, the University of Kansas Civil Engineering Department, and the Dakota State University School of Business and Information Systems. The work was an examination of the technologies, potential applications, and appropriate processes for applying semantic information in the service of knowledge management in the transportation domain. In particular, this research group examined taxonomies and ontologies, along with supporting technological infrastructure which have been or could be applied to matters related to DOT knowledge management. Since ontologies provide an overarching framework for expressing and embedding information, sufficient ontological foundations are essential. Since the entirety of transportation knowledge exceeded the scope of this project, two aspects were pursued: a broad, shallow portion ontology which would provide a context for other work, along with a narrow, deep ontology which would support examining knowledge representation issues in more detail.

During the project, the importance of re-using ontologies became apparent, along with the value of combining multiple ontologies to cover a domain. This was particularly true of the broader (upper level) ontologies and of those which are more generally applicable (e.g. ontologies for time, location, or documents). In examining a narrow, deep ontology, focused on a transportation topic, this research focused on bridges. First, we worked to identify the information structures necessary to describe bridges, in sufficient detail to represent those facets of most interest to DOTs. A key aspect of such work is determining a sufficiently fine representation. Since a key aspect of DOTs'

operations involve interacting with transportation resources throughout their life-cycle, our group then developed an ontological model for the information involved in the long-term management and maintenance of bridges. In the course of this work, we adapted methodologies borrowed from software engineering to apply to ontology development.

The key results of this work are identifying the proximity of semantic tools such as ontologies to practical applications in the transportation domain, the importance of combining and re-using ontologies (along with the identification of a variety of such resources applicable for DOTs), and the value of developing and applying engineering processes to manage the development of ontologies.

ACKNOWLEGDEMENTS

The research presented in the report was carried out with the support of a grant from the Kansas Department of Transportation and grant CMS-0324326 from the National Science Foundation. The information and feedback provided by Ben Nelson and Cindy Wade from KDOT is gratefully acknowledged.

The authors would like to acknowledge the support provided by the Kansas University Center for Research – providing grant support and administration, the University of Kansas – the School of Engineering and Department of Civil, Environmental and Architectural engineering, research support and resources, and Dakota State University – the School of Business and Information Systems, research support and resources.

Note: Portions of this report were drawn from the Transportation Research Board paper on this work (Sudre, 2007); in particular, introductory material, and material related to the discussions of Industry Foundation Classes (IFCs) and the Dublin Core.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 - INTRODUCTION

This report discuses research carried out as a collaboration between the Kansas Department of Transportation, the University of Kansas Civil, Environmental, and Architectural Engineering Department, and the Dakota State University School of Business and Information Systems. The work focused on examining technologies, potential applications, and appropriate processes for using semantic information for the purpose of knowledge management within the transportation domain.

The research group examined taxonomies and ontologies, along with supporting technological infrastructure which had been or could be applied to matters related to DOT knowledge management. Since ontologies provide an overarching framework for expressing and embedding information, well defined ontological foundations are essential. Because knowledge from different fields is interrelated, one of the major challenges in knowledge management is the delimitation of the domain that is being defined. Because the entirety of transportation knowledge exceeded the scope of this project, two aspects where pursued: a broad, shallow ontology which would provide a context for other work, along with a narrow, deep ontology which would support examining knowledge representation issues in more detail.

During the project, the importance of re-using ontologies became apparent, along with the value of combining multiple ontologies to cover a domain. This was particularly true of the broader (upper level) ontologies and of those which are more generally applicable (e.g. ontologies for time, location, or documents). In examining a narrow, deep ontology, focused on a transportation topic, this research focused on bridges. The first goal of the research was to identify the information structures necessary to describe bridges, in sufficient detail to represent those facets of most interest to DOTs. A key aspect of such work was determining a sufficiently fine representation. Since a key aspect of DOT operations involves interacting with transportation resources throughout their life-cycle, our group then developed an ontological model for the information involved in the long-term management and maintenance of bridges. In the course of this work, we adapted methodologies borrowed from software engineering to apply to ontology development.

The key results of this work were identifying the proximity of semantic tools such as ontologies to practical applications in the transportation domain, the importance of combining and re-using ontologies, and the value of developing and applying engineering processes to manage the development of ontologies. In the course of this work, we identified a number of resources including existing ontologies, languages and standards for representing ontologies, and a variety of tools for working with these systems. Some of this work is directly related to and of obvious value for potential transportation applications of semantic knowledge. Creation of an adherence to standards to facilitate the combination and reuse of such resources is an essential aspect of current and future work in the development of ontologies, tools, and applications.

1.1 Motivation for using ontologies and ontology research

The key element of the work is the semantic content provided by ontologies. Information in its raw form is primarily syntactic. It is possible to identify identical elements or syntactically similar elements, but impossible to deal with syntactically identical, but semantically distinct elements. The meaning of the word *chip* cannot be distinguished by syntax alone because it can refer to various different objects. It is the semantic relationships among fragments of information which will enable much broader use. This is primarily because the information which can be explicitly represented (for example in database tables or in the fixed text of a document) is a tiny fraction of the information that could be be inferred from such information given an appropriate context. Just as things which are syntactically identical require semantic knowledge and inference to be distinguishable, other things which may be syntactically distinct can be identified given sufficient and appropriate semantic background – we know that a *computer chip* and a *microprocessor* are the same thing, but from a strictly syntactic view such knowledge is difficult to impossible to represent in a general and broadly applicable way. Ontologies are the essential element in providing the semantic context to other information, enabling inference engines to derive some significant part of the information implicit in what is explicitly stored.

1.1.1 Integrating information from different sources

Data is stored using a wide variety of file formats and on diverse platforms. Any hope of combining such resources requires the use of *metadata,* data which describes the rest of the data. Ontologies are the most complete form that such metadata can take. In typical systems, only sufficient metadata is incorporated to support the explicit information storage. Often, this takes the form of details constraining the types and ranges for the explicit data and no more. Integration of data from different sources poses the challenge of recognizing when such integration is meaningful and when it is nonsense. Data from two different sources can be readily integrated given a carefully developed mapping between the representations of the two sources, however such mapping is a labor which increases as the square of the number of different sources and is wholly dependent on sufficient and sufficiently useful metadata being present. Since metadata is normally only included within a resource to the extent necessary for internal use of the data, it is often not appropriate for interchange. For both of these reasons, such an approach to interoperability is limited. In contrast, if an information resource is provided in the context of an ontology, then semantic relations among the data can be inferred, making possible both greater integration as well as automation (of some aspects at least) of the mapping between information from the disparate sources.

1.1.2 Integration will happen – efficiency of effort will be vital

There are a number of different trends which indicate the importance of a migration toward semantically rich data. The first indicator is simply the quantity of data which is being stored in electronic form and which is, in theory, available through various sorts of search engines. Closely related to this is the rapidly expanding accessibility of such data, via the increasingly large and complex networks of intercommunicating computer systems, including such communications resources and services as wireless communications and global positioning systems. The data is there (and growing), access is there (and increasing in quantity, duration and bandwidth), the processing resources exist to perform significant operations on data/information, and applications are beginning to be developed. An obvious example is the proliferation of services related to wireless services and geolocation. Similarly, advertisement services associated with websites are beginning to exhibit the potential for targeted advertisement addressing the needs and interests of the viewer. Such targeting becomes possible and effective (from the standpoint of an advertiser) and useful (from a the perspective of a consumer) as the underlying systems and services become able to combine sufficient data, information, and semantic knowledge to recognize what might be of interest or utility to the viewer.

A more relevant example of the potentials possible through data integration is provided by the increasing use of global positioning systems (GPSs) as driving aids. Integration with DOT information services can clearly enhance such devices, so that the information they provide regarding routes, road conditions, traffic and other matters of interest to both travelers and the DOT can be more timely, more accurate, and more wide-ranging. Nor is such an information flow strictly from a DOT to travelers. Even if no other information is available beyond a log of the queries initiated by such mobile devices, that log information itself, with the appropriate semantic context and analysis can serve to drive systems to better understand, anticipate, and meet the needs of the users of a transportation system.

The opportunities enabled by the semantic integration of our growing information resources are clear. In any domains with substantial stores of information which *can* be integrated with other data in a useful and profitable fashion – that data *will* be integrated and the semantic work supporting the integration will have to be done. The efficiency with which isolated information stores with limited metadata can be integrated through sufficiently general and applicable ontologies, will be a key element determining how quickly, and in what domains, with what priorities, and with what increase in value such semantic integration will occur. The inevitability of such integration should encourage research and development now which will facilitate and hasten the integration. Two areas will contribute: research within a domain which brings parts of it toward formal ontological representation and identifies particular challenges, and development in theory, practice, and tools to enable the efficient creation, integration, and testing of ontologies. In particular, tools and practices addressing the combining and reuse of ontologies are particularly promising.

1.2 Definition of basic terms

In this report a few basic terms are used and the most common ones are explained here to facilitate reading of this report.

Domain – a field of knowledge, a collection of related concepts grouped together. For example, the *transportation domain* refers to those concepts, issues, ideas, theories and activities related to transportation. The *time domain* refers to those concepts, relations, ideas, etc. related to time, including measuring it, specifying durations or particular points in time, locating particular events or activities in within some extended period of time, and so on. The particulars addressed as part of a domain may vary relative to context – a particle physicist is concerned with different spans of time than an engineering considering the lifetime and maintenance requirements of a bridge. However the needs to identify times, spans of times, and order events is meaningful to both, even though the details of scales and units considered would differ.

Concept – this is a sort of catch-all word and may be used to refer to virtually anything that comes under discussion, though usually it corresponds to a *category* or *class* or *collection* of things (which might be physical objects or abstractions). *Concept* is often used in contrast with *relation* which is used to describe some connections between concepts.

Relation – an association or connection among one or more concepts (or among objects which are specific *instances* of some concepts). Some common examples of relations include the *part-of* relation (an engine is part-of a car), the *is-a* relation (an employee is-a person) – indicating one concept represents a subclass of another concept, and the *instance-of* relation (bob is an instance-of person).

Ontology – a formal and explicit characterization of the concepts and relations comprising some domain. *Ontology* is used flexibly, sometimes to refer to a specific part of a larger system, and sometimes to refer to a larger system comprised of many subparts, which might also be called ontologies.

Upper-level – ontologies are sometimes described as upper-level, with the intent that they be regarded as more abstract, generic, general-purpose, and broadly applicable. The concepts found in an upper-level ontology should be useful across a wide variety of domains and rarely, if ever, reflect details of usage peculiar to a specific domain.

CHAPTER 2 - BACKGROUND

Due to advances in sensor and computer technology the amount of information that is acquired, stored, distributed and managed has been growing at a phenomenal and increasing rate. The current state of practice includes information stored in computer files using various different formats, which are ofter proprietary in nature. Standards for information storage have not been able to keep up and even when they exist have often been applied to only a fraction of the data which they might govern. When standards exist and information is stored in compliance with them, there are still challenges since the standards may prescribe only some narrow view of the data, leaving much unspecified. These factors pose barriers to both using and sharing data. As proprietary formats age, change, and are perhaps abandoned over time, details necessary to access and exploit data may be lost. This may render potentially important information useless. For these reasons new ways to describe, organize, manage, retrieve and apply data are needed. Users need better tools to keep pace with the exploding proliferation of data, formats, and communications. Common information storage and retrieval tasks, such as searches and comparisons must be improved, and automated reasoning must be enabled to support inferences of information implicit among the vast quantities of explicit data.

The use of ontologies and descriptive metadata have been shown to be effective in overcoming common barriers encountered in information management. These techniques have been used effectively in a number of different knowledge fields (domains) including: transportation (Cihon, 2003), finances (Sujanani, 2005), legal (Corcho, 2005), time (Pinto, 2003), and the corporate world (Razdow, 2005).

The terms ontology and metadata are explained at greater length in this chapter, as well as the relationship between them. Other fundamental concepts needed to understand the use of ontologies, including such topics as characteristics of a good ontology, typical applications and uses of ontologies, and approaches to building ontologies based on a specific domain are addressed as well.

2.1 Definition of an ontology and metadata

An ontology is a formal and explicit description of concepts in a certain domain. It features properties and their restrictions for each concept, as well as relationships among the concepts. A concept can be any physical object or abstract idea which bears a definition in a domain area. For example, analyzing the bridge domain, one can identify the structural components of a bridge (i.e. girder, pier, abutment, etc.) as concepts. Two of the most important properties of an ontology are its scope and granularity. The scope of an ontology defines the regions of a domain that will be referenced in the ontology, such as structural components, materials, and function. Granularity refers to the level of detail used to describe the information of a domain. For the bridge domain example, the number of structural components (concepts) that constitute the ontology is dependent on these two properties.

The term *metadata* means data about data. In other words, metadata is any kind of information that can be used to identify or describe a concept. For example, one can think about the information on a card from an old library card catalog as metadata about a book. Similarly, metadata about a text document might include information about the language, the contents, the author, file size, and the program used to write the document. While an ontology maps the relationships among the concepts within a domain, provides context for and supports inferences explicitly stored information, having metadata is essential for specifying what that explicit data is. The metadata normally specifies types, valid ranges and other constraints on formats or values. The metadata often provides names or labels for various fields. A table in a database constitutes explicit data and the entire table can be thought of as defining a relation among the elements of each record. The description of the table – including table name, field names, types, and sizes, along with any other constraints constitutes the metadata for that table. The combination of having a well-developed ontology to describe a domain and metadata about the data improves the chances of finding specific information within a large collection of data. It also provides the capability of using reasoning to derive conclusions about the data, and decreases the cost and time that must be invested in finding it.

Compared with the standard keyword-based search performed by many of the current search engines, a context-based search using the domain described by an ontology presents greater capabilities. To illustrate, if an engineer is looking for the parts of the superstructure of a bridge that have been inspected on a given date, a keyword-based search will only reference certain documents if they contain the word *superstructure* in them. Because an ontology would describe concepts such as *deck* and *girder* as components of the superstructure, all documents that contain such concepts would also be included in the search, whereas without an ontology these documents would not show in the results. In this way, a context-based search paired with an ontology has potential to maximize the relevant results of a search, ultimately increasing productivity.

The term ontology is often used loosely in most of the documents in the information technology literature. Within this report, the terms *ontology*, *taxonomy*, and *thesaurus* will be used with different meanings. While a thesaurus is a collection of words and their synonyms, a taxonomy is a set of terms that are related to each other in a hierarchical tree-like structure (normally an *is-a* hierachy). Several tools applied to thesauri development are available online (Willpower, 2006), as can additional information elaborating the principles and practice of thesauri. Furthermore, a taxonomy has parental relationships because everything that is said about a parent object is also true for all its children. This is a consequence of the fact that the tree represents an is-a or subclass hierarchy. Since every instance of a child class is necessarily part of the parent class, anything true of all instances of the parent class will be true of any instance of a child class. To illustrate, if one has in a taxonomy the term *Human*, and has the terms *Man* and *Woman* specified as its children, the statement *"Every human has an opposable thumb."* implies that *"Every man and every woman has an opposable thumb."* More information on the creation of taxonomies and automated tools for such task can be found readily online (Herd, 2001).

However, these parental, is-a relationships are the only type of relationships that are routinely included in taxonomies. Ontologies, on the other hand, can have arbitrarily many different properties and relationships expressed among its concepts. For example, if one had the concept *Water* in an ontology, he or she could link it to *Human* with the relation *"All humans drink water."* (Such a relation might be expressed more formally, perhaps as a relation *consumes* between a class and a material, with the meaning that individuals of the class consume quantities of the material.) Other features of ontologies are properties and restrictions. *Properties* is typically used to refer to a particular kind of relation, a functional one from instances of a class to the value of the property for that particular instance. Following the previous example, one can have pH as a property of *Water*, or number of toes, as a property of *Humans*. However, careful attention is required. Concepts can represent both classes or collections of things, but may also be instances of some other concept. So *Humans* can be a class with it's own instances (bob, carol, sue, etc.) but it can also be an instance of the class *species*. The precise meaning of a *number-of-toes* property might be a property of species and specify the typical number of toes a member of that species would have. Alternatively, it could be treated as a property of individual members of class *humans,* providing the number of toes for each individual member of the class. Within a specific concrete knowledge representation, it is necessary to attend to such distinctions. There are many choices and ways of expressing knowledge. The concept *Water* might be *partitioned* (divided into) the children (subclasses) *Carbonated* and *non-Carbonated.* Alternatively, *Carbonated* and *non-Carbonated* might be more general categories partitioning a broader parent category (*beverages* or *liquids*) and intersecting with other subcategories (perhaps *water*, *soft drinks*, and *alcoholic beverages*). Or, one might take *carbonated* and *non-carbonated* as unary properties of beverages. Again one can express a very similar distinction by having a binary relation, perhaps *contains* or something similar, e.g., "*Club soda contains carbonation.*" One can impose restrictions using such relationships and state such things as a constraint on one's beverage choices, saying that *"Some humans only drink non-carbonated water."* Though this last example raises yet another interesting subtlety – a formal representation of that natural language statement have to distinguish between the cases of some humans who only drink non-carbonated water *when they are drinking water* and other humans who drink no beverages at all, except non-carbonated water. Restrictions such as these are related to the complement of a set and the two previous alternatives correspond to complementing with respect to water or with respect to all beverages.

In order to start this brief description of knowledge modeling, it is crucial to adopt a naming convention to be used throughout the rest of this document. First, a *class* is the representation of a concept in an ontology. In order to specify individuals in a certain class, one creates instances. For example, *John* and *Paul* would be instances of the class *Male*, while *Katie* and *Kim* would be instances of the class *Female*. Classes (and their instances) can have properties (or slots), relationships with other classes or instances, and restrictions to these relationships.

The following picture is an example of a very small ontology:

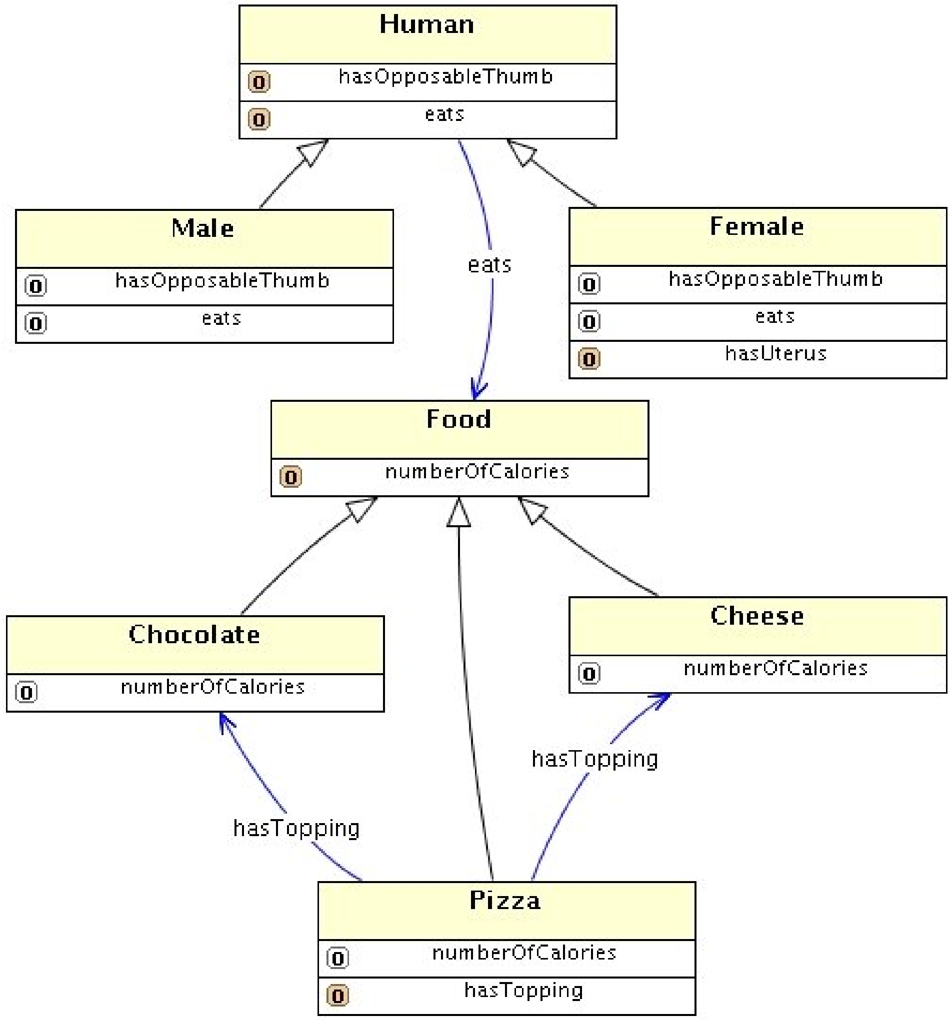

Figure 1.1: A Simple Ontology Diagram

The boxes represent classes, which have different properties and relationships (also represented by the arrows). The arrows with triangular heads represent the relationship between parent and children classes, also known as is-a relationships, and all other arrows are user defined relationships.

Note that child classes inherit properties from the parent classes, but they can still have additional properties of their own.

Evidently, ontologies are a powerful way to describe a domain. Using concepts, definitions, properties, relationships, and restrictions, systems can be created with many different goals, from domain generalization to automated reasoning.

2.2 How to use ontologies to manage information

There are multiple ways to use ontologies in the field of information technology (Noy, 2001). The most important ways one can use ontologies to improve efficiency are:

- Knowledge Sharing: to share common understanding of the structure of information among agents (e.g. software, people) is crucial in a corporation environment. All the agents that will use the information need to understand the same vocabulary to achieve better connectivity.
- Reuse of Domain Knowledge: the process of "re-inventing the wheel" can be inefficient and time consuming. By integrating several existing ontologies which describe portions of a larger domain, an ontology characterizing the entire domain may be produced. Dealing with the seams between the different ontologies can be a smaller task than constructing them from scratch, enabling productivity to be increased. In other words, it is possible (and often desirable) to incorporate existing ontologies to address a domain, rather than using the time to recreate the component ontologies as part of a larger one. Additionally, the contrast between ontologies and typical approaches to interoperability is that ontologies are intended more as a description of what is rather than as metadata for a particular application. As a result, ontologies support the possibility of enabling the implicit, inferable data which wasn't considered in the original context. However, the effort involved to construct more general

ontologies is greater than that of creating focused metadata for a specific purpose. Good examples of ontologies which may be reused are ontologies describing system of units, time, and geometric figures. These concepts and the relations among them are underlying constituents of many different domains.

- Make Domain Assumptions Explicit: because every important concept needs a definition, the assumptions in a domain will be formalized during the development of an ontology. These explicit assumptions are also useful for new users of a domain, who are often unfamiliar with such assumptions and so can not understand conclusions which rely on the assumptions. Furthermore, once such assumptions are made explicit, it becomes easier to update and refine the concepts and relations of a domain as knowledge, understanding, and information stored about the domain changes. Interaction among those assumptions and other factors in the domain become explicit and objective.
- Separate Domain Knowledge from Operational Knowledge: the same domain knowledge described in an ontology can be used in multiple practical areas. For example, if one has an ontology about the basic parts of a bridge, it can be used in conjunction with information stored on bridge management or or information created during bridge design. This separation of concerns facilitates reuse and extension of ontologies, and additionally makes possible unanticipated operational applications.

- Automated Reasoning: with the help of a reasoner (an inference engine), logical conclusions can be derived from a well-constructed ontology. To illustrate, if the question *"What is the food with most calories?"* was asked of a system based on the ontology of Figure 1, an agent would be able to identify *Pizza*, *Pizza with Chocolate topping*, and *Pizza with Cheese topping* as types of food. For example, suppose that *numberOfCalories* has values 50, 100, and 80, for pizza, chocolate, and cheese, respectively. Then, the agent would return *Pizza with Chocolate topping* (50 + 100 calories) as the food with the most calories. The underlying data provides specific information about pizza, chocolate, and cheese. An inference engine using the ontology would be able to conclude that the calories of pizza toppings are additive with the calories of the pizza. In it's most general form, this is an inference about combining quantities of physical substances.

2.3 Characteristics of a good ontology

Primarily, a good ontology can be used for any of the applications mentioned in the previous section – the hallmark is flexibility and the value added is that the implicit information which can be derived given a data store, an ontology, and an inference engine dwarfs the quantity of data explicitly stored. Perhaps the best way to characterize and understand what constitutes a good ontology is by listing some of the features an ontology should have:

- Clarity: all the definitions should be objective and as formal as possible, so that users have no question about the meaning a concept, property, or restriction mean.

- Coherence: an ontology should strictly reflect the corresponding elements of the real-world domain. If an inference is possible based on the ontology, the corresponding conclusion should hold in the real-world domain described by the ontology.
- Consistency: an entity in an ontology should always retain its definition. Furthermore, when merging two or more ontologies, consistency needs to be checked to be sure no elements with conflicting definitions arise. In the event of inconsistency, concepts must be analyzed to determine a resolution. This may be a matter of recognizing that the definitions are in fact of two separate concepts and simply need distinct formal representations; or perhaps that there is a finer grained definition which would subsume both of the original definitions.
- Extensibility: one should be able to define new terms for as needed to represent domain knowledge – based on and consistent with the existing ontology, in a way that does not require the revision of the existing definitions.
- Minimal Encoding Bias: the conceptualization of an ontology should be defined at the knowledge level, without depending on a particular language which will be used for future encoding. The goal is to be able to implement a given ontology in any language possible. While any concrete encoding is constrained by the formal representation language, concepts and relations among them aren't dependent on the characters used to represent them.
- Granularity: an ontology should be specific and consistent on the level of detail represented within the domain that it addresses. For example, any physical

material might ultimately be represented at a molecular, atomic, or even sub-atomic level. However, if the domain under consideration is transportation, then those aspects of a physical material drawn from material science and from economics are presumably more relevant than the sub-atomic structure (except in so far as it is reflected in macro-level properties!)

- Well-Defined Identities: every category has an identity criterion that should be obeyed. For example, the abstract concept of an individual person has different identity criterion than the physical concept of that person's body. On the individual's death, their body will gradually cease to exist as a coherent object (though the constituent materials and elements persist), but the abstract individual (e.g. her history, attributes, accomplishments, etc.) does not disappear.
- User Independent: Different kinds of software agents as well as human beings should be able to use a given ontology and all find it useful. The value of the description of the concepts and their relations comprising the ontology is not constrained by any particular use and is open to application in any way the explicit information and sound inferences from it can be used.

CHAPTER 3 - ENGINEERING ONTOLOGIES

In order to explore the power of machines to reason through information, it is necessary to represent the knowledge in such a way that computers can read. One of the main goals of using such machine power is to develop the future of the current World Wide Web, in which all the information will be handled more actively by computers: the Semantic Web (Berners-Lee, 2001). Among the many tools developed for knowledge representation, this project chose to work with XML, RDF, and OWL, mainly for their flexibility and acceptance in the community. Additionally, the use of graphical ontology development environments and reasoners facilitate the process of creating ontologies, which promotes the process of generating metadata.

3.1 Languages and tools for representing ontologies

Many acronyms are used when metadata and the Semantic Web are being discussed. The terms OWL, XML, and RDF are often used in conjunction, but it is important to know what each one of these tools can do in order to get a better understanding of the power of knowledge representation.

XML stands for eXtended (or eXtensible) Markup Language, and by using a small set of standard tags, it allows users to define their own tags to describe data (Bray, 2001). Then, these user defined tags must be explained to all the agents who are going to be using the XML file, because otherwise the new tags will not be recognized by any tools. For example, the following XML code represents information about a bridge:

```
<bridge>
      <name>A Big Bridge</name>
      <type>Arch</type>
      <type>Truss</type>
      <location>
      <roadway>I-70</roadway>
      <intersects>Dawson's
Creek</intersects>
      </location>
      <state>Kansas</state>
      <needs_repair/>
</bridge>
```

Figure 3.1: XML example

The code above is only useful if the program also receives instructions on how to read the file. To illustrate, the above code would be linked to a definition file like this:

```
<!ELEMENT bridge (name, type+, location, state, needs_repair?)>
<!ELEMENT location (#PCDATA | roadway, intersects)>
<!ELEMENT name (#PCDATA)*>
<!ELEMENT type (#PCDATA)*>
<!ELEMENT state (#PCDATA)*>
<!ELEMENT roadway (#PCDATA)*>
<!ELEMENT intersects (#PCDATA)*>
<!ELEMENT needs_repair EMPTY>
```

Figure 3.3: Document Type Definitions (DTD) example

The definitions above state that a *bridge* element has one (and only one) *name, location,* and *state*. Furthermore, it states that it can have one or more *type* and it may or may not have *needs_repair*. The elements *name, type,* and *state* are composed of a text string, while *needs_repair* is always empty. Finally, *location* can have just a text string, or have one *roadway* and one *intersects*. By using constructs such as these, XML provides the capabilities for developers to their own tags as needed, which in turn can be used to represent information. Note that the tags are strictly syntactic and any semantic interpretation is something *we* imposed based on familiar terms.

Although XML supports some structure and the invention of tags as needed, it is not sufficient to organize metadata. As explained by Bray, one of the areas where it lacks support is scalability. If an organization were to classify all the content of the Web like books in a library, billions of metadata tags could be generated. The order in which elements are presented in an XML file is significant, and that generally need not be the case for metadata. For example, it does not matter if the name of a bridge is listed before its location, as longs as both items are represented in the information store and can be considered in a search. Also, XML allows for complicated code structure which can become hard to handle with lots of metadata comes into play.

In order to better organize metadata it is more common to use RDF, which stands for Resource Description Framework (XULPlanet, 2005). RDF consists of triples of a subject, predicate, and object to describe some piece of information. The subject is always a URI (Unique Resource Identifier), which guarantees the uniqueness of information being described. The object can be a literal (e.g. text strings, numbers), or another URI. For example, the following structure represents two RDF structures, *BigBridge* and *BigLocation*:

```
<http://neespop.ceae.ku.edu/BigBridge> -> rdf:type ->
<http://neespop.ceae.ku.edu/Bridge>
<http://neespop.ceae.ku.edu/BigBridge> -> name -> A Big Bridge
<http://neespop.ceae.ku.edu/BigBridge> -> type -> Arch
<http://neespop.ceae.ku.edu/BigBridge> -> type -> Truss
<http://neespop.ceae.ku.edu/BigLocation> -> rdf:type ->
<http://neespop.ceae.ku.edu/Location>
<http://neespop.ceae.ku.edu/BigLocation> -> roadway -> I-70
<http://neespop.ceae.ku.edu/BigLocation> -> intersects ->Dawson's Creek
<http://neespop.ceae.ku.edu/BigBridge> -> location ->
<http://neespop.ceae.ku.edu/BigLocation>
```

Figure 3.3: RDF Example

A group of RDF structures can be imagined as a graph where the nodes are the resources and literals, and the edges are the predicates. It is important to notice that even the predicates are resources by themselves, to assure the uniqueness of each predicate. Also, RDF can be expressed in many ways, and one of the most popular methods to do it is using RDF/XML. Even using XML, there are many ways in which the structures can be described. This way, the above piece of code could look like the following:

```
<?xml version="1.0"?>

<rdf:RDF xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
         xmlns:neespop="http://neespop.ceae.ku.edu/"
         xmlns:predicates="http://neespop.ceae.ku.edu/predicates/">

<neespop:Bridge rdf:about="http://neespop.ceae.ku.edu/BigBridge"
predicates:name="A Big Bridge">
      <predicates:type>Arch</predicates:type>
      <predicates:type>Truss</predicates:type>
      <predicates:location>
      <neespop:Location rdf:about="http://neespop.ceae.ku.edu/BigLocation”>
            <predicates:roadway>I-70</predicates:roadway>
            <predicates:intersects>Dawson's Creek
            </predicates:intersects>
      </neespop:Location>
      </predicates:location>
</neespop:Bridge>

</rdf:RDF>
```

Figure 3.4: RDF Example expressed in XML

One of the big advantages of RDF is that the structures do not need to be described in any particular order, which allows for great modularity. Also, it has some built-in structures, such as ordered and unordered lists, which facilitates the process of describing data.

A big difference between XML and RDF is that although both are able to express basic relations, such as “XYZ is a bridge in Kansas”, only with RDF it is possible to give meaning to this relationship. In other words, in RDF it is possible to express semantics about the “is a bridge in” property, which will be necessary for further reasoning to occur with this information. Furthermore, there is a semantic extension to RDF called RDF Schema (RDFS), which is basically a language for describing vocabularies in RDF (Wikipedia, 2006). It is a standard for encoding limited schema information about RDF documents (Cerebra, 2005). This way, it is possible to describe groups of related resources (such as classes, subclasses, and their properties) and the relationships among them.

Finally, OWL stands for Web Ontology Language. It incorporates elements from RDFS, and it is built on top of RDF (and therefore, XML). OWL allows for exact expressions of relationships between classes and properties, and also adds features such as logical expressions and cardinality to properties.

3.1.1 OWL for describing ontologies

There are three “flavors” of OWL: Lite, DL, and Full. The main difference among them is the degree of freedom to express knowledge that each one of the flavors offers.

- OWL Lite: supports simple constraints (e.g. cardinality of properties can be only 0 or 1) and can be seen as a simple way to migrate taxonomies and thesauri to a concrete ontology formalism.
- OWL DL: contains all OWL statements, but they have to be used with certain limitations (e.g. a class cannot be an instance of another class). Moreover, it guarantees decidability (all reasoning computations can be done in finite time) and completeness (all reasoning computations reach a conclusion).
- OWL Full: supports all OWL statements, but because of its expressiveness

some of the computations based on it may never reach a conclusion, perhaps because an inference algorithm enters into an infinite loop.

OWL has momentum toward a broad role as a standard language for describing ontologies. It is a well-defined open standard, so anyone can easily get the full language specification without cost (OWL, 2004). Open specification will likely encourage applications which can utilize the format (OWL, 2004b). Also, OWL is a flexible and expressive language, so it can express most relations that would be needed to describe an ontology. This includes relationships such as equivalence classes, cardinality of properties, inverse relations, and general logical constraints and statements which can be created to describe a wide variety of other relationships. The ISO standard Common Logic (CL) is based on an abstract syntax and provides somewhat greater expressivity. However, OWL can be regarded as a concrete syntax which can be mapped to Common Logic for information exchange with sources using other concrete representations of CL (e.g., CGIF or CLIF)

The following piece of code represents the same structures described above in RDF, but this time OWL is used:

```
<?xml version="1.0"?>
<rdf:RDF
    xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
    xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
    xmlns:owl="http://www.w3.org/2002/07/owl#"
    xmlns="http://www.owl-ontologies.com/unnamed.owl#"
  xml:base="http://www.owl-ontologies.com/unnamed.owl">
  <owl:Ontology rdf:about=""/>
  <owl:Class rdf:ID="Bridge"/>
  <owl:Class rdf:ID="Location"/>
  <owl:ObjectProperty rdf:ID="location">
    <rdfs:range rdf:resource="#Location"/>
    <rdfs:domain rdf:resource="#Bridge"/>
  </owl:ObjectProperty>
  <owl:DatatypeProperty rdf:ID="roadway">
    <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
    <rdfs:domain rdf:resource="#Location"/>
  </owl:DatatypeProperty>
  <owl:DatatypeProperty rdf:ID="name">
    <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
    <rdfs:domain rdf:resource="#Bridge"/>
  </owl:DatatypeProperty>
  <owl:DatatypeProperty rdf:ID="intersects">
    <rdfs:domain rdf:resource="#Location"/>
    <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
  </owl:DatatypeProperty>
  <owl:DatatypeProperty rdf:ID="type">
    <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
    <rdfs:domain rdf:resource="#Bridge"/>
  </owl:DatatypeProperty>
  <Bridge rdf:ID="BigBridge">
    <name rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
    >A Big Bridge</name>
    <location>
      <Location rdf:ID="BigLocation">
        <roadway rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
        >I-70</roadway>
        <intersects rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
        >Dawson's Creek</intersects>
      </Location>
    </location>
    <type rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
    >Truss</type>
    <type rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
    >Arch</type>
  </Bridge>
</rdf:RDF>
```

Figure 3.5: OWL Example

3.1.2 The future of the Semantic Web

The concept of the Semantic Web was originally envisioned by Tim Berners-Lee, and it will handle data very differently from the current World Wide Web. The current web is an extremely data rich environment, but unfortunately is sparse (or poor) in organization, metadata, and semantic underpinnings. There is little or no metadata available for virtually all the information accessible via the web. In order to use the data sources on the web effectively, a very intelligent agent (usually a human) is required to interact with and analyze the data retrieved from the web, often during the retrieval process. Some automated tools from companies such as Google Inc. perform some analysis of the content of web pages and can determine some useful information about the content.

However, these methods are unlikely to be as complete or accurate as an explicit description of page content, offered as an adjunct to the content data. This is where the Semantic Web enters the picture. If web content is annotated with appropriate semantic context, far more elaborate inference become possible, supporting the derivation of vastly more implicit data from that explicitly available. For example, suppose a person wanted to perform a search for all reports written by John Smith about a certain bridge. If the documents do not contain an attribution to John Smith as the author, it would be hard to differentiate between documents that were written by John Smith and the ones that only contain his name. Moreover, there should be a way to guarantee that the search results refer to the unique John Smith in question, and not just any person called *John Smith*.

In a complete semantic web, all data would be annotated so that a less intelligent agent, such as a computer program, can retrieve data from the it and determine the meaning of its contents to easily analyze, reason, and filter information based on the semantic consequences of the explicit data. This dramatic enhancement to the utility of information stores is key goal of researchers and developers who are contributing to the creation and evolution of the Semantic Web, and to the extent that semantics can be added to web information store the power and utility of searches and interaction with data online will be greatly improved. (Warren, 2006).

3.1.3 Ontology development with Protégé

Protégé is an ontology development environment developed by Stanford University. Although it was originally designed for developing an ontology about medicine, it has now become a very general tool for developing all kinds of ontologies. Protégé supports many ontology languages, such as OWL, XML Schema, DAML + OIL, RDF, and CLIPS.

The following is a screenshot of Protegé during an editing session of the bridge parts ontology:

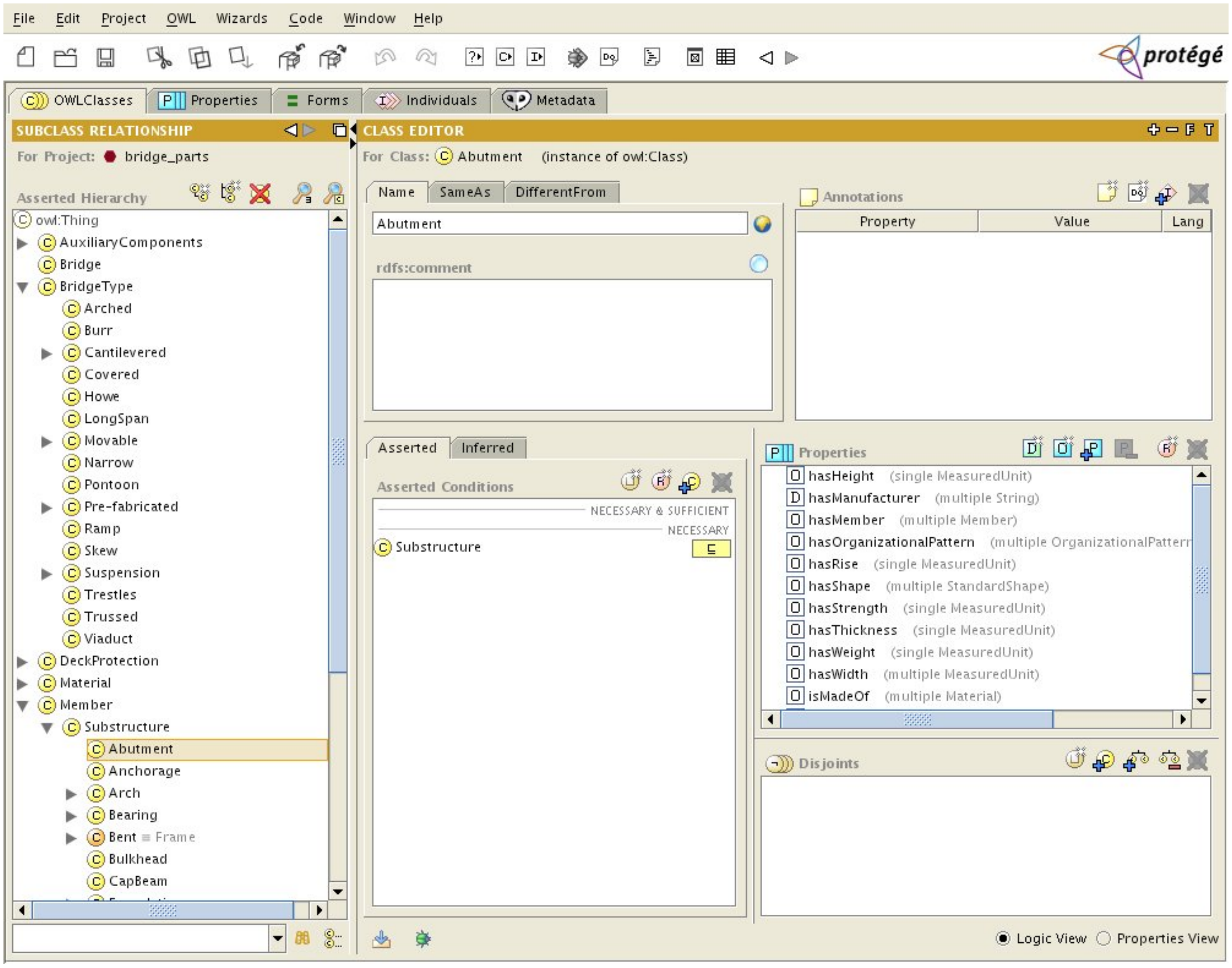

Figure 3.6: Protegé Ontology Development Environment

Protegé has many different features, but this research project particularly used the program's capacity to abstract from OWL code, providing the user with a simple tree-based interface to edit classes and properties hierarchy. Another advantage of Protegé is that it is written in Java. This means that it cannot only run in many different platforms, but because of the way the software was designed, it is also easy to write plugins that extend the program's capabilities. Examples of the plugins written for Protegé and used in this project are the OWL plugin and Ontoviz, which is to draw ontologies in a graphical format.

Several other tools can be found online to create and edit ontologies. Michael Denny (Denny, 2004) summarized the manual editing tools available at the time to practitioners interested in building structured ontologies suitable for information management and other applications. Some of the tools listed also have capabilities for automatically extracting information from domain documents. The article also mentions that it is common to use different tools at the same time in order to complete each other's features. Although this project experimented with similar tools, none of them seemed to perform better than Protegé.

3.1.4 Reasoning with Ontology Data

During this research project, a limited effort was made to explore the capacity and utility of various rule systems and engines. An example of such an engine would be Fact++. While such languages and engines are essential to the implementation of practical systems built incorporating ontologies, they pose a risk of re-introducing operational concerns during the ontology development process. However, they have a role in ontology development, since they can function to validate ontologies by identifying inconsistencies and by deriving explicit elements of an ontological hierarchy which may only have been stated implicitly by the ontologist.

In subsequent sections, the researchers address the importance of reuse in ontology development, including the identification and combination of existing ontologies to fill gaps in one under development. Under such circumstances, the possibility of performing automated consistency checks (and perhaps transformations) in order to verify (or create) compatibility between two overlapping ontologies becomes increasingly valuable. The larger and more complex the ontologies being combined are, the more difficult it will be for human users to detect non-obvious inconsistencies. Inference engines should contribute to detecting, isolating, and generating alternatives to inconsistencies in overlapping areas between two ontologies.

3.2 Importance of Re-usability and Engineering of reusable ontologies

Reusing ontologies is one of the keys to promote the creation of metadata. The benefits of ontologies will only be realized if ontologies cover a sufficient broad area of interest, but it is significantly difficult to have ontologies that cover so many topics. Challenges such as time and monetary costs come into play if a project this big is envisioned, and the additional barriers that the researchers would find along the way (such as agreement about domain representations) would definitely harm the final product.

One of the solutions for this problem is to develop multiple ontologies which overlap to cover an area. For example, while defining the bridge domain, researchers need to consider sub-domains such as bridge parts, location, materials used, and many others. Instead of developing a single, extensive, monolithic ontology that covers all these areas, it is beneficial to the project to design the ontology as an amalgam of many smaller ontologies that each describe a smaller, restricted domain. Moreover, often times other projects have already faced the task of describing these sub-domains, so the main effort would go towards finding the representation that best matches the researcher's current focus domain.

Although re-using ontologies leverages ontology development, researchers must deal with consistency issues when merging ontologies. Inconsistency may come in many ways, but the most common are the difference in implementations and disagreements on representations of a domain. The first type of inconsistency happens when there is an ontology to be merged and it was implemented in a different language than the current ontology project. For example, if the developers of the bridge ontology, which is written in OWL, wanted to use the ontology EngMath (Gruber, 1994) for units representation, some sort of conversion of the latter would be required, since it is not written in OWL, and therefore the merging process would not be possible. The second type of inconsistency happens when designers have different views of the domains, which can conflict when ontologies are merged. To illustrate, the bridge ontology contains a class Timber, which represents the wood of trees cut and prepared for use as building material. If merged with a different ontology which contains a class Wood, some modification would be needed to identify the relationship between both classes.

3.3 Optimizing ontology engineering

Ontology engineering is still a relatively new field compared with other engineering areas, such as structural engineering, or even other areas of computer science such as software engineering. For this reason, there is no standard method or guideline to build an ontology, which means that there is not an agreed-upon best method to do it.

Fernandez (Fernandez, 1998) points out that there are three methods which are more commonly used to design ontologies:

- M. Fernández A. Gómez-Pérez and N. Juristo, "METHONTOLOGY: From Ontological Art towards Ontological Engineering," Proc. AAAI Spring Symp. Series. AAAI Press, Menlo Park, Calif., 1997, pp. 33-40.
- Uschold M., Grüninger M. “ONTOLOGIES: Principles, Methods and Applications”. Knowledge Engineering Review, Vol. 11, No. 2. (1996), pp. 93-155.
- Grüninger M. and Fox, M. (1995). “Methodology for the design and evaluation of ontologies.” In Proceedings of the Workshop on Basic Ontological Issues in Knowledge Sharing held in conjunction with IJCAI-95, Montreal, Canada.

The author also argues that Methontology is currently the most mature method for developing ontologies. This methodology has well defined steps to construct an ontology, and it is also the most documented, with examples of its applications easily found online (Lopez, 1999).

Another method to create ontologies is by extracting terms from texts and other sources of data pertinent to a domain. Ding and Foo reviewed the the state-of-the-art techniques and work done on semiautomatic and automatic ontology generation, as well as the problems facing these researches (Ding, 2002). One of the most important conclusions shared by the authors was that learning ontology from free-text or heterogeneous data sources is still within the research lab and far beyond the real applications. Even when some results are reached from such process, a significant amount of human manual intervention still needs to be done.

3.3.1 Design patterns

Another concept, borrowed from software engineering, and applied to ontologies during this project was *design patterns.* According to a book by Alan Shalloway and James Trott (Shalloway, 2002), this is a relatively new perspective in software design, so it was interesting to consider how these ideas could be applied to ontology engineering. Also, the authors state that one of the motivations for the study of design patterns is that traditional approaches to software engineering are insufficiently flexible. Most software development can clearly benefit from increasingly flexible processes. Similarly, the creation of more flexible ontologies, and ontology development processes and practices should contribute to ontology modularity and reuse, which in turn to contribute an increase in productivity. The creation of reusable solutions is one of the main elements comprising the study of design patterns. Another goal is establishing a common terminology which captures and expresses greater complexity more readily. This goal has a clear resonance with and connection to ontology engineering. Agreement among researchers and domain experts regarding a common representation for concepts, relations and ideas is a significant step toward creating a coherent and sharable ontology.

The inspiration for design patterns comes from anthropology and architecture. According to the authors, individuals will agree to a large extent on what is considered to be a good design and what is beautiful, within a given culture (and domain). Moreover, one can identify an objective basis to quality designs within architectural systems, so people can discern similarities among designs that are high quality. Their proposition is that the quality of software systems can also be measured objectively. In order to do so, researchers need to ask themselves what is present in a good quality design that is not present in a poor quality design. Similarly, they also need to wonder what is present in a poor quality design that is not present in a good quality design, so they can assess what to include and exclude from the patterns representing high quality designs.

In architecture, many times one can identify two different structures with shared qualities, which both solve the same problem. That is the basic definition of a pattern: the recurrent elements of solutions to a problem in a context. In this book, the authors describe eleven patterns and it is possible to find applications for some of these patterns in the ontology engineering field. As an example, consider what is called the *Adapter* Pattern. A system may have the right data and behavior, but the wrong interface. Using the Adapter Pattern, a shortcut can be implemented to make the interface more convenient for all agents. This scenario can be observed in combinations of upper level ontologies that define very abstract concepts, with finer grained ontologies where the merging of the ontologies requires the aid of a mid-level ontology. As a concrete illustration, take into consideration the bridge and the SUMO ontologies (discussed in greater detail in subsequent sections of this report). It is desirable to be able to represent the geographical features a bridge intersects, such as roads and creeks, and the property *featuresIntersected* was created for this task. The upper-level ontology SUMO has classes that represent generic types of geographical features (e.g. *StationaryArtifact*), but these classes are not as specific as *Creek* or *Road*. While these and similar classes might be created as direct children of StationaryArtifacts, a wealth of potentially valuable information is unavailable unless there are additional, finer grained concepts bridging the conceptual gaps between *creek, road,* and *StationaryArtifacts.* Additionally, *creek* and *road* may be too specific for a broad upper-level ontology, but they are more general than what one would expect in a narrow ontology focused on bridges. For this reason, a mid-level ontology would be beneficial to connect the bridge ontology to SUMO so one can better describe the relationship between their classes. If an appropriate mid-level ontology were available, the bridge ontology could just link the *featuresIntersected* property of a bridge to the more specific classes from the mid-level ontology, instead of linking it directly to the generic classes in SUMO or having to create new, overly general classes as a part of the bridge ontology.

Although the perspective of using design patterns appears to be quite useful in software design, it is relatively early to claim similar value in the field of ontologies. It has clear potential, since many of the reasons why design patterns benefit software development appear to be shared with ontology engineering. However, more research is necessary in ontology development to determine the applicability of these ideas and the risks of unforeseen problems. Approaches to assess the benefits of design patterns in ontology development are needed. And comparisons between design pattern inspired ontology development and alternative techniques for designing ontologies should be done to determine whether this approach indeed increases productivity, quality, or reuse of ontologies.

3.3.2 Adapting the software life-cycle

The approach adopted to build the ontology for this project was a hybrid derived from various methodologies documented in the ontology literature. Fernández-López wrote an excellent article analyzing several methodologies to build ontologies

(Fernández-López, 1999). Besides evaluating the three methodologies already mentioned in this report, the author provides a summary of other promising techniques to complete a range of important readings for anyone deciding to start an ontology project.

During this project, the ontology development work could be assigned to seven relatively clear tasks: specification, knowledge acquisition, integration, conceptualization, documentation, implementation, and maintenance. However, it is important to note that these steps were not carried out in chronological order, but that instead tasks often took place concurrently, and various tasks were revisited repeatedly. As with much software development, a spiral model revisiting elements of the process is a more accurate representation than a sequential, waterfall model.

3.3.2.1 Specification

During the specification phase, the developers identify the crucial parameters which will guide the rest of the ontology development process, such as why the ontology is being built, what are its intended uses, and a set of terms that need to be present in the ontology. It is during this stage that the scope and granularity of the ontology are defined. Moreover, the end-users, developers, and maintainers of the ontology should be identified in this step. A document should be produced with all this information in order to keep developers bounded by a set of prior guidelines.

3.3.2.2 Knowledge Acquisition

This phase can extend itself through the whole development process because, after all, one can always learn new things about a domain. During this step, the developers research the domain in order to have a clear perspective of what are the most important concepts and how they relate to each other. Other people that contribute during this step are the subject matter experts (SMEs), because they can be consulted by the developers regarding questions about the domain.

Still in this step, a list of competency questions (questions the ontology should be able to answer when finished) is formulated. For example, if one wants the ontology to answer the question: "Will this bridge collapse if a X tons truck drives over it?", then he or she will need to have representations for (at least) the bridge, the truck, how heavy the truck is, and how much weight can the bridge support.

Another way of knowledge acquisition is by using textual analysis. By identifying the sentence structure in documents frequently used in the domain, it is possible to separate nouns and verbs, which will be future classes and properties (respectively) in the ontology. To illustrate, the sentence "The bridge supports X tons trucks" hints for future classes representing a bridge, a truck, and the measuring unit ton. Additionally, one can identify the need for a property that links trucks with a certain weight, and another one that links bridges to trucks it supports.

3.3.2.3 Integration

Although many developers overlook this step, it can be very productive to spend some time here. Integration involves searching for other ontologies that were already developed and which cover smaller parts of the ontology being developed. This way, one does not need to "reinvent the wheel", which increases productivity. Also, more specific ontologies can be reused in different domains, and this modularity allows the ontology developers to have more freedom in choosing the representation of a specific area of the domain.

Another advantage of using individual ontologies is that they are easier to be modified as long as the external interfaces are kept the same. Finally, it is important to notice that smaller ontologies that apply to different domains help to develop a standard in order to share information, since different domains will be using the same way to represent a specific sub-area that they share.

Good examples of ontologies that can be reused are ontologies that describe time, geometric figures, document attributes (e.g. Dublin Core, which will have its own section later in this text), and units. And the task of searching for ontologies has become easier since the development of specialized tools that browse the Internet for metadata:

- Swoogle *(http://swoogle.umbc.edu/)*: Despite the similarity in its name, this search tool was not designed by Google. It is a project of the University of Maryland – Baltimore County, and it features searches by terms, annotated documents, and ontologies. It has a good database size, and it returns results ranked by an internal mechanism.
- Google *(http://www.google.com)*: This powerful Internet search engine can also be used to look for ontologies. Basic searches such as “people ontology” or “units ontology” can yield results with the usual accuracy for which Google is known. Moreover, many times the engine returns links to documents explaining how to use the ontology and describing all the features in it, which can help in understanding how the ontology was created and result in a smoother merging process.

- Knowledge Zone

(http://smi-protege.stanford.edu:8080/KnowledgeZone/index.html): This website was created by the same creators of Protegé, and it is a repository of different ontologies organized by domains. It has ratings by users and reviews, which are very useful when looking for others' experiences merging ontologies. It currently does not have a very big database, but it surely has potential to grow and be a very useful repository of ontologies.

When looking for ontologies to be re-used, it is important to pay attention to certain details. First, the popularity of an ontology is a good indicator of how many people agree with that particular representation of the domain, which is a forward step towards reaching a standard in the area. Additionally, it is crucial to make sure that the new ontology represents the initial domain requirements. To illustrate, if during specifications phase it was agreed that the representation of a person should include his or her address and cellular phone number, it is evident that the chosen ontology to be merged should contain such information. Otherwise, more work will be required to add more data to this ontology to fit the needs specified before. Finally, it is important to choose an ontology that can be easily expanded, so it can be extended to suit the needs of the project. Many times an ontology will be suited to be merged, but it still misses some information that is required by the project. Then, the ability to add data to the ontology without damaging its structure becomes a key factor in the decision of using that ontology or not.

3.3.2.4 Conceptualization

The conceptualization stage marks the time when the developers start to formally define classes, properties, and restrictions based on the domain knowledge acquired. There are usually three common approaches to describe a domain (Semy, 2004):

- Top-down Approach: starts with the definition of the most general concepts in the domain and subsequent specialization of the concepts. For example, if one was to describe the domain of a small office, he or she could start with the furniture, then desk, then drawer, and then start describing more specific parts of the office.
- Bottom-Up Approach: starts with the definition of the most specific classes (a leaf of a hierarchy tree) with subsequent grouping of these concepts into more general concepts. In the office example, one would start with pen, then writing aids, then objects.
- Middle-Out Approach: a combination of top-down and bottom-up approaches. It starts defining the most important concepts first, and then generalizes and specializes them appropriately.

The approach to be chosen depends on the domain to be described and how easily it will make the task of listing and classifying all the objects in an hierarchic tree. However, several articles advocate the use of the middle-out approach, because it brings up the most important concepts first, and these are usually the easier terms to remember. Then, the developers can expand the tree by using a broader or narrower point of view.

3.3.2.5 Documentation

The documentation for all the ontology should be done after the conceptualization phase is finished, but before implementation. An ontology should be documented while the elements of the ontology are still described in an abstract and strictly conceptual form, independent of any kind of implementation. Following the documentation stage, any person should be able to code the design in any language he or she desires. By referring to the documentation, the developers build a computable model representing the ontology using a specific computational language.

Every single class and its definition should be documented extensively. Properties should also be the target of special attention, because their documentation must include information such as source and target concepts, cardinality, inverse relations, and etc. All the instances of classes should also be part of the documentation.

3.3.2.6 Implementation

This is the step in which a computable model representing the ontology is built in a computational language. This step should depend only on the ontology documentation.

Examples of languages to implement ontologies are Ontolingua and OWL. The use of Ontology Design Environments (ODEs) makes it easier for developers to construct ontologies. Such environments give the developers the power to define classes and properties graphically, which leaves it to the application to output the code. Examples of ODEs are Protegé and WebODE.

3.3.2.7 Maintenance

Maintenance is an on-going phase for every ontology. The ontology should frequently be checked for accuracy, particularly if the concepts described in the ontology are likely to change with time. Also, other people that use the ontology can identify errors that will need to be fixed.

Finally, it is important to remember to always update the documentation according to any changes made to the ontology, including the ones made during the maintenance phase.

CHAPTER 4 - DEVELOPING ONTOLOGIES IN THE TRANSPORTATION DOMAIN

The goal of this chapter is to describe the process used to develop the two ontologies created during the project. The implementation phase consisted of applying the theoretical and practical considerations described in the previous chapters to develop the two ontologies encompassing knowledge used in the transportation domain. One of the goals of the project was to create an ontology that would include broad, upper-level concepts necessary for providing a conceptual framework for transportation knowledge. Additionally, ontological models were developed to describe both the structure and management of bridges and the data associated with bridges, in the context of the information resources of the Kansas Department of Transportation (KDOT).

4.1 Overview

The current structure used by KDOT to store their documents consists of four different libraries: Accidents, Public Documents, Personnel, and KDOT documents. All these libraries are accessed through a Web Portal, and each one uses from 12 to 15 document classes (metadata) to classify the documents, such as keywords, court number, name, date. Some of these metadata elements are required, and some are not. Since there are no tools to automatically generate metadata and classify the documents, the work is done manually, and not always by the authors of the documents. KDOT worked to develop an automated metadata extractor for their email archive, but an evaluation of the system showed that the metadata obtained from it was not sufficiently accurate to replace manual labor.

The information at KDOT is generally collected based on operational needs. This is in direct contrast with a general goal for ontology development which requires separating conceptual and operational knowledge. A focus on operational needs permits a filtering and simplification of information and metadata stored, which is a definite advantage to any particular application considered in isolation. A large part of this filtering and simplification results in incomplete metadata when considered from a more general, application neutral stance. As a result, there are challenges that are difficult to bridge without additional common standards or contextual information when one tries to separate domain knowledge from operational use and origins. Nevertheless, the conceptual knowledge can still be useful in an ontological context, because such a system includes domain definitions and relations which can be used by a reasoner. Although such implicit information may be far from complete, an agent can still find relations and draw conclusions exploiting the ontology and the metadata which previously could only be done by humans.

4.2 Background Research

Before starting to develop ontologies for the transportation domain, it was important to indentify other efforts that already had been made towards organizing information in this area. By identifying the goals, accomplishments, and limitations of such efforts, this group was able to selectively apply their results in the ontology that was developed and tailored to the objectives of this project. Later, these sources of information were used for the purpose of evaluating the ontologies that were created by verifying that the ontologies under development included provisions for representing all the necessary information about the domain of bridges.

4.2.1 Library of Congress Classification and Dewey Decimal System

The Library of Congress Classification system (LCC) is widely used in the world to organize different sorts of documents in libraries. The goal of observing this classification system was to create a taxonomy based on its data, and then elaborate on the initial taxonomic tree in order to add properties intrinsic to the transportation domain. The categories of the LCC that suited the needs of the project were HE – Transportation and Communications (http://lcweb.loc.gov/catdir/cpso/lcco/lcco_h.pdf) and TA – Civil Engineering (http://lcweb.loc.gov/catdir/cpso/lcco/lcco_t.pdf). In the end, the subcategories presented by the LCC were found not to be well suited for use as a model for developing this effort because the subcategories were not sufficiently comprehensive. The granularity of the LCC representation suffices for the purposes of organizing texts in a library, but do not categorize documents into fine enough categories for DOT operational use. The character of the documents managed suggest this – with larger numbers of smaller, simpler, less formal documents (e.g., archived email and memos) as a significant component of DOT document archives.

Similar to the LCC, the Dewey Decimal system is used in many different libraries around the world as a model for organizing the constituent texts. In observing this system, the researchers were particularly interested in what types of knowledge and criteria were used to divide the domain into finer subparts. It was found that, for each domain listed in the Dewey Decimal system, experts in the area were responsible for finer grained partitioning. This attribute gave the knowledge embedded in the Dewey Decimal classification scheme more credence as a domain knowledge structure embodying domain expertise. This organization of the domain subject mater by specialists in the civil engineering domain, along with the practical, applied expertise provided by personnel from KDOT (workers who deal with the information daily), provided crucial foundations for constructing the ontology.

4.2.2 Bungee-jumping thesaurus

Although not directly related to bridges, this online thesaurus (Acme, 2005) was found to be very helpful with the classification of some of the terms related to bridges. The biggest challenge encountered when using this source was to separate terms that belonged to the bridge domain, from those terms which were drawn from the bungee-jumping domain. As these issues were resolved, this thesaurus proved useful as an initial resource characterizing terms incorporated into the bridge description part of the ontology.

4.2.3 TRB thesaurus

The TRB (Transportation Research Bureau) thesaurus was one of the most complete sources of information found during this project. It contains a comprehensive tree of terms (Transportation, 2005) related to the transportation domain, and covers all subjects related to the following transportation modes: air, land, water, space, and ground. The ground transportation subject is covered in the greatest depth, a valuable aid for this research project since the part of the thesaurus hierarchy related to bridge description and bridge management terminology were found among the topics addressed in greater depth.

The terms listed in this thesaurus and the way they were organized also complemented the information the research group had already found in other sources. Also, many cases the hierarchy as organized by TRB did not agree with the data previously collected by the researchers. In such cases, TRB ontological choices were given priority because they reflect compilation by a well-known entity, an organization central to professional practice in the civil engineering field. Relying on acknowledged authorities is a contributing step towards the creation of standards within a domain. Building on sources which already represent a broad consensus simplifies the process for adopting standards.

However, it is important to keep in mind that, although the TRB thesaurus is remarkably complete with relation to the terms it classifies, it still has the limitations inherent to such type of document. The relations embodied are still primarily the parental (and sibling) relationships characteristic of thesauri. Thus, all other relationships that are intrinsic to the transportation domain and potentially valuable in an ontology still need to be added to the thesauri terms and relations in order to construct a robust and more complete ontology.

4.2.4 Third-party software

When trying to describe the domain of bridges, it was important to discover the many different ways people can use to describe a bridge. For this reason, third-party software for bridge design and bridge management were important tools used to identify specific data used in widely adopted computer programs to characterize different types of bridges and their components. Because the software was proprietary, it was not possible to analyze the manner in which the different programs used the information internally, and how it was stored in binary files. Still, by analyzing input and output data, and by using help files and interacting with the program, the researchers identified several pieces of information that were missing in the ontology, and that were crucial for properly identifying the components of a bridge.

Another factor to be considered is the level of the detail used to describe bridge components in these programs. Because some of them were developed for the purpose of bridge design, bridges and components are described using the maximum level of detail possible. Because the goal of this project involved a certain level of granularity, the level of detail of the concepts identified from these programs was evaluated before adding new features to the ontology. This way, the group focused its effort on developing robust relationships between the concepts needed to represent knowledge deemed important for the overall goals of the project rather than investing a great amount of effort in defining every concept to the greatest level of detail possible.

The following programs were evaluated during this information gathering stage:

- AASHTOWare® Products *(http://www.aashtoware.org/)*: the programs analyzed were Pontis, for Bridge Management, and Virtis/Opis, for bridge design and rating. Besides looking at the overall functioning of the programs and the information they needed to operate, other related tools were used, such as tutorial videos on how to use the programs, and a paper (Thompson, 2000) that summarized the bridge terms the program commonly-recognized.
- BRASS™ Suite of Computer Programs *(http://www.dot.state.wy.us/Default.jsp?sCode=hwyov)*: this is a comprehensive set of programs designed by the Wyoming Department of Transportation for bridge design and analysis. The manuals and screenshots found on the Wyoming DOT website were particularly useful to develop a good

understanding of the concepts used to define bridges and components in these programs.

- PennDOT Engineering Programs *(http://penndot.engrprograms.com/home/)*: developed by the Pennsylvania Department of Transportation, this broad set of software is suited for bridge analysis, rating, and design. These programs do not have a graphical user interface and operate by reading an input text file and returning an output text file. An evaluation of the structure for the input and output files (available online) was sufficient to gather useful information about bridges that was added to the ontology.

4.2.5 TransXML

This is a project of the National Cooperative Highway Research Program (NCHRP) to develop a set of XML schema for transportation applications. The project objectives are to create broadly accepted public domain XML schemas for the exchange of transportation data, and to create a framework for development, validation, dissemination, and extension of current and future schemas (TransXML, 2006). One of the intended outcomes of the project was to create a standard format for the exchange of transportation related data. The scope of this project also included testing the ability the the XML schemas that were developed to represent data created with the AASHTOWare set of programs (mentioned earlier in this text).

Although the ultimate goal of the TransXML project was to create a broad set of schemas for data from all crucial transportation business areas, the initial focus was on four areas considered prioritary for AASHTOWare XML migration: surveying and roadway design, transportation construction and materials, transportation safety, and highway bridge structures. Among these areas, the latter was of the most interest to this ontology development effort.

The results of the TransXML project were very interesting to this group, and the group heavily considered using the project schemas as the basis for the ontology that was being developed. However, after careful study of the TransXML UML Description for Highway Bridge Structures (TransXML, 2005) the group concluded that the TransXML schemas focused on the design and analysis of bridges, leaving behind important areas for the ontology project such as inspection, inventory, history, finances, and personnel. Moreover, because the efforts of the TransXML group focused on pre-stressed I-Beams, and because the manner in which the TransXML would adopt the use of GML (which will be covered in more details later) to describe geometric forms was unclear, the integration to the ontology project was halted.

Because of the amount of information contained in the domain of bridges is very large, the decision by the TransXML group to focus its initial effort on a few areas and then expand to a broader spectrum is appropriate. However, for the purpose of the ontology project knowledge related to the management of bridges is very important given its importance to KDOT. For this reason the development of the ontology included other subdomains not covered by the TransXML project. If the TransXML schema were to become a widely adopted standard in the industry, interoperabilty with the bridge ontology could be achieved by mapping the concepts included in the two.

4.3 Bridge ontology: design goals

The main objective of the bridge ontology was to create a resource to improve the management of information about different types of bridges. In order to achieve this objective data about bridges was organized in a manner conducive to maximize relevant search results and minimize wasted time. The process of finding similar facts about bridges can be eased by pre-establishing relations between different concepts in this domain. The ability to describe the relationship between concepts is one of the most useful features of an ontology. Also, the use of an ontology promotes the creation of a common-ground to share information about bridges.

In similar fashion to the TransXML development effort, the first step taken in the development of the bridge ontology was to narrow down the vast transportation domain to a manageable sub-domain in order to focus the efforts of the group. As a result group chose to focus on creating an ontology to describe the sub-domain of bridges. Two different ontologies were created, each having a different scope and development approach:

- Broad, shallow ontology: it defines general concepts to be used by domain-specific ontologies.
- Narrow, deep ontology: defines a narrower domain to a greater degree of granularity.

The bridge_record ontology was developed to encompass broader concepts about the domain of bridges, and its role was to provide the semantic connections between the elements of a bridge record. The record of a bridge contains broad information such as inventory and personnel data, and it is crucial to identify and manage information about different bridges. The bridge_parts ontology was developed with a much narrower and deeper focus to contain relations and definitions about the parts of a bridge. To illustrate, while the Bridge Record ontology can be used to describe information about the repair reports of a bridge, the Bridge Parts ontology can be used to describe information about the parts to be repaired.

It is also important to note that the classification of the two ontologies is relative and depends on the domain of knowledge that is being considered. While the bridge_record ontology was cataloged as a broad shallow ontology when compared with the bridge_parts ontology (which seems logical considering that the former relies on the latter), this classification is not appropriate if the bridge_record ontology is placed in the context of the entire transportation domain. In that case, an ontology describing the entire transportation domain would be considered as a broad and shallow ontology, and the record of a bridge would be a finer part of that domain. Likewise, the ontology describing the bridge_parts would have to be considered a broad and shallow ontology if compared with other ontologies describing the narrow fields of materials or types of bolts and connections.

4.4 Specification

The ontologies developed in this project were created not only to improve the management of bridge information, but also to assess the standards of the state-of-the-art on ontologies and how well they can be used to represent knowledge in the domain of bridge structures. Given the amount of information that a bridge record contains, many different questions can be answered by drawing conclusions about the data. The following are a few examples of possible uses of the ontology:

- Bridge location: given the many different ways a customer can inquiry about a specific bridge, it is possible to verify that the same bridge is being referred to independently of the description.

- Common defects: if a bridge has been reported to have been repaired because of a certain defective part, it is possible to identify other bridges that will possibly be affected by the same defect.
- Personnel identification**:** people who performed a role in the construction of a bridge can be identified as performing similar or different roles in the construction of other bridges.

4.5 Knowledge Acquisition

During this phase the researchers were responsible for gathering information about bridges and bridge management. Several sources were used in order to leverage this type of knowledge, such as experts in the subject, online resources, books, and manuals.

4.5.1 Subject Matter Experts

Besides counting on the expertise of the researchers who were already part of the project, it was necessary to survey information about other people with experience in the areas of ontologies, transportation, and bridges. They would not only contribute to the ontology with new insights, but also test what was already being represented so that the researchers would have a different perspective in a problem already approached. This way, the ontology would be able to agree with a bigger realm of opinions, instead of being the product of the point of view of a few individuals.

Although not all of the following people were contacted for this research, they were all identified as SMEs in a sub-domain being addressed in the ontology:

Table 4.1: Subject Matter Experts

Name	***Affiliation***	***Area of Expertise***	***Contact***
Yaser Bishr	ImageMatters	Semantic Aspects of Interoperable GIS	
Werner Kuhn	University of Münster	Semantic interoperability and GIS	http://ifgi.uni-muenster.de/kuhn/
Max Egenhofer	University of Maine	Spatial Information Science and Engineering	http://www.spatial.maine.edu/~max/
David Mark	University at Buffalo	Geographic Information Science	http://www.geog.buffalo.edu/~dmark/
Mariano Fernandez-Lopez	Universidad Politecnica de Madrid	Ontologies Expert	
Mark Mlynarski	Michael Baker Jr., Inc.	TransXML Research Team	mmlynarski@mbakercorp.com
Loren Risch	KDOT	State Bridge Design Engineer	

4.5.2 Books and manuals used

Several textbooks, reports, and computer program manuals were used as a reference to conduct a survey of bridge-related terminology. Using different sources was important to understand the various synonyms used to describe bridge components and to make sure that definitions of concepts related to bridges found in different sources in the literature were consistent with one another. While all the sources were useful in the development of the ontology, the following sources were particularly important in the development of the bridge_record part of the ontology because their content focused on bridge management, inspection, and guidelines for storing such data:

- AASHTO's Manual for Condition Evaluation of Bridges, 1994, Second Edition: *hardcopy*
- Bridge Inspection Manual TexasDOT: *http://manuals.dot.state.tx.us/docs/colbridg/forms/ins.pdf*

Although the following resources had little information about bridge management, they were very important because of their vast content of vocabulary related to the bridge domain:

- Final XML format recommendation for bridges: *http://www.transxml.org/Bridge+Structures+Schema/Group+Documents/Downloads_GetFile.aspx?id=300*
- Barker, R. and Puckett, J. 1997. Design of Highway Bridges. Wiley-Interscience Publication. John Wiley & Sons, Inc.: *hardcopy*
- Bridge Design Manual – TexasDOT: *http://manuals.dot.state.tx.us/docs/colbridg/forms/des.pdf*
- Model Highway Data Dictionary Roadway Bridge Data Elements: *http://tsims.aashtoware.org/ContentManagement/PageBody.asp?PAGE_ID=11*
- Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges :: *http://www.fhwa.dot.gov/BRIDGE/mtguide.pdf*
- Wisconsin County Highway Association Policy & Procedure Manual: *http://www.iti.northwestern.edu/publications/fish/highway_manual.html*

4.5.3 Online resources

Less formal resources were also used during the development of the bridge ontology. The main source of information came from the the National Bridge Inventory Project (NBI), which is the collection of data over 600,000 bridges on the Nation's Interstate Highways, U.S. Highways, State and County Roads, and other routes of national significance (NBI, 2001). Because this data has to be submitted annually by the States to the Federal Highway Administration (FHWA), the ability of the ontology to describe this information was considered to be of paramount importance. The information collected for storage in the NBI is listed and explained at *http://massroads.com/nbiDesc.htm*.

Other sources consulted to gather definitions of more basic terms:

- Roebling's Bridge Division: *http://www.inventionfactory.com/history/RHAbridg/*
- How Bridges Work: *http://science.howstuffworks.com/bridge.htm*
- Bridges and Tunnels of Allegheny County and Pittsburgh, PA: *http://pghbridges.com*
- About bridges: *http://www.nireland.com/bridgeman*
- Glossary of bridge terms: *http://www.dot.state.oh.us/preventivemaintenance/Glossary/glossaryset.htm*

4.6 Integration

The objective during this phase was to incorporate work that had already been done to represent auxiliary fields in the ontology. Although the ontology was not specifically developed to describe for example concepts in the sub-domains of geographic coordinates, units, and materials, these are all sub-domains that contain terms that are necessary to describe concepts in the bridge domain. The approach adopted was to focus on describing knowledge in the core areas of the ontology and to use existing standards to represent the supporting sub-domains. One of the main advantages of this approach is that it facilitates interoperability with other agents. Criteria used to select the supporting standards were that there should be a high degree of compatibility with the manner in which concepts were defined in the core domain and that the respective standards should be broadly adopted (i.e. being used by more than one project) to facilitate interoperability.

Another task undertaken during this phase of the project was to find a broad upper-level ontology that could be linked to the bridge ontology so that concepts in the bridge ontology could be given a context within the realm of general knowledge. For this reason this broad upper level ontology had to be capable of providing an abstract representation of generic terms. The bridge_record ontology would then be developed as an extension of this upper-level ontology. Consequently, the main classes in the bridge_record ontology would be children of classes in the upper-level ontology (Russomanno, 2005). It would be ideal if this broad and shallow ontology also contained representations for the supporting sub-domains of the bridge ontology (e.g. units, coordinates, etc). However, if that was not the case, or if their representation did not match the goals of the project, other standards to represent knowledge in the subdomains were adopted instead.

The following sections briefly summarize some of the work that was evaluated for integration into the ontology. There were several upper-level ontologies that were mentioned in articles and other sources but were found not to be suitable for the project. These include: Mikrokosmos, SENSUS, OCHRE, BFO, and GUM.

4.6.1 Industry Foundation Classes

The IFCs (IAI, 2004) were created to provide a single platform in which all members of the construction and facilities management industries could exchange data more effectively. Technically, the IFCs are an ontology because they describe concepts and the relationships between those concepts. However, the IFCs are not, by themselves, a good ontology, because the concepts that they describe are generally only physical concepts. For example, if the IFCs were used to describe a bridge construction project, there would be no description available to specify the elements of the substructure and superstructure, which are important concepts in the bridge domain. In the building domain, the IFCs do not describe the concepts of floors or rooms, only the elements that those concepts are built from. The goal of the IFCs is truly to capture data about all of the physical concepts in the domain. Because the IFCs are a type of ontology that captures all of the data in a domain, but not necessarily all of the concepts, they are better defined as a data model than an ontology.

The ontology developed in this project did not import the whole IFC data model because of its size and the amount of unrelated information it would bring about. Instead, the researchers decided to mirror the ways it represents certain auxiliary domains, shaving off unnecessary classes and properties. Some of the sub-domains that were mirrored were units, agents (person, organization), and GPS location.

4.6.2 Dublin Core

The Dublin Core Metadata Initiative (DCMI, 2005a) was developed to provide a standard set of metadata fields to describe many different types of resources. It is often used to describe documents in a business or research setting, but the fields are applicable to many types of resources such as literature, visual artwork, or music. The DCMI defines the following key terms (DCMI, 2005b):

Table 4.2: Dublin Core Metadata Initiative (DCMI) Key Terms

Term	Definition
Contributor	An entity responsible for making contributions to the content of the resource.
Coverage	The extent or scope of the content of the resource.
Creator	An entity primarily responsible for making the content of the resource.
Date	A date associated with an event in the life cycle of the resource.
Description	An account of the content of the resource.
Format	The physical or digital manifestation of the resource.
Identifier	An unambiguous reference to the resource within a given context.
Language	A language of the intellectual content of the resource.
Publisher	An entity responsible for making the resource available
Relation	A reference to a related resource.
Rights	Information about rights held in and over the resource.
Source	A reference to a resource from which the present resource is derived.
Subject	The topic of the content of the resource.
Title	A name given to the resource.
Type	The nature or genre of the content of the resource.

Several projects and organizations (DCMI, 2005c) all over the world have adopted the use of the DCMI. One of the problems with adopting the DCMI is that there is no standard for implementation of their use. Each implementation independently establishes which of these terms are useful in describing the given resources. For example, the field Language may not be very useful if the DCMI is being used to describe sculptures. In the bridge ontology, the DCMI was used to describe bridge-related documents, such as reports, structural drawings, pictures, and other data files in the ontology.

To exploit the DCMI as a metadata model for DOT documents, a number of the key terms appear essential, some likely to be useful, and others unlikely to be useful. The following lists attempt such a classification with respect to KDOT documents. However, these lists reflect assumptions by the project members and ignorance of the complete range of KDOT documents, so they are a first-level approximation of the relevant key terms, rather than an authoritative compilation. Further, the selection of relevant terms reflects potential applications in the bridge parts and bridge management ontologies. A rationale for some of the classifications follows the lists. Essential key terms include: *creator*, *date*, *format*, *identifier*, and *type*. Among the other key terms, the following seem highly likely to be of use in classifying and accessing KDOT documents: *contributor*; one or more of *coverage*, *description*, *subject*, or *title*; *relation*; and *source.* The following key terms seem less likely to be useful to KDOT: *language*, *publisher*, and *rights.*

The key terms listed as essential should be uncontroversial, with the possible exception of the term *format* – in this particular case it could be possible to create a functional dependence of the format on the document *type.* It was decided that adopting this approach would have the drawback of introducing too fine a level of detail onto the *type* concept, which would be more appropriately placed under *format.*

The reasons for classifying terms as highly likely to be useful are as follows: *Contributor* – it will be commonplace for documents to be cumulative products of multiple contributors over a significant span of time. The key terms *coverage, description, subject,* and *title* all share the role of describing the contents of a document so that at least one such term is really essential, and a convention could be adopted to force all content description to be associated with a single one of these terms. However *subject* and *title* often clearly correspond to existing fields of various types of documents and using them for other than those corresponding fields could easily lead to errors. *Description* and *coverage* are less conventional in their use and one of the two might serve if parsimony is seen as particularly valuable. There will clearly be *relations* among documents, often significant and complex, so explicit inclusion of this informations seems wise. Similarly, documents are likely to be derived from other *source* documents. Issues of *language, publisher,* and *rights* seem less relevant for KDOT internal documents, though depending on context a case could be made for any of these. As an example, individuals might be considered the agents as *creators* or *contributors*, while a more abstract entity such as a department or project team might be treated as the *publisher* of a document.

4.6.3 SUMO, MILO, and others

SUMO (Niles, 2001) was created as part of the IEEE Standard Upper Ontology Working Group, and it stands for Standard Upper Merged Ontology. According to their website (SUMO, 2005), SUMO "is limited to concepts that are generic, abstract, or philosophical, and hence are general enough to address (at a high level) a broad range of domain areas." Its use is free for research and it was developed in KIF, which is more expressive than OWL, specifically in the case of axioms. Because of this, some of the information (e.g. conversion formulas) was lost or converted as string properties in the process of translating it to the version released in OWL.

The efforts by the group that created SUMO also include a few ontologies devoted to more specific domains, such as government, economy, transportation and geography. All these domain ontologies were developed as extensions of SUMO, using it to define the more abstract concepts. In fact, they all use MILO (MId-Level Ontology), which is also available in OWL. MILO is intended to act as a bridge between the high-level abstractions of the SUMO and the low-level detail of the domain ontologies. Finding the concepts that SUMO and MILO are capable of representing is a straight-forward process by using the implementation of the SUMO Ontology Browser (http://sigma.ontologyportal.org:4010/sigma/Browse.jsp?kb=SUMO&lang=en). The SUMO Ontology Browser links common terms in the English language to classes and properties in the ontologies.

Because SUMO describes many different domains, the bridge ontology could make use of it to represent many supporting domains, such as agents (person, organization), units, directions, and stationary artifacts. When the representation done by SUMO was considered to be not sufficiently detailed, or when it did not agree with the definition of concepts used in the bridge ontology, other ontologies were and can be used to replace or even complement the work done by SUMO. The following diagram shows how SUMO was integrated with the bridge ontologies:

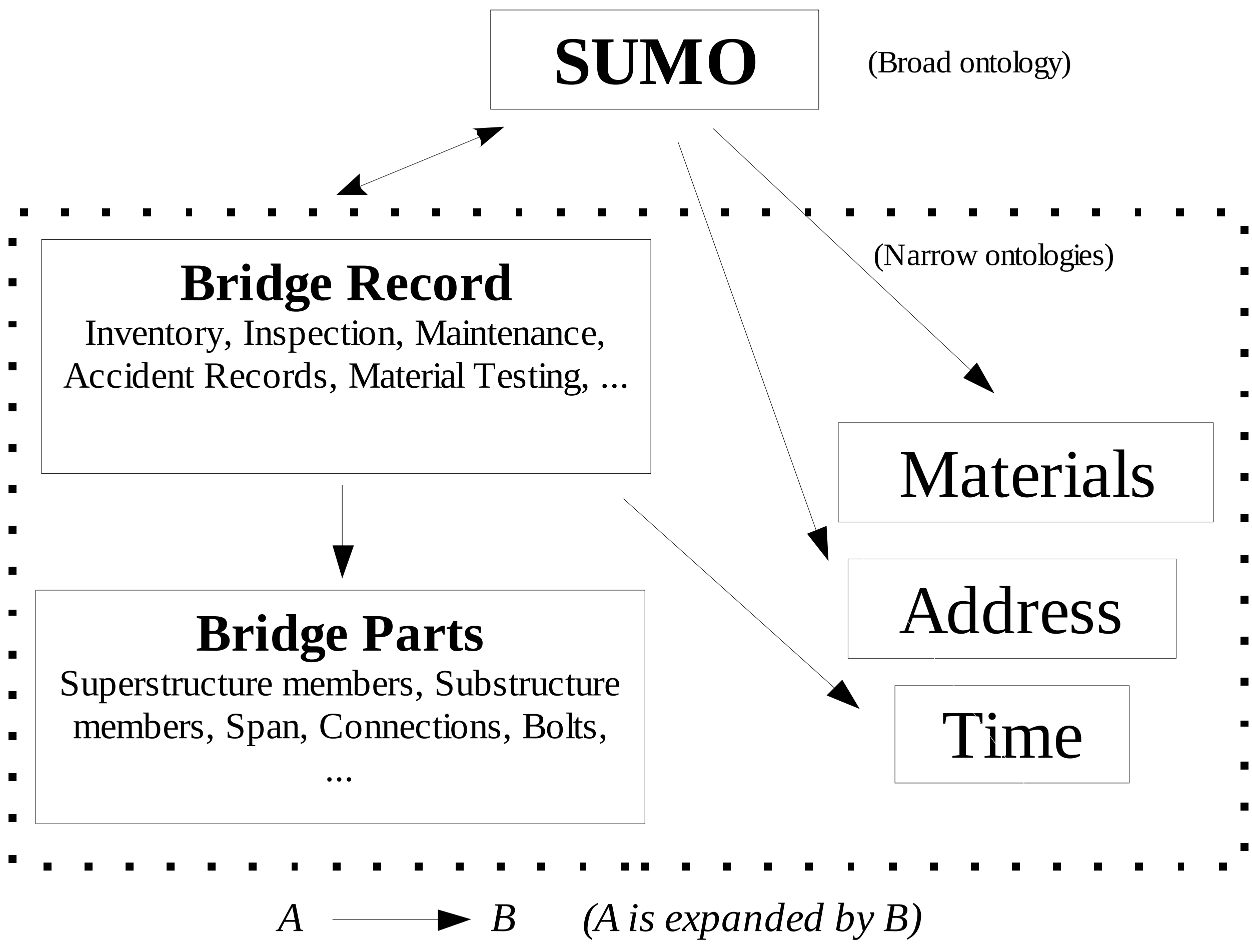

Figure 4.1: Bridge Ontology Structure

SUMO satisfies many of the criteria used in the project to select an upper-level ontology to provide the basis for the bridge ontology. The ability to represent time was one of them, and SUMO excelled in some of the different ways to do so. For example, in order to represent an interval of time, as in the sentence “The construction took 15 months”, the class TimeInterval can be used. Similarly, in order to express a certain point in time, such as “The repairs started in 1983”, one can use the class TimePoint. If the time period has not been clearly specified, like in “The construction has been going on for a long time”, the class TimeDuration can be used. In fact, all three of these classes are children of TimeMeasure, so one could use this single class to map all of the time references above.

Another domain in which SUMO satisfied the project criteria was in regard to units. SUMO divides its classes that represent units by their type, and they are all children of ConstantQuantity. For example, US-Cent and US-Dollar are represented under CurrencyMeasure, and Hour, Minute, and Second are under TimeMeasure. SUMO also includes representations for temperature, angles, mass, information, and length. These classes can also be used to describe latitude, longitude and other positioning coordinates for the location domain. Figures 9 through 13 show the manner in which a few supporting domains are represented in SUMO.

In summary, SUMO has a good description for the majority of the supporting domains of the bridge ontology. However, its representations are often very basic and demand some adjustments and extensions before fulfilling all the requirements previously envisioned. For this reason other ontologies were evaluated to either replace the SUMO representation of a specific domain in its entirety, to extend it, or at least to give the group insights on how to expand the SUMO representation to better suit the needs of the bridge ontology.

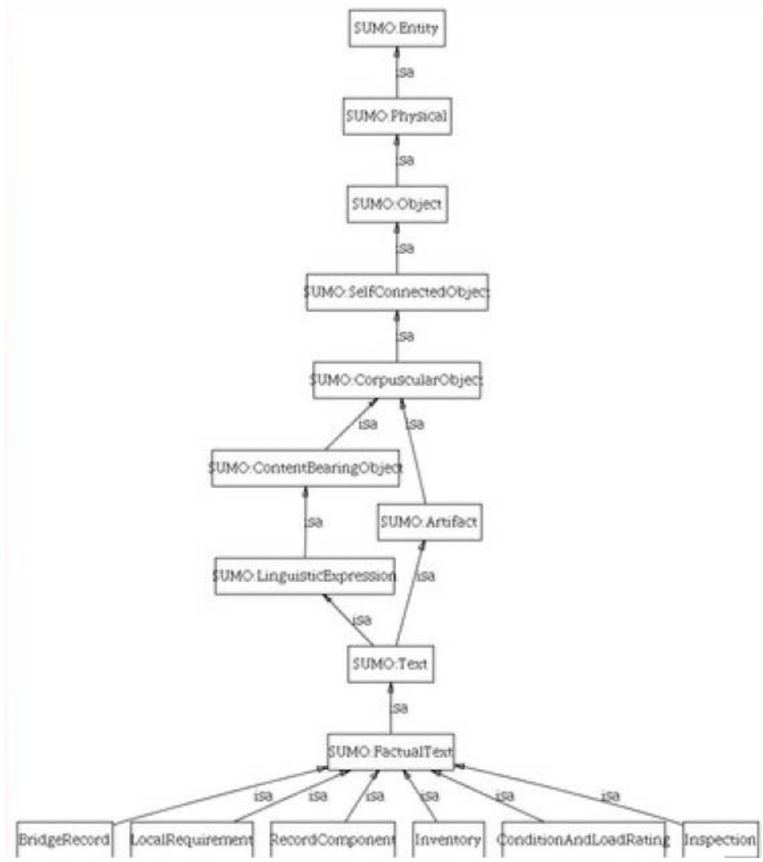

Figure 4.2: Integration of bridge_record ontology and SUMO

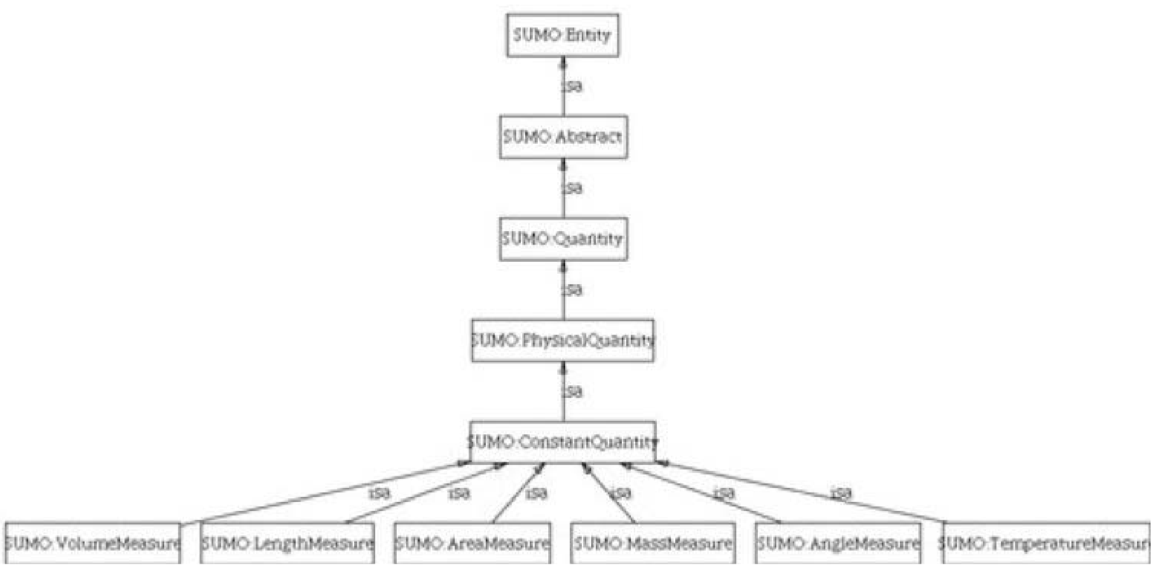

Figure 4.3: Classification of Units

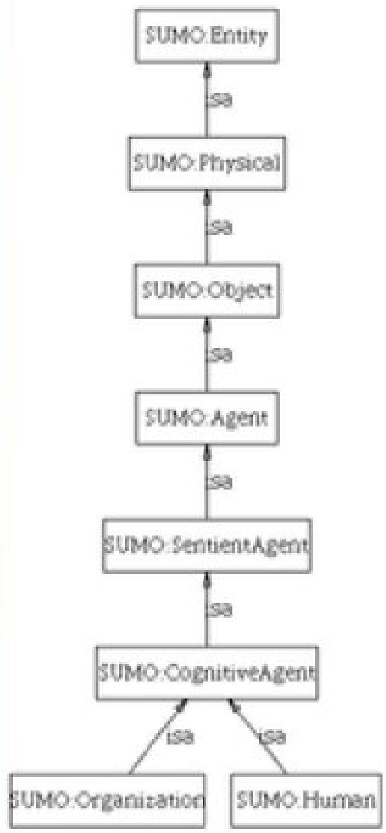

Figure 4.4: Representation of Agents

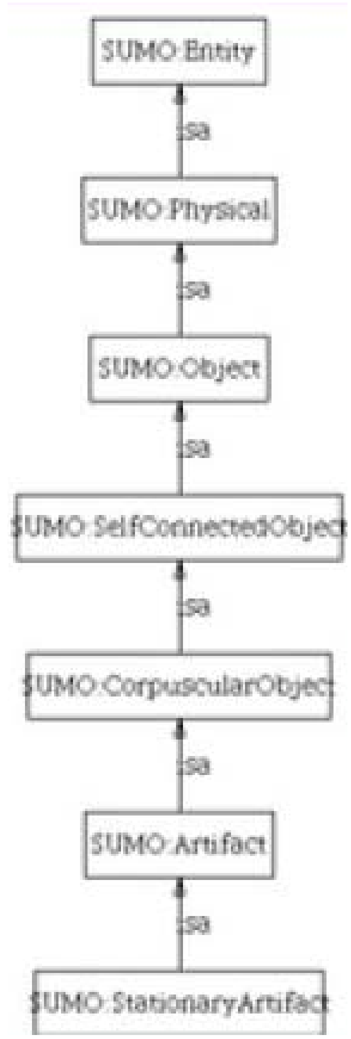

Figure 4.5: Representation of Physical Referentials

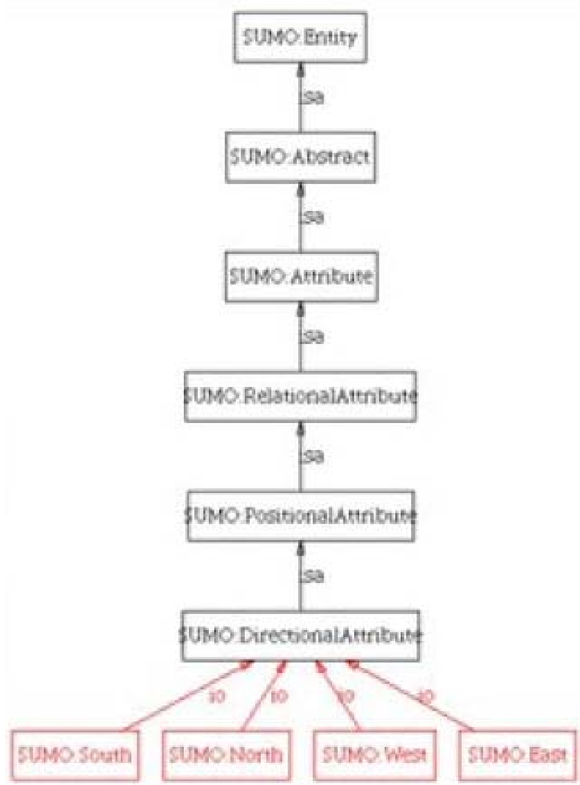

Figure 4.6: Representation of Directions

4.6.4 OpenCyc

OpenCyc is an open source version of the Cyc technology, which is the largest and most complete general knowledge base and reasoning engine with hundreds of thousands of concepts and millions of assertions (www.opencyc.org). OpenCyc 1.0 contains 6,000 concepts and 60,000 assertions that form relationships that define, interrelate, and restrict the concepts. OpenCyc 1.0 is written in CycL, which is a language that uses logic to avoid ambiguity in the expression of relationships between concepts. In theory, integrating the bridge ontology with OpenCyc is a reasonably attainable goal because version 0.7.8b is written in OWL and available for download at www.opencyc.org. However, before carrying out the integration there should be a detailed evaluation to determine if OpenCyc is the best suited platform to work with.

Such factors as OpenCyc's level of detail and the applications that will employ the bridge ontology should be considered before taking on the task of integration. Below is a figure taken from the supporting documentation of OpenCyc (www.opencyc.org). This figure illustrates that the bridge ontology would integrate well with the OpenCyc scheme. There would be integration in human activities under transportation and logistics; the bridge ontology could also be integrated under Physical Stuff & Objects. These are just two examples of areas of the OpenCyc ontology where the bridge ontology may be integrated.

According to the information in the OpenCyc web site, version 0.7.8b is over 700MB in size and takes approximately nine hours to load into Protege (platform used in the development of the bridge ontology). Given the difficulties inherent to working with such a large file and such a large ontology is was decided that the use of SUMO would be preferable.

4.6.5 DOLCE

http://www.loa-cnr.it/Papers/odbase71CR.pdf

http://www.aifb.uni-karlsruhe.de/WBS/phi/resources/publications/SWIntO.pdf

DOLCE (Descriptive Ontology for Linguistic and Cognitive Engineering) is another foundational or upper level ontology. Its base distinction separates entities into two categories: Endurants and Perdurants. Endurants are physical objects or substances, whereas perdurants are considered as events or processes fundamental relationship between endurants and perdurants is participation. An endurant passes time by participating in a number of different perdurants. Consider a track star running in a race. The track star would be the endurant. The race is a perdurant or an event in time.

While DOLCE excels in its reference axiomatization, it does not maintain an extensive and detailed taxonomy like that of SUMO. This gives that impression that DOLCE could be a good ontology to use as a starting point, but because its concepts are so abstract, it would need a lot more development on its taxonomy. Its implementation would require significantly more work compared with other ontologies available for integration.

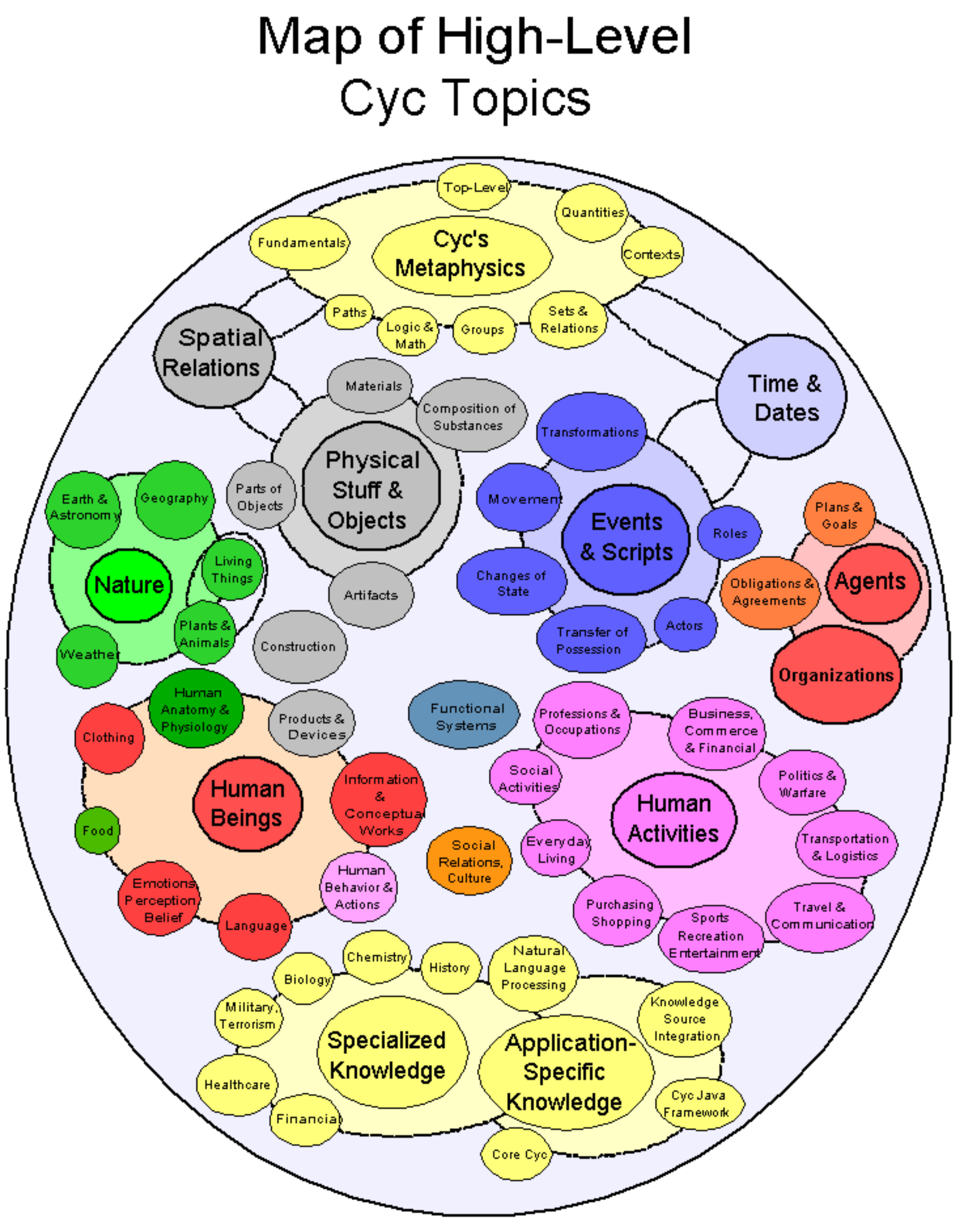

Figure 4.7: Cyc Topics

4.6.6 GML

The Geography Markup Language (GML) is used to represent geographical data in the form of text. It is written in XML-Schema for the modeling, transport and storage of geographic information. It has many different objects for describing geography, such as coordinate reference systems, geometry, topology, time, and units of measure. GML models the world as a set of features, where a feature is a real world entity existing in space and time. A feature collection, which could also be a feature itself, is a collection of features. A city would be an example; a city is a feature that would contain other features such as roads, rivers and buildings. Below is an image depicting the abstract feature model used by the Open GIS Consortium:

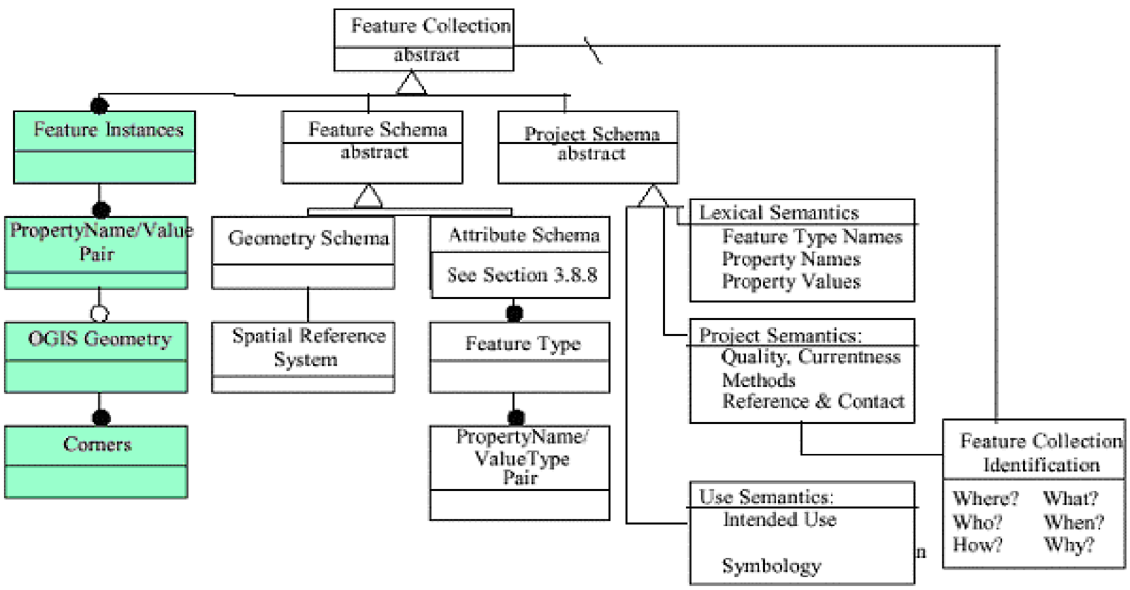

Figure 4.8: Abstract Feature Model as Described by the Open GIS Consortium (taken from the OGC Recommendation Paper).

The figure above helps visualize the anatomy of a feature collection.

The coordinate reference system would be of particular interest to integrate with the bridge ontology as a means of representing the location of bridges and the dimensions of beams and other materials associated with bridges.

Because the bridge ontology is written in OWL and GML is written in XML-Schema, integration between the two would be difficult. Currently, there is no OWL version of GML available, so one would have to look for tools to convert XML-Schema to OWL in order to make use of GML with the bridge ontology. Even though such a translation is feasible it would require a significant amount of conformance testing and debugging, and future improvements and modifications to GML would necessitate repeating the process. In this respect it was deemed preferable to use GML as a model to develop an extension to the bridge domain ontology.

4.6.7 Time and Time Zones

As stated before the bridge ontology relies on definitions included in SUMO, which is very complete. In this respect, it is preferable to rely on the concept definitions in SUMO, creating expansions to them if specific needs require it. In case a more robust implementation of this domain is required the Time ontology (Hobbs and Pan, 2005) was identified as a very well suited resource to complement the capabilities of SUMO.

4.6.8 Units

This is area in which the SUMO ontology can be greatly improved. Some suggestions for classes to improve the SUMO implementation include *Kilogram, Slug, Kilometer, Angstron, ForceMeasurement* (Newton, Pound-force), *PressureMeasurement* (Pascal, KSI), *EnergyMeasurement* (Joule, BTU), *LuminousMeasurement* (Candela), *SubstanceMeasurement* (Mole), *CurrentMeasurement* (Ampere), and conversion factors/relations for all these units.

EngMath (set of Ontolingua ontologies) (Gruber and Olsen, 1994) is a good alternative for an improved implementation of the units domain. However, EngMath is written in KIF, which is different from the platform used to develop the bridge ontology. As in the case of GML the difference in platform presents a significant challenge, and the effort of a manual translation was outside the scope of this research project. Another advantage of the The EngMath ontology is that it would also encompass the money domain which is important to describe cost of bridge projects, budgets, and cost of repairs.

4.6.9 Materials

An ontology to describe concepts in this domain was necessary to represent the properties of different materials used in bridge construction and repair, such as steel and concrete. In general, resources for representing the materials domain are sparse, an implementation required developing an ontology to significantly enhance the base provided by SUMO. Part of an ontology previously developed for a different research project (Kritikos et. al, 2006) was used.

4.7 Conceptualization

As described in Section 4.3 of this report one of the most difficult challenges in developing an ontology to describe concepts of a given domain is that in essence the designer must deal with two conflicting objectives. In order to make the project manageable it is essential to establish a well-defined scope for the domain of the ontology and to focus on describing knowledge within that domain. The main problem of that approach is that all knowledge is interrelated and it is impossible to isolate concepts within a domain from other related knowledge outside of the domain. For example, one of the properties of a bridge is its cost. Although in the Bridge ontology cost is a well-defined property of a bridge, knowledge about currency and its fluctuations with respect to time are essential to give a meaningful context to cost.

A cost of 50 million must be associated with a currency, say dollars, and even then it is relevant to know how 50 million dollars at the time the bridge was built relate to the present value of the dollar. The cost may reference the bridge projected cost, the actual cost of construction, or its replacement cost. As this simple example illustrates a general knowledge base is essential to describe concepts within a domain, in spite of the fact that the ontology is being developed to have a limited scope. In the case of the bridge ontology the general knowledge base was obtained by importing the SUMO ontology. This is illustrated in Fig. 9. The *bridge_record* and *bridge_parts* ontologies were developed to provide greater granularity in the domain of bridges and linked to one another and to the SUMO ontology (Fig. 9 and Fig. 10). This general structure also allows the future expansion and improvement of the ontology by linking domain-specific ontologies to provide greater granularity in other sub-domains if needed.

The *bridge_record* ontology is integrated with the SUMO ontology under the class *SUMO:FactualText* which includes sub-classes such as *Inspection*, *BridgeRecord*, and *Inventory* (Fig. 16). Closer integration among the SUMO, *bridge_parts*, and *bridge_record* ontologies can be achieved by establishing other relationships between specific classes of each ontology. For example, the SUMO class *SUMO:StationaryArtifact* is intended for artifacts that have fixed spatial location. It is appropriate to define a bridge as a sub-class of *SUMO:Stationary Artifact*. Establishing this particular relationship was not essential for the scope of this project, but it is important to note that closer integration among the classes in the ontologies would improve the ability to find specific information.

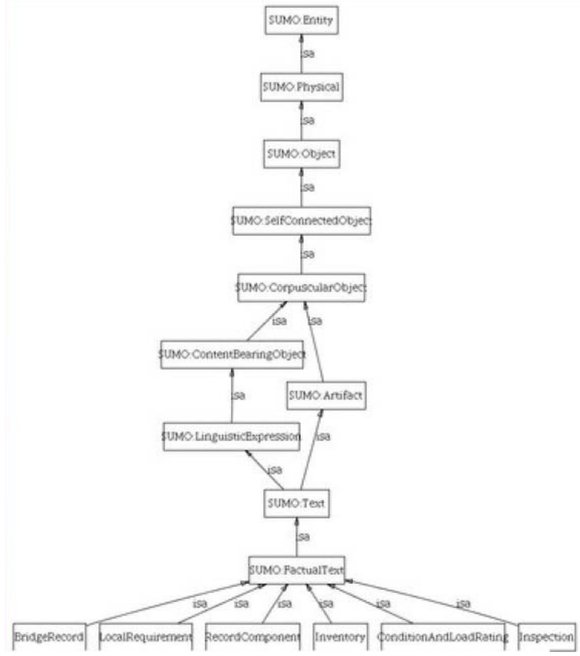

Figure 4.9: Integration of the bridge_record and SUMO ontologies

4.7.1 Class and Property Descriptions

This section describes a few of the elements from the bridge ontology. A full representation of the ontolgy is presented in the form of an XML Schema in Appendix A of this report. An html representation of the ontology can be found at http://neespop.ceae.ku.edu/downloads/Onto/. The *bridge*, *bridge_parts*, and *bridge_record* ontologies were created using the Protege tool. The ontologies are stored in an OWL format file, which can be accessed with the Protege tool.

The central class for this ontological investigation was designated *bridge*, which is an instance of the class *owl:thing.* It is described as a structure, including its supports, erected over a depression or an obstruction, such as water, highway, or railway. In order to be considered a bridge a structure has to have a track or passageway for carrying traffic or other moving loads, an opening of more than 20 feet (6.1 meters). The opening of a bridge must be measured along the center of the roadway, between undercopings of abutments, spring lines of arches, or extreme ends of openings for multiple boxes. It may also include multiple pipes, where the clear distance between openings is less than half of the smaller contiguous opening. The class *bridge* was created with the following properties:

Slot(hasActualTotalCost)

Slot(hasAssistantChiefEngineer)

Slot(hasAuxiliaryDocumentation)

Slot(hasBridgeApproachAlignment)

Slot(hasChiefEngineer)

Slot(hasConstructionEngineer)

Slot(hasConsultingEngineer)

Slot(hasCounty)

Slot(hasDeadLoad)

Slot(hasDetourLength)

Slot(hasEstimatedTotalCost)

Slot(hasGeographicLocation)

Slot(hasHighwayAgencyDistrict)

Slot(hasHistory)

Slot(hasLandCost)

Slot(hasLength)

Slot(hasLiveLoad)

Slot(hasMedianType)

Slot(hasMember)

Slot(hasNumberOfLanesUnder)

Slot(hasRise)

Slot(hasRoadwayWidth)

Slot(hasSite)

Slot(hasSpan)

Slot(hasSpanOver)

Slot(hasState)

Slot(hasStructureNumber)

Slot(hasTollStatus)

Slot(hasType)

Slot(hasWeight)

Slot(isArchitectedBy)

Slot(isDesignedBy)

Slot(isFlared)

Slot(isInNationalNetworkForTrucks)

Slot(isMadeOf)

Slot(isMaintainedBy)

Slot(isOwnedBy)

Slot(isReinforcedBy)

Slot(isUsedFor)

Slot(wasCommencedIn)

Slot(wasCompletedIn)

Slot(wasConstructedBy)

Slot(wasDedicatedIn)

Slot(wasDemolishedOn)

Slot(wasRetiredIn)

Note that this definition of "bridge" is appropriate for those of interest to departments of transportation, but is not sufficiently general to include such structures as footbridges on walking trails.

Also note that the description includes such elements as "isOwnedBy" and "IsMaintainedBy" which address the management of bridges and not simply their structural characteristics.

A relation "isMadeOf" holds between a bridge and multiple materials, where a material is an owl:thing which may be: Aluminum, Concrete, Fiber Reinforced Polymer, Iron, Masonry, Soil, Steel, Stone, or Timber (which is the same as Wood). In addition to bridges, there are other classes that may be part of the "isMadeOf" relationship with some of these materials. These include Members, AuxiliaryComponents and ReinforcementConfigurations.

Materials also may have finer descriptions, such as "*Concrete*", which is an *owl:Material*, but could be "*Reinforced*" or "*Unreinforced*", with subtypes of "*Reinforced*" "*Concrete*" including: "*NonPrestressed*", "*PostTensioned*", and "*Prestressed*".

Properties of the class "*Materials*" include such things as whether the material "*IsOrthotropic*" described as specifying whether "The material is isotropic or orthotropic". Other materials have properties such as "*isCast*", "*isWrought*", "*hasPlaceOfCast*", "*hasNumberOfLeaves*",or "*isHeatTreated*".

Due to the manner in which information is related within the ontology it is possible to have one-to-many relationships between classes and sub-classes. For instance, *bridge* may have multiple members, where a "*Member*" is an *owl:Thing*. *Members* maybe be *Substructure* or *Superstructure*. Within the *Superstructure*, we find such refinements as: *Beam*, *Brace*, *Cable*, *Curb*, *Dec*, *Diaphragm*, *Frame*, *Girder*, *Rod*, *Safety*, *Sidewalk*, *Slab*, *Stay*, *Stringer*, *Tower*, or *Truss*. A *Frame*, for example, is equivalent to a *Bent* in the Bridge ontology, and may appear as a component of the *Substructure* or the *Superstructure*. In turn, we find refinements of the *Bent* including *PileBent* and *TrestleBent*, while refinements of the *Frame* may also include *Cross* and *Sway*. The properties of a *Sway:Frame:Superstructure:Member:Bridge* object include:

Slot(hasAuxiliaryDocumentation)

Slot(hasHeight)

Slot(hasManufacturer)

Slot(hasMember)

Slot(hasOrganizationalPattern)

Slot(hasRise)

Slot(hasShape)

Slot(hasStrength)

Slot(hasThickness)

Slot(hasWeight)

Slot(hasWidth)

Slot(isMadeOf)

Slot(isReinforcedBy)

The Deck:Superstructure:Member:Bridge object has the property hasWearingSurface. Exploring WearingSurfaces in the Protege toolwe would find that it is an owl:thing with subdivisions including: Bituminous, EpoxyOverlay, Gravel, IntegralConcrete, LatexConcrete, LowSlumpConcrete, or MonolithicConcrete.

Note that this section is merely intended to present a general overview of components and properties expressible within the Bridge ontology. The Bridge ontology is sufficiently complex that the description presented in this section provides a very limited view. Careful understanding of the structures describable would require working within the Protege tool or careful examination of the complete of classes and properties presented in Appendix A or on the web at http://neespop.ceae.ku.edu/downloads/Onto/.

4.8 Implementation

After the scope of the bridge ontology was defined, supporting domains were identified. These supporting domains consisted of areas (e.g. units of measure, coordinates) in which existing ontologies could be adopted with minor modifications in order to avoid duplicity of efforts.

The general structure of the bridge ontology relies on three main sub-ontologies and a series of supporting ontologies to describe related sub-domain. SUMO is used as the undelying layer to describe general concepts and many related sub-domains.

The implementation of SUMO was complemented with two different ontologies designated *bridge_record* and *bridge_parts,* each created in a separate OWL file. This type of structure allows other developers to use either the *bridge_parts* or *bridge_record* ontologies for a different operational area, or to use the representation of a bridge record with different metadata to describe the parts of the bridge. Classes and properties in these two ontologies were created based on the knowledge acquired from the resources described in previous sections of this chapter. Finally, the existing ontologies needed to describe supporting sub-domains (for example the Dublin Core) to a greater degree of granularity were integrated with the *bridge* ontology.

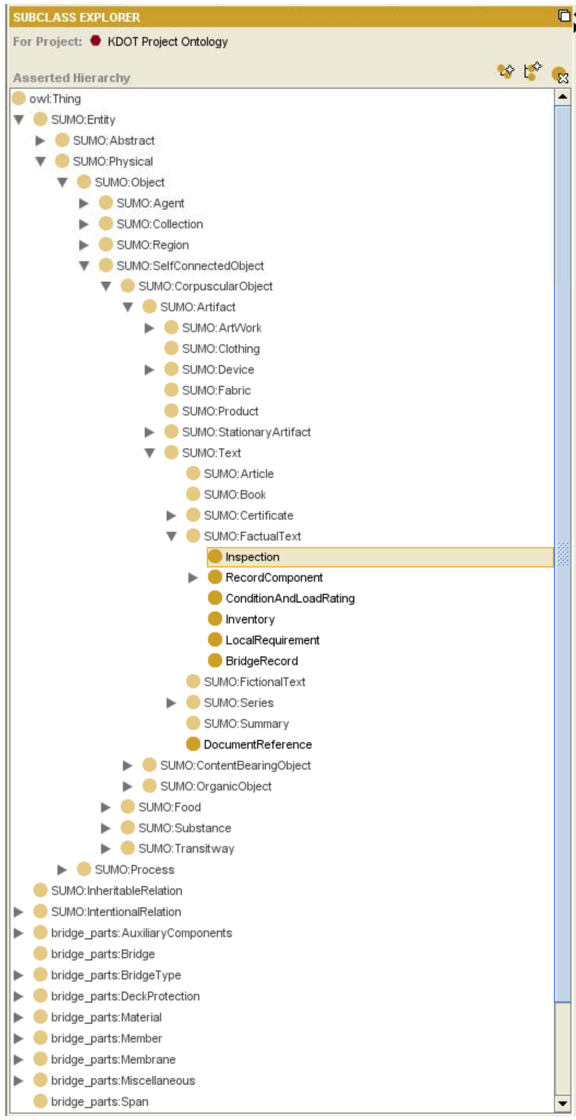

Figure 4.10: Structure of the Bridge Ontology Displayed in Protégé. The highlighted class (SUMO:FactualText) is one of the locations where SUMO and bridge_record are integrated.

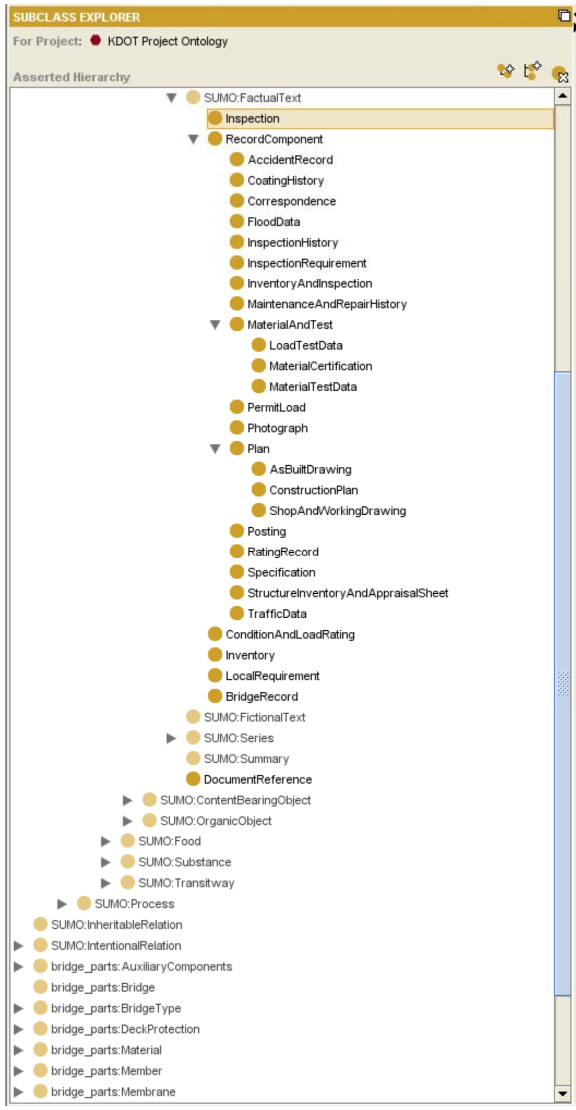

Figure 4.11: Structure of the bridge_record ontology

4.8.1 Implementation of the Dublin Core

One of main advantages of the Dublin Core ontology for describing files is that it has already been converted to the OWL format by the developers of Protégé. Consequently all that was needed to implement the use of the DCMI was to import the file into bridge ontology and to map the concepts to similar concepts in the various other components of the bridge ontology.

4.8.2 Implementing Modularity

As described in the previous sections the bridge ontology was developed by integrating several different sub-ontologies to cover specific domains and a general knowledge ontology (SUMO) to provide a knowledge base. Integrating several modules presents the advantage that it allows leveraging existing work to suit specific needs. A similar structure could be used to facilitate management of knowledge in specific areas without the need to re-engineer the entire ontology. What would be required is to develop sub-ontologies for specif sub-domains and attach whatever modules are considered necessary.

4.9 Maintenance

The modularity described earlier allows for easy maintenance of the entire ontology. If extensive changes need to be made to the SUMO portion of the ontology, such as if a new version of the SUMO were released, there is only one file to be modified or replaced. Also, because the data files will import the SUMO ontology OWL file, changes made to this file will be seen throughout all of the data files. This means that as long as someone is maintaining the SUMO ontology OWL file, everyone using this ontology can always have the most up to date version of the ontology.

The main drawback of this type of structure is that because it relies on multiple ontologies being integrated into one, changes in the sub-ontologies may lead to conflicts in the relationships across domains.

CHAPTER 5 - ASSESSMENT

This section is separated into two sub-sections: Use Cases and Proof of Concepts. In each case these represent potential applications or data stores which could leverage an ontological framework and its inferences to provide more or more relevant data. Since the purpose of this project was exploratory rather than implementation, such potential applications were considered in an abstract fashion and the use cases and proof of concepts considered were gedanken experiments used to assess the ability of the ontology to represent the essential data and support the desired inferences. With sufficient resources, concrete realization of one or more of these exercises would provide a more rigorous test of the ontology and the practicality of a given application. Absent such resources, these gedanken experiments provide some assessment of the completeness and suitability of the ontology. Additionally, they may function as initial "paper prototypes" of possible systems which can function as rough schematics for later implementations or can suggest directions for alternative or more extended applications of transportation ontologies to be used in creating systems based on integrating information from multiple sources.

Use case is a term borrowed from software engineering which means a scenario of interaction between a user and a system which exercises some (key) system functions. The research group explicitly chose this terminology in an attempt to focus discussions of possible applications of a transportation ontology. In many respects, this was the most challenging aspect of the project – attempting to envision uses of semantic technology which thus far are only beginning to migrate from restricted domains in research labs. In particular, knowledgeable users of traditional information systems appear to have “trained themselves” to avoid asking systems for information beyond the system's capacity. This doesn't appear to be a conscious constraint, but rather an unconscious pruning of queries for a system, focusing on those most likely to get results. In a practical sense, users ought not waste time querying a system for information which is not in it and could not possibly be derived from what is explicitly stored there. The combination of ontologies, inference engines and multiple data stores dramatically expand what is possible to derive from the explicitly stored data.

The use cases which were developed during the research effort are considered in the following sections, some at greater length than others. The benefit of treating these scenarios as use cases was to bring hypothetical applications into a more concrete form with considerations of user and system interactions and the necessary inputs and possible outputs. For some participants, use cases were characterized as “a detailed description of a single activity (in a business process)” with the intent that activities which previously had required multiple sources of data synthesized by a knowledge worker might be (at least partially) automated through the combination of data, ontology and inference engine.

5.1 Hypothetical Questions

A first step in evaluating the potential utility of the bridge ontology was to consider hypothetical questions which DOT knowledge workers or their constituencies might wish answered. There were a number of constraints intended for these inquiries: first, that the information required to answer the question actually be available in some combination of information resources; second, that the question be sufficiently complex, interesting or innovative that it requires the use of information from more than one source; third, that the cost of answering the question with current resources (a manual search by a human agent) was prohibitively expensive; and fourth, that there is some apparent value in answering such a question. The following is a list of such questions with little critical analysis – more the result of brainstorming than analysis, with the goal being to inspire or list several potential questions, some of which would be examined in greater detail.

- Within the bridge maintenance model, detailed information regarding the bridge designer, construction contractor, and construction materials aren't incorporated, that that information should be available in other data stores accessible within KDOT. A query that would link one or more of these concepts could meet our criteria.
    - Suppose a problem was found with the some specific materials in a specific bridge:
        - Query: What other bridges were made (or repaired, or modified) with similar materials from the same supplier during the same time frame?
- In a homeland security context, bridges are potentially valuable and vulnerable elements of the infrastructure. Suppose a threat is received threatening the destruction (bombing) of a bridge:
    - Query: Which bridges are vulnerable to the threatened attack? (Based on structure, materials, condition, etc.)
    - Query: Which bridges pose the greatest risk? (Based on traffic patterns and nature, utilization, and costs of alternative routes.)

- New technology has enabled a sensor array which can potentially contribute increased safety and reduced costs for bridge operation (perhaps based on traffic, weather, bridge condition ...).
    - Query: What are likely candidate bridges for installing such sensor arrays?
        - Based on cost-benefit analysis for the specific bridge?
        - Based on suitability for the installation? (Perhaps there are specific requirements in terms of bridge structure, design, materials, etc.)

- In a limited sample, a research has observed a correlation between the quantity of commentary in bridge inspection records and increased risks and costs associated with the bridges.
    - Query: What are all the bridges where there is an unusually large amount of commentary in bridge inspection records?
    - Query: What other factors (if any) do these bridges share?
    - Query: What bridges have an unusually high quantity of emails in which they are mentioned? (Perhaps there is a similar correlation?)
- A common approach in data entry on a particular bridge data system involves copy/pasting from similar records and then modifying the new entry. A common error involves failure to completely modify the new entry after copy/pasting so some (incorrect) residue from the original bridge record persists?
    - Query: How do we automate recognition of such inconsistent records?

- A bridge data system incorporates a free text field of somewhat limited size. Data is entered into this field by a wide variety of field personnel.
    - Query: How could we automate recognition of inconsistent abbreviations in the free text field?
- In the interest of constructing more economical bridges:
    - Query: What sort of bridge deck has been the most economical over the past X years per traffic volume?
        - This query requires automatically finding and adjusting building and maintenance costs (over a significant period of years) to some normalized value; similarly the costs would need to be adjust based on different spans and other factors which would affect the costs associated with different styles of decks. Both demographic and economic information is needed in addition to more specific bridge and traffic related data.
    - Similar queries might be asked of virtually any bridge feature where alternatives might have a significant impact on costs or durability or...

The following list doesn't contain specific hypothetical questions but general issues which might inspire questions with the desired attributes:

- preserve aging structures
    - would require information regarding structures, the effects of aging, and alternative repair/maintenance techniques (Do some techniques work better under certain conditions or in conjunction with certain bridge attributes?)

- cost effective public safety and risk reduction
  - combining bridge information, accident data, costs of safety measures and accident damages ...
- user convenience and road work
  - combine local events schedules with maintenance requirements and scheduling to minimize impact of roadwork?

Another (untested) approach to generating hypothetical problems and applications for semantic data was to examine query logs against various data stores to determine what queries are made but fail and are then abandoned as the user becomes convinced the current system can't actually answer the query.

5.2 Use Cases

A few hypothetical questions were considered in more detail. These are discussed in this section.

5.2.1 Bridge Connection Photo

Suppose we have a bridge inspection record containing a photo and identify a defective connection with some photographic evidence. Our data store for bridge inspections includes photos from many other bridge inspections. How would we find pictures of (all) similar connections in other bridges? Perhaps to search for similar defective components, or maybe to validate the photographic evidence. How many connections like this are out there? (with or without photos?) How recently have they been inspected? Perhaps the risk as a result of the defective connection is significant and an estimate is needed of the costs of additional inspections of similar connections.

5.2.2 John Smith

Among KDOT employees there are (and have been) several different individuals named *John Smith.* Suppose we are interested in any documents authored by the particular John Smith who designed the XXYYZ bridge. In our search we need to avoid the glut of documents authored by all the *John Smith* employees other than this particular bridge designer. Similarly, it is important to recognize documents authored by this individual even though they aren't clearly labeled that way. Perhaps they are labeled according to a role (Chief Engineer on a particular project?) or a department or a team during a period when this particular *John Smith* would have been an important contributor to any document from that office or team. Perhaps some details of John Smith's records have changed – maybe there are some documents from when John Smith was an employee, and others from when he was a contractor. Maybe John's name has changed for some reason during his tenure at KDOT? Maybe through some quirk of hiring, leaving, re-hiring John has more than one "unique" identifier associated with documents he has authored?

Perhaps a customer has a document authored by a *John Smith* and wants documents authored by that individual, but we don't know which john smith was the author. As a specific scenario, suppose the goal is to find all the maintenance records for bridges such that: The same John Smith was part of the design team and John Smith was a senior engineer on the project.

The current approach would require performing a syntactic/keyword search in the document database using words that describe the situation, perhaps "John Smith maintenance report design team senior engineer". Problems include issues such as: the difficulty identifying the specific John Smith; whether John Smith was part of the design team, or the design team was just mentioned in the document; is the document in question a maintenance record, or does it just refer to such record? Was John Smith the senior engineer or was someone else listed as the senior engineer in a given document?

Again, metadata annotation can enable more specific reasoning: Perhaps the customer's document is annotated with John Smith's unique ID, or perhaps various properties of John Smith mentioned in the document or included in the metadata will enable the correct identification. Perhaps the document is dated from a period when only one specific john smith was employed. The reasoning engine might be able to recognize statements in a document specifying the senior engineer or the design team and eliminate records where John Smith is not listed. Perhaps a contractor is responsible for the design or maintenance of the bridge, and the reasoning engine can check whether John Smith is a designer or senior engineer at that company. Perhaps another john smith can be eliminated because his engineering degree wasn't awarded until after the bridge's construction date. Perhaps the reasoning engine has access to the fact that "John Smith" is the main designer for the organization XYZ, and can infer that documents authored by the "main designer of XYZ" should be included in the search results.

5.2.3 Which Bridge?

A customer contacts KDOT with an issue regarding a specific bridge, however the customer identifies the bridge in what to them is a clear and unique reference, but which is completely unfamiliar to the KDOT employee. The KDOT needs to access information stored about the bridge, but first has to determine *which bridge* the customer is referring to.

The current approach entails entering the information provided by the customer and performing a syntactic search, but the information might be the “two-span bridge at I-70 mile X” or the “pre-stressed concrete bridge Y miles west of Lawrence” or the “Farmer's Turnpike bridge” or ....

Problems in this scenario include issues such as: the representation of distances and locations of bridges used in the database; different ways to describe the properties of a bridge; string based descriptions without standardized semantics; regional or historical names that do not correspond to the official naming convention; and so on.

Semantic/metadata annotation in the text enables reasoning, rather than a simple keyword search. Distances are instances of a length measurement, which can be converted and compared for match based on the unit being used. Concrete is a subclass of materials, so it inherits a variety of properties which can be used for further reasoning. An inference engine could combine a relative location “Y miles west of Lawrence” with information about the location of Lawrence and a standard scheme for identify positions on I-70 to determine that Y miles west of Lawrence corresponds to “I-70 mile X”.

5.3 Proof of Concepts

Another approach applied in evaluating the utility of the ontology was to examine various data sources and determine whether the ontology was: (1) complete enough to represent the particular data or (2) complete enough to infer important relations not explicitly stated.

5.3.1 KDOT Projects Portal

One useful source for test cases of information to represent to explore the completeness of the ontology was the KDOT Project Information Portal, accessible via the web at http://www.ksdot.org/projects/search.asp. Queries were run against this data source for projects related to bridges and then an attempt was made to represent the information regarding that bridge using the concepts and relations provided by the bridge ontology. The following subsection provides an example of the ontology terms used to represent a description of a bridge extracted from one of the project records.

5.3.1.1 KDOT Project Description

The following statement provides an example of mapping a bridge description from KDOT's Project Information Portals to a formal representation in terms (concepts and relations) defined in the ontology. A bridge from one project was described as: "Lightning Creek bridge (32) 5.7 miles west of K-7".

"Lightning Creek bridge" ➔ a string for #bridgeName (Inventory)

"Lightning Creek" ➔ string for #featuresIntersected (Inventory)

➔ the specific #featuresIntersected was marked as an instance of MILO::Creek

"32" ➔ numeric value for #structureNumber

"5.7 miles west of K-7" ➔ a BridgeLocation with #referential (StationaryArtifact)

➔ K-7 (the StationaryArtifact) was marked as an instance of

SUMO::StationaryArtifact,

SUMO::Roadway, or an even more specific concept using MILO

rather the SUMO

➔ the BridgeLocation has #distanceToReferential (SUMO::LengthMeasure)

➔ 5.7 is an instance of SUMO::MileMeasurement.

➔ BridgeLocation has #directionToReferential, which refers to a SUMO::DirectionalAttribute

➔ west: SUMO has instances for each of the four main directions

5.3.2 Other data sources

Other data sources were examined in the interest of creating test cases. These included accident reports, “city connections” information available online, and descriptions of bridges drawn from newspaper articles again, available on line. In particular, we had hoped to identify descriptions of specific bridges in “local” resources such as the website or newspaper (with records of articles accessible online) with the “official” KDOT descriptions embedded in the project portal. With appropriate test cases, this would have corresponded extremely well to the “Which Bridge?” use case described earlier, given the assumptions that a newspaper description would be representative of a KDOT customer's “local” description of a bridge, while the KDOT project portal description could serve as the official description.

Unfortunately, we didn't identify use cases which required interesting semantic inferences. Either the connections were obvious or we were unable to identify corresponding bridges from the two sources or the connection was simply an arbitrary difference in naming without additional information which would have permitted a semantically-based inference of the bridge identity. Part of the problem was the relatively incomplete nature of the data sources. The project portal only mentioned bridges with (relatively) current projects. Newspapers articles rarely mentioned bridges at all or with sufficient descriptive information to identify them with one of the bridges from the project portal. The approach provided the potential for interesting test cases, but our data sources didn't contain enough overlap. If there were some way to collect the actual descriptions used by customer's in queries to KDOT along with the corresponding internal description when the KDOT employee is able to make the identification, then this would be a more useful test. Such data collection was outside the scope of this project, however.

In the course of examining the bridge descriptions drawn from KDOT's project portal, it became clear that the description field was free text and that there was a wide variety of approaches to describing bridges using that field. In general, a unique id was present in the description which should resolve identity for anyone with access to a database using that id as a key. An unexpected complication was observed when one of the fields included more than one of the identifiers. This highlighted a shortcoming of the ontology – there was no provision for a “bridge” to be an aggregate system comprised of more than one component bridges. Another observation resulting from working with these descriptions was the significant frequency and variability in the use of abbreviations in the free text description field.

CHAPTER 6 - CONCLUSIONS

The key results of this work are identifying the proximity of semantic tools such as ontologies to practical applications in the transportation domain, the importance of combining and re-using ontologies, and the value of developing and applying engineering processes to manage the development of ontologies. In the course of this work, we identified a number of resources including existing ontologies, languages and standards for representing ontologies, and a variety of tools for working with these systems. Some of this work is directly related to and of obvious value for potential transportation applications of semantic knowledge. Creation of and adherence to standards that facilitate the combination and reuse of such resources is essential as part of any effort in the development of ontologies, tools, and applications.

The opportunities enabled by the semantic integration of rapidly expanding networked information resources are clear. In any domains with substantial stores of information which *can* be productively combined with other data, such combination is inevitable. The work required to support the integration will have to be done. The efficiency with which isolated information stores with limited metadata can be integrated through sufficiently general and applicable ontologies, will be a key element in determining the ultimate value such semantic integration will yield. Research and development which will facilitate such integration can only be beneficial in the long run. Two areas will contribute: research within a domain which brings parts of it toward formal ontological representation and identifies particular challenges, and development in theory, practice, and tools to enable the efficient creation, integration, and testing of ontologies. In particular, tools and practices addressing the combining and reuse of ontologies are both necessary and promising.

REFERENCES

AASHTOWare, 2005. Transportation Software Solutions [online]. Available from World Wide Web: (http://www.aashtoware.com/aashtoware/management/management.nsf/allpages/overview).

AASHTO Software Webpage. American Association of State Highway and Transportation Officials. Washington, DC. http://www.aashtoware.org. Accessed July 26, 2006.Acme Bungee Corporation, 2005. Thesaurus [online]. Available from World Wide Web: (http://www.slais.ubc.ca/courses/libr512/04-05-wt2/thesauri/Acme/topterm.htm).

About Bridges. Bridgeman, 2000. http://www.nireland.com/bridgeman. Accessed July 26, 2006.

Barker, R. and J. Puckett. *Design of Highway Bridges*. John Wiley & Sons, Inc., 1997.

Bechhofer, S., F. van Harmelen, J. Hendler, I. Horrocks, D. L. McGuinness, P. F. Patel-Schneider, and L A. Stein. Editors, Dean, M., and G. Schreiber. OWL Web Ontology Language: Reference. W3C, 2004. http://www.w3.org/TR/owl-ref. Accessed July 26, 2006.

Berners-Lee, T., Hendler, J., Lassila, O., 2001. The Semantic Web. *Scientific American*. May 2001.

BRASS Suite of Computer Programs Webpage. Wyoming State Government, 2005. http://www.dot.state.wy.us/Default.jsp?sCode=hwyov. Accessed July 26, 2006.

Bray, T. 2001. What is RDF? [online] Available from World Wide Web: (http://www.xml.com/pub/a/2001/01/24/rdf.html?page=1).

Bridge Design Manual – TexasDOT. Texas Department of Transportation, 2001. http://manuals.dot.state.tx.us/docs/colbridg/forms/des.pdf. Accessed July 26, 2006.

Bridge Inspection Manual – TexasDOT. Texas Department of Transportation, 2002. http://manuals.dot.state.tx.us/docs/colbridg/forms/ins.pdf. Accessed July 26, 2006.

Bridge UML Description. Cambridge Systematics, Inc., 2004. http://www.transxml.org/Bridge+Structures+Schema/Group+Documents/Downloads_GetFile.aspx?id=519. Accessed July 26, 2006.

Bridges and Tunnels of Allegheny County and Pittsburgh, PA. Bruce S. Cridlebaugh, 2004. http://pghbridges.com. Accessed July 26, 2006.

CDB Enterprises, Inc. Transportation Research Thesaurus. Transportation Research Board. http://ntl.bts.gov/trt/trt_entire.html. Accessed July 26, 2006Cerebra, 2005. The Inner Circle FAQs. Available from World Wide Web: (http://www.cerebra.com/products/faqs.html).

Cihon, R., 2003. Why Data? The Need to Consider Other Issues for GIS-T. [online] *Washington State DOT.* Available from World Wide Web: (http://www.gis-t.org/yr2003/gist2003sessions/Session412.ppt).

Corcho O, Fernández-López M, Gómez-Pérez A, López-Cima A., 2005. Building legal ontologies with METHONTOLOGY and WebODE. *Law and the Semantic Web*. *Legal Ontologies, Methodologies, Legal Information Retrieval, and Applications*. March 2005. Springer-Verlag, LNAI 3369.

Cycorp, Inc., 2006. Opencyc [online]. Available from World Wide Web: (http://www.opencyc.org/)

DCMI, 2005a. Dublin Core Metadata Initiative [online]. Available from World Wide Web: (http://dublincore.org/).

DCMI, 2005b. DCMI Metadata Terms [online]. Available from World Wide Web: (http://www.dublincore.org/documents/dcmi-terms/).

DCMI, 2005c. Dublin Core Projects – Alphabetical [online]. Available from World Wide Web: (http://www.dublincore.org/projects/).

Denny, M., 2004. Ontology Tools Survey, Revisited [online]. Available from World Wide Web: (http://www.xml.com/pub/a/2004/07/14/onto.html).

Ding, Y., and Foo, S. 2002. Ontology Research and Development: Part 1 - A Review of Ontology Generation. Available from World Wide Web: (http://www.ece.ucf.edu/~crcd/ml_courses/ml2/student_projects/crcd_5(ref)/Review%20of%20Ontology%20Generation.pdf).

Fernández, M., Blázquez, M., García-Pinar, J.M., Gómez-Pérez, A., 1998. Building Ontologies at the Knowledge Level using the Ontology Design Environment [online]. Available from the World Wide Web: (http://ksi.cpsc.ucalgary.ca/KAW/KAW98/blazquez/).

Fernández-López, M. Overview of Methodologies for Building Ontologies, in: IJCAI99 Workshop on Ontologies and Problem-Solving Methods: Lessons Learned and Future Trends, Stockholm, 1999.

Glossary of bridge terms. Ohio Department of Transportation. http://www.dot.state.oh.us/preventivemaintenance/Glossary/glossaryset.htm. Accessed July 26, 2006.

GML – The Geography Markup Language. Open Geospatial Consortium, Inc, 2004. http://www.opengis.net/gml. Accessed July 27, 2006.

Gruber, T., and Olsen, G. 1994. An Ontology for Engineering Mathematics [online]. Available from World Wide Web: (http://ksl.stanford.edu/knowledge-sharing/papers/engmath.html).

Hobbs, J.R., and Pan, F., 2005, “Time Ontology in OWL,” Eds. W3C, http://www.isi.edu/~pan/SWBP/time-ontology-note/time-ontology-note.html. Accessed July 27, 2006.

Final XML Format Recommendation for Bridges. Cambridge Systematics, Inc., 2002. http://www.transxml.org/Bridge+Structures+Schema/Group+Documents/Downloads_GetFile.aspx?id=300. Accessed July 26, 2006.

Herd, J., 2001. Resources for Taxonomy Creation and Content Management [online]. Available from World Wide Web: (http://www.loc.gov/flicc/wg/taxonomy.html).

IAI, 2004. IFCs/ifcXML Specifications [online]. Available from the World Wide Web: (http://www.iai-international.org/Model/IFCs(ifcXML)Specs.html).

Introduction to the RDF Model. XULPlanet.com, 2005. http://www.xulplanet.com/tutorials/mozsdk/rdfstart.php. Accessed July 26, 2006.

Kansas Highway Patrol Crash Logs. Kansas.gov, 2005. https://www.accesskansas.org/ssrv-khp-crashlogs/index.do. Accessed July 27, 2006.

KDOT Project Information Portal. Kansas Department of Transportation, 2004. http://www.ksdot.org/projects/search.asp. Accessed July 27, 2006.

Knowledge Zone. Stanford Medical Informatics, 2005. http://smi-protege.stanford.edu:8080/KnowledgeZone/index.html. Accessed July 26, 2006.

Kritikos, W., Sudre, G., Hanson, S., Matamoros, A., and Graham, S.K., Various Ontologies for Management of Data in the Engineering Domain, http://neespop.ceae.ku.edu/ontologies/kdot/, Accessed July 26, 2006.

Kritikos, W., Sudre, G., and Matamoros, A., "Semantic Web Approach to Manage Knowledge in the Earthquake Engineering Domain," *SM Report No. 87*, University of Kansas Center for Research, Inc., Lawrence, Kansas, July 2006.

Library of Congress Classification Outline, Class H – Social Sciences, Subclass HE – Transportation and Communications. The Library of Congress. http://lcweb.loc.gov/catdir/cpso/lcco/lcco_h.pdf. Accessed July 26, 2006.

List of OWL Ontologies Based on Norms. http://loki.cae.drexel.edu/~wbs/ontology/list.htm. Accessed July 27, 2006.

López, M. F., Gómez-Pérez, A., Sierra, J. P., and Sierra, A. P. 1999. Building a Chemical Ontology Using Methontology and the Ontology Design Environment. *IEEE Intelligent Systems* 14, 1 (Jan. 1999), 37-46.

Manual for Condition Evaluation of Bridges, Second Edition. AASHTO, 2000

Model Highway Data Dictionary Roadway Bridge Data Elements. AASHTO, 2003. http://tsims.aashtoware.org/ContentManagement/PageBody.asp?PAGE_ID=11. Accessed July 26, 2006.

Morrissey, M. How Bridges Work . HowStuffWorks, Inc., 2006. http://science.howstuffworks.com/bridge.htm. Accessed July 26, 2006.

National Bridge Inventory – Data Dictionary. Federal Highway Administration. http://massroads.com/nbiDesc.htm. Accessed July 26, 2006.

NCHRP 20-64, XML Schemas for Exchange of Transportation Data. Cambridge Systematics, Inc, 2004. http://www.transxml.org. Accessed July 26, 2006.NBI, 2001. Quick Facts about your National Bridge Inventory [online]. Available from World Wide Web: (http://www.nationalbridgeinventory.com/).

Niles, I., and Pease, A. 2001. Towards a Standard Upper Ontology. In Proceedings of the 2nd International Conference on Formal Ontology in Information Systems (FOIS-2001), Chris Welty and Barry Smith, eds, Ogunquit, Maine, October 17-19, 2001.

Noy, N., McGuiness, D., 2001. Ontology Development 101: A guide to creating your first ontology. *KSL Technical Report.* Standford University, 2001.

OWL, 2004. OWL Web Ontology Language: Reference [online]. Available from World Wide Web: (http://www.w3.org/TR/owl-ref/).

OWL, 2004b. OWL Web Ontology Language: Use Cases and Requirements [online]. Available from World Wide Web: (http://www.w3.org/TR/webont-req/).

PENNDOT LRFD and Engineering Programs: Program Support Site. Commonwealth of Pennsylvania, 2005. http://penndot.engrprograms.com/home. Accessed July 26, 2006.Razdow, A., 2005. Extending the Power of XML to the Engineering Enterprise: How XML Will Improve Product Development, Quality, Compliance and Integration [online]. Available from World Wide Web: (http://www.mathsoft.com/solutions/papers/2528.asp).

Pinto, H. S. and Peralta, D. N., 2003. Combining ontology engineering subprocesses to build a time ontology. In *Proceedings of the international Conference on Knowledge Capture* (Sanibel Island, FL, USA, October 23 - 25, 2003). K-CAP '03. ACM Press, New York, NY, 88-95.

Quick Facts about your National Bridge Inventory. NBI, 2000. http://www.nationalbridgeinventory.com. Accessed July 26, 2006.

RDF Schemas. Wikipedia, 2006. http://en.wikipedia.org/wiki/RDF_Schema. Accessed July 27, 2006.

Russomanno, D., Kothari, C., and Thomas, O. 2005. Building a Sensor Ontology: A Practical Approach Leveraging ISO and OGC Models,The 2005 International Conference on Artificial Intelligence, Las Vegas, NV.

Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges. U.S. Department of Transportation, 1995.

http://www.fhwa.dot.gov/BRIDGE/mtguide.pdf. Accessed July 26, 2006.

Roebling's Bridge Division. John Roebling's Son's Co. http://www.inventionfactory.com/history/RHAbridg. Accessed July 26, 2006.

Semy, S. K., Hetherington-Young, K. N., and Frey, S. E. Ontology Engineering: An Application Perspective. Unpublished research report. The MITRE Corporation, August, 2004 – mitre.org.

Shalloway, A., and Trott, J. R. 2002. Design Patterns Explained – A New Perspective on Object-Oriented Design. Addison-Wesley, Pearson Education.

Sujanani, A., Ray, P., Paramesh, N., and Bhar, R., 2005. The development of ontology driven ulti-agent systems: a case study in the financial services domain. In *Proceedings of the IEEE Eee05 international Workshop on Business Services Networks* (Hong Kong, March 29 - 29, 2005). ACM International Conference Proceeding Series, vol. 87. IEEE Press, Piscataway, NJ, 1-1.

Sudre ,Gustavo, Samuel Hanson, Adolfo Matamoros, and Steven K. Graham, Ontology Engineering for Management of Data in the Transportation Domain, National Transportation Research Board (TRB 86th Annual Meeting), January 21-25, 2007, Washington, D.C.

SUMO Ontology. http://ontology.teknowledge.com. Accessed July 26, 2006.

SUMO Ontology Browser.

http://sigma.ontologyportal.org:4010/sigma/Browse.jsp?kb=SUMO&lang=en. Accessed July 26, 2006.

Swoogle: Semantic Web Search. Swoogle, 2006. http://swoogle.umbc.edu. Accessed July 26, 2006.

The Lawrence Journal-World. The Lawrence Journal-World, 2006. http://ljworld.com. Accessed July 27, 2006.

The Protégé Ontology Editor and Knowledge Acquisition System. Stanford Medical Informatics, 2006. http://protege.stanford.edu. Accessed July 26, 2006.

Thompson, P. and Shepard, R. 2000. AASHTO Commonly-Recognized Bridge Elements - Successful Applications and Lessons Learned. Prepared for the National Workshop on Commonly Recognized Measures for Maintenance. June, 2000.

Time Ontology in OWL. J. R. Hobbs and F. Pan, Eds. W3C, 2005. http://www.isi.edu/~pan/SWBP/time-ontology-note/time-ontology-note.html. Accessed July 27, 2006.

Transportation Research Bureau, 2005. Transportation Research Thesaurus [online]. Available from World Wide Web: (http://ntl.bts.gov/trt/trt_entire.html).

TransXML, 2006. NCHRP 20-64, *XML Schemas for Exchange of Transportation Data [online]. Available from World Wide Web: (*http://www.transxml.org/*).*

TransXML, 2005. Bridge UML Description [online]. Available from World Wide Web: (http://www.transxml.org/Bridge+Structures+Schema/Group+Documents/Downloads_GetFile.aspx?id=519).

Warren, P. Knowledge Management and the Semantic Web: From Scenario to Technology. *IEEE Intelligent Systems*, vol. 21, no. 1, 2006, pp. 53–59.

Wikipedia, 2006. RDF Schemas. Available from World Wide Web: (http://en.wikipedia.org/wiki/RDF_Schema).

Willpower Information, 2006. Information management and consultants [online]. Available from World Wide Web: (http://www.willpower.demon.co.uk/).

Wisconsin County Highway Association Policy & Procedure Manual. Infrastructure Technology Institute, 2005.

http://www.iti.northwestern.edu/publications/fish/highway_manual.html. Accessed July 26, 2006.

XULPlanet, 2005. Introduction to the RDF Model. [online]. Available from World Wide Web: (http://www.xulplanet.com/tutorials/mozsdk/rdfstart.php).

APPENDIX A. OWL-FORMAT FILE DESCRIBING BRIDGE ONTOLOGY


```
<?xml version="1.0"?>
<rdf:RDF
  xmlns="http://neespop.ceae.ku.edu/ontologies/kdot/bridge_parts.owl#"
  xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
  xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
  xmlns:owl="http://www.w3.org/2002/07/owl#"
 xml:base="http://neespop.ceae.ku.edu/ontologies/kdot/bridge_parts.owl">
 <owl:Ontology rdf:about="">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >DublinCore wasn't imported using Protege's wizard because it was causing errors
with the OWL language validator. Still, the Protege validator thinks this is a OWL Full
ontology if DC is imported. Another validator
(http://phoebus.cs.man.ac.uk:9999/OWL/Validator), analyzes it as an OWL DL
ontology.</rdfs:comment>
 </owl:Ontology>
 <owl:Class rdf:ID="Concrete">
  <rdfs:subClassOf>
   <owl:Class rdf:ID="Material"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A mixture of aggregate, water, and a binder, usually portland cement, which hardens
to a stone-like mass.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="PedestrianScreen">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Protect pedestrians from the traffic.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:ID="Safety"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="DeckProtection">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Collection of materials to protect the bridge deck.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="Aluminum">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Silvery nonferrous metal found in the ore bauxite. It is used in making hard, light,
corrosion-resistant materials.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Material"/>
  </rdfs:subClassOf>
 </owl:Class>
```

```
 <owl:Class rdf:ID="Monolithic">
  <rdfs:subClassOf>
   <owl:Class rdf:ID="Connection"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="CartesianPoint">
  <owl:disjointWith>
   <owl:Class rdf:ID="GeographicCoordinate"/>
  </owl:disjointWith>
  <owl:disjointWith>
   <owl:Class rdf:ID="PossibleUnit"/>
  </owl:disjointWith>
  <owl:disjointWith>
   <owl:Class rdf:ID="StationReference"/>
  </owl:disjointWith>
  <owl:disjointWith>
   <owl:Class rdf:ID="OrganizationalPattern"/>
  </owl:disjointWith>
  <owl:disjointWith>
   <owl:Class rdf:ID="MeasuredUnit"/>
  </owl:disjointWith>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A point in a cartesian coordinate system (X, Y, and Z axis).</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:ID="Miscellaneous"/>
  </rdfs:subClassOf>
  <owl:disjointWith>
   <owl:Class rdf:ID="GeographicLocation"/>
  </owl:disjointWith>
 </owl:Class>
 <owl:Class rdf:ID="Suspender">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A wire cable, a metal rod or bar connecting to a catenary cable of a suspension
bridge at one end and the bridge floor system at the other, thus transferring loads from
the road to the main suspension members.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:ID="Superstructure"/>
  </rdfs:subClassOf>
  <owl:equivalentClass>
   <owl:Class rdf:ID="Hanger"/>
  </owl:equivalentClass>
 </owl:Class>
 <owl:Class rdf:ID="PotBearing">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Bearing made of high quality natural rubber (elastomer) is enclosed in a steel
pot.</rdfs:comment>
```

```
  <rdfs:subClassOf>
   <owl:Class rdf:ID="Bearing"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="Burr">
  <rdfs:subClassOf>
   <owl:Class rdf:ID="BridgeType"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Bridges inspired by the bridges built by Theodore Burr, who added arch segments to
a multiple kingpost truss to attain longer spans.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="SwayFrame">
  <rdfs:subClassOf>
   <owl:Class rdf:ID="Frame"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A complete panel or frame of sway bracing.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="OtherCoatedReinforcing">
  <owl:disjointWith>
   <owl:Class rdf:ID="InternallySealed"/>
  </owl:disjointWith>
  <owl:disjointWith>
   <owl:Class rdf:ID="GalvanizedReinforcing"/>
  </owl:disjointWith>
  <rdfs:subClassOf rdf:resource="#DeckProtection"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Any other types of coated reinforcements.</rdfs:comment>
  <owl:disjointWith>
   <owl:Class rdf:ID="CathodicProtection"/>
  </owl:disjointWith>
  <owl:disjointWith>
   <owl:Class rdf:ID="EpoxyCoatedReinforcing"/>
  </owl:disjointWith>
 </owl:Class>
 <owl:Class rdf:about="#Safety">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Collection of devices designed to prevent injury.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Superstructure"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="StayPlate">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A tie plate or diagonal brace to prevent movement.</rdfs:comment>
```

```
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Superstructure"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="Timber">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Wood suitable for building purposes.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Material"/>
  </rdfs:subClassOf>
  <owl:equivalentClass>
   <owl:Class rdf:ID="Wood"/>
  </owl:equivalentClass>
 </owl:Class>
 <owl:Class rdf:ID="Suspension">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A bridge in which the floor system is supported by catenary cables which are
supported upon towers and are anchored at their extreme ends.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:about="#BridgeType"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="NoiseWall">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Isolates bridge noise.</rdfs:comment>
  <rdfs:subClassOf rdf:resource="#Safety"/>
 </owl:Class>
 <owl:Class rdf:ID="Bituminous">
  <owl:disjointWith>
   <owl:Class rdf:ID="EpoxyOverlay"/>
  </owl:disjointWith>
  <owl:disjointWith>
   <owl:Class rdf:ID="MonolithicConcrete"/>
  </owl:disjointWith>
  <owl:disjointWith>
   <owl:Class rdf:ID="Gravel"/>
  </owl:disjointWith>
  <owl:disjointWith>
   <owl:Class rdf:ID="LowSlumpConcrete"/>
  </owl:disjointWith>
  <owl:disjointWith>
   <owl:Class rdf:ID="IntegralConcrete"/>
  </owl:disjointWith>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A soft coal that, when heated, yields considerable volatile matter.</rdfs:comment>
  <owl:disjointWith>
```

```
   <owl:Class rdf:ID="LatexConcrete"/>
  </owl:disjointWith>
  <rdfs:subClassOf>
   <owl:Class rdf:ID="WearingSurface"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="ElastomericPadBearing">
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Bearing"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Bearing pad made of flexible, low modulus material capable of expanding and
contracting and returning to original dimensions without fatigue.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="AuxiliaryComponents">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Other components of a bridge.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="StandardSteelShape">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Standard geometric shapes usually found in steel structures.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:ID="StandardShape"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:about="#Material">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Different materials of which the members of a birdge can be made.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="Rivet">
  <rdfs:subClassOf rdf:resource="#AuxiliaryComponents"/>
 </owl:Class>
 <owl:Class rdf:ID="Fence">
  <rdfs:subClassOf rdf:resource="#Safety"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A barrier that serves to enclose an area.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="Post">
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Superstructure"/>
  </rdfs:subClassOf>
  <rdfs:subClassOf>
   <owl:Restriction>
    <owl:onProperty>
     <owl:FunctionalProperty rdf:ID="hasRelativePosition"/>
    </owl:onProperty>
```

```
    <owl:cardinality rdf:datatype="http://www.w3.org/2001/XMLSchema#int"
    >1</owl:cardinality>
   </owl:Restriction>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A member resisting compressive stresses, located vertical to the bottom chord of a
truss and common to two truss panels.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="Curb">
  <rdfs:subClassOf>
   <owl:Restriction>
    <owl:onProperty>
     <owl:FunctionalProperty rdf:ID="polarOrientation"/>
    </owl:onProperty>
    <owl:cardinality rdf:datatype="http://www.w3.org/2001/XMLSchema#int"
    >1</owl:cardinality>
   </owl:Restriction>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A short barrier paralleling the side limit of the roadway to guide the movement of
vehicle wheels and safeguard constructions and pedestrian traffic existing outside the
roadway limit from collision with vehicles and their loads.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Superstructure"/>
  </rdfs:subClassOf>
  <rdfs:subClassOf>
   <owl:Restriction>
    <owl:onProperty>
     <owl:ObjectProperty rdf:ID="hasWidth"/>
    </owl:onProperty>
    <owl:cardinality rdf:datatype="http://www.w3.org/2001/XMLSchema#int"
    >1</owl:cardinality>
   </owl:Restriction>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="ConcreteDeckType">
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Miscellaneous"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Different types of concrete decks.</rdfs:comment>
  <owl:equivalentClass>
   <owl:Class>
    <owl:oneOf rdf:parseType="Collection">
     <ConcreteDeckType rdf:ID="FLAT"/>
     <ConcreteDeckType rdf:ID="ENCASED"/>
```

```
    <ConcreteDeckType rdf:ID="SIP"/>
    <ConcreteDeckType rdf:ID="JACK"/>
   </owl:oneOf>
  </owl:Class>
 </owl:equivalentClass>
</owl:Class>
<owl:Class rdf:about="#CathodicProtection">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >A means of preventing metal from corroding; this is done by making the metal a cathode through the use of impressed direct current and by attaching a sacrificial anode.</rdfs:comment>
 <rdfs:subClassOf rdf:resource="#DeckProtection"/>
 <owl:disjointWith>
  <owl:Class rdf:about="#GalvanizedReinforcing"/>
 </owl:disjointWith>
 <owl:disjointWith>
  <owl:Class rdf:about="#InternallySealed"/>
 </owl:disjointWith>
 <owl:disjointWith rdf:resource="#OtherCoatedReinforcing"/>
 <owl:disjointWith>
  <owl:Class rdf:about="#EpoxyCoatedReinforcing"/>
 </owl:disjointWith>
</owl:Class>
<owl:Class rdf:ID="SelfAnchored">
 <rdfs:subClassOf rdf:resource="#Suspension"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Suspension bridge in which the main cables do not attach to the ground via large anchorages; instead, the main cables attach to the ends of the road deck, which experiences compression equal to the tension in the cables. </rdfs:comment>
</owl:Class>
<owl:Class rdf:ID="ReinforcedConcrete">
 <rdfs:subClassOf rdf:resource="#Concrete"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Concrete with steel reinforcing bars bonded within it to supply increased tensile strength and durability.</rdfs:comment>
</owl:Class>
<owl:Class rdf:ID="FlangeSplice">
 <rdfs:subClassOf>
  <owl:Class rdf:about="#Connection"/>
 </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="ThruTruss">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >A truss which carries its traffic through the interior of the structure with crossbracing between the parallel top and bottom chords.</rdfs:comment>
 <rdfs:subClassOf>
```

```
   <owl:Class rdf:ID="Truss"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="W-Shape">
  <rdfs:subClassOf rdf:resource="#StandardSteelShape"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Doubly-symmetric wide-flange shapes used as beams or columns whose inside
flange surfaces are substantially parallel. </rdfs:comment>
 </owl:Class>
 <owl:Class rdf:about="#EpoxyCoatedReinforcing">
  <rdfs:subClassOf rdf:resource="#DeckProtection"/>
  <owl:disjointWith>
   <owl:Class rdf:about="#InternallySealed"/>
  </owl:disjointWith>
  <owl:disjointWith>
   <owl:Class rdf:about="#GalvanizedReinforcing"/>
  </owl:disjointWith>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Layer of a a synthetic resin which cures or hardens by chemical reaction between
components which are mixed together shortly before use.</rdfs:comment>
  <owl:disjointWith rdf:resource="#CathodicProtection"/>
  <owl:disjointWith rdf:resource="#OtherCoatedReinforcing"/>
 </owl:Class>
 <owl:Class rdf:ID="Arch">
  <rdfs:subClassOf>
   <owl:Class rdf:ID="Substructure"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  > A curved structure which supports a vertical load mainly by axial
compression.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="Rod">
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Superstructure"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A long thin implement made of metal or wood.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="Pontoon">
  <rdfs:subClassOf>
   <owl:Class rdf:about="#BridgeType"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A bridge which floats on pontoons moored to the riverbed; a portion may be
removable to facilitate navigation.</rdfs:comment>
 </owl:Class>
```

```
<owl:Class rdf:ID="ClosedSpandrelArch">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Arch bridge with a closed area above the extrados and below deck level.
</rdfs:comment>
 <rdfs:subClassOf rdf:resource="#Arch"/>
</owl:Class>
<owl:Class rdf:about="#GalvanizedReinforcing">
 <owl:disjointWith rdf:resource="#OtherCoatedReinforcing"/>
 <owl:disjointWith>
  <owl:Class rdf:about="#InternallySealed"/>
 </owl:disjointWith>
 <rdfs:subClassOf rdf:resource="#DeckProtection"/>
 <owl:disjointWith rdf:resource="#EpoxyCoatedReinforcing"/>
 <owl:disjointWith rdf:resource="#CathodicProtection"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Coated with zinc.</rdfs:comment>
</owl:Class>
<owl:Class rdf:about="#Miscellaneous">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Variety of classes of supporting domains.</rdfs:comment>
</owl:Class>
<owl:Class rdf:ID="I-Shape">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >The cross-section is in the shape of a capital I (or the Roman algorithm for
1).</rdfs:comment>
 <rdfs:subClassOf>
  <owl:Class rdf:about="#StandardShape"/>
 </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="Eccentric">
 <rdfs:subClassOf>
  <owl:Class rdf:ID="SteelConnection"/>
 </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="Dolphin">
 <rdfs:subClassOf rdf:resource="#AuxiliaryComponents"/>
</owl:Class>
<owl:Class rdf:about="#StandardShape">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Standard geometric shapes commonly found in the bridge domain.</rdfs:comment>
</owl:Class>
<owl:Class rdf:about="#MeasuredUnit">
 <owl:disjointWith>
  <owl:Class rdf:about="#PossibleUnit"/>
 </owl:disjointWith>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
```

```
  >Generic unit for any measurements.</rdfs:comment>
  <owl:disjointWith>
   <owl:Class rdf:about="#StationReference"/>
  </owl:disjointWith>
  <owl:disjointWith>
   <owl:Class rdf:about="#GeographicLocation"/>
  </owl:disjointWith>
  <owl:disjointWith rdf:resource="#CartesianPoint"/>
  <owl:disjointWith>
   <owl:Class rdf:about="#OrganizationalPattern"/>
  </owl:disjointWith>
  <rdfs:subClassOf rdf:resource="#Miscellaneous"/>
  <owl:disjointWith>
   <owl:Class rdf:about="#GeographicCoordinate"/>
  </owl:disjointWith>
 </owl:Class>
 <owl:Class rdf:ID="Pipe">
  <rdfs:subClassOf rdf:resource="#AuxiliaryComponents"/>
 </owl:Class>
 <owl:Class rdf:ID="T-Shaped">
  <rdfs:subClassOf rdf:resource="#Monolithic"/>
 </owl:Class>
 <owl:Class rdf:ID="Girder">
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Superstructure"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A flexural member which is the main or primary support for the structure, and which
usually receives loads from floor beams and stringers; any large beam, especially if built
up.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="Riprap">
  <rdfs:subClassOf rdf:resource="#AuxiliaryComponents"/>
 </owl:Class>
 <owl:Class rdf:ID="T-Shape">
  <rdfs:subClassOf rdf:resource="#StandardShape"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >The cross-section is in the shape of a capital T.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="Ramp">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >An inclined traffic-way leading from one elevation to another.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:about="#BridgeType"/>
  </rdfs:subClassOf>
 </owl:Class>
```

```
 <owl:Class rdf:ID="FootingOnPedestals">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Enlarged lower portion of the foundation which rests directly on the soil, bedrock, or
piles; usually below grade and not visible. </rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:ID="Foundation"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="HaunchedGirder">
  <rdfs:subClassOf rdf:resource="#Girder"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A girder with an increase in the depth usually at points of support.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:about="#StationReference">
  <owl:disjointWith>
   <owl:Class rdf:about="#PossibleUnit"/>
  </owl:disjointWith>
  <owl:disjointWith>
   <owl:Class rdf:about="#GeographicLocation"/>
  </owl:disjointWith>
  <owl:disjointWith>
   <owl:Class rdf:about="#GeographicCoordinate"/>
  </owl:disjointWith>
  <owl:disjointWith rdf:resource="#CartesianPoint"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Describes a referential to the position of a station.</rdfs:comment>
  <owl:disjointWith rdf:resource="#MeasuredUnit"/>
  <rdfs:subClassOf rdf:resource="#Miscellaneous"/>
  <owl:disjointWith>
   <owl:Class rdf:about="#OrganizationalPattern"/>
  </owl:disjointWith>
 </owl:Class>
 <owl:Class rdf:about="#Wood">
  <rdfs:subClassOf rdf:resource="#Material"/>
  <owl:equivalentClass rdf:resource="#Timber"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >The hard fibrous lignified substance under the bark of trees.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="Paint">
  <rdfs:subClassOf rdf:resource="#AuxiliaryComponents"/>
 </owl:Class>
 <owl:Class rdf:ID="Cable">
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Superstructure"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
```

```
  >A tension member comprised of numerous individual steel wires twisted and wrapped in such a fashion to form a rope of steel.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="WoodConnection">
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Connection"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="Anchorage">
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Substructure"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  > Located at the outermost ends, the part of a suspension bridge to which the cables are attached. Similar in location to an abutment of a beam bridge.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="Brick">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Rectangular block of clay baked by the sun or in a kiln; used as a building or paving material.</rdfs:comment>
  <rdfs:subClassOf rdf:resource="#Material"/>
 </owl:Class>
 <owl:Class rdf:ID="Bulkhead">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Wall or other structure designed to retain or prevent sliding or erosion of the land, as well as used to protect against wave action.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Substructure"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="Viaduct">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A series of spans carried on piers at short intervals.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:about="#BridgeType"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="Prestressed">
  <rdfs:subClassOf rdf:resource="#ReinforcedConcrete"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Concrete in which cracking and tensile forces are greatly reduced by compressing it with tensioned cables or bars.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="Epoxy">
  <rdfs:subClassOf>
   <owl:Class rdf:ID="Membrane"/>
```

```
  </rdfs:subClassOf>
  <owl:disjointWith>
   <owl:Class rdf:ID="PreformedFabric"/>
  </owl:disjointWith>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Any of various resins capable of forming tight, cross-linked polymer structures
characterized by toughness, strong adhesion, and corrosion
resistance.</rdfs:comment>
  <owl:disjointWith>
   <owl:Class rdf:ID="Built-up"/>
  </owl:disjointWith>
 </owl:Class>
 <owl:Class rdf:ID="MedianType">
  <rdfs:subClassOf rdf:resource="#Miscellaneous"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Different types of medians in a bridge.</rdfs:comment>
  <owl:equivalentClass>
   <owl:Class>
    <owl:oneOf rdf:parseType="Collection">
     <MedianType rdf:ID="None"/>
     <MedianType rdf:ID="Open"/>
     <MedianType rdf:ID="Closed"/>
    </owl:oneOf>
   </owl:Class>
  </owl:equivalentClass>
 </owl:Class>
 <owl:Class rdf:ID="RetainingWall">
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Substructure"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A structure designed to restrain and hold back a mass of earth.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:about="#Frame">
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Substructure"/>
  </rdfs:subClassOf>
  <owl:equivalentClass>
   <owl:Class rdf:ID="Bent"/>
  </owl:equivalentClass>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Structure supporting the bridge.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Superstructure"/>
  </rdfs:subClassOf>
 </owl:Class>
```

```
<owl:Class rdf:about="#Substructure">
 <rdfs:subClassOf>
  <owl:Class rdf:ID="Member"/>
 </rdfs:subClassOf>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >The portion of a bridge structure including abutments and piers which supports the superstructure.</rdfs:comment>
</owl:Class>
<owl:Class rdf:ID="Barrier">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >A structure or object that impedes free movement.</rdfs:comment>
 <rdfs:subClassOf>
  <owl:Class rdf:about="#Superstructure"/>
 </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="HP-Shape">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Wide-flange shapes generally used as bearing piles whose flanges and. webs are of the same nominal thickness and whose depth and width are essentially the same.</rdfs:comment>
 <rdfs:subClassOf rdf:resource="#StandardSteelShape"/>
</owl:Class>
<owl:Class rdf:ID="WebSplice">
 <rdfs:subClassOf>
  <owl:Class rdf:about="#Connection"/>
 </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="Bailey">
 <rdfs:subClassOf>
  <owl:Class rdf:ID="Pre-fabricated"/>
 </rdfs:subClassOf>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >A steel bridge designed to be shipped in parts and assembled rapidly.</rdfs:comment>
</owl:Class>
<owl:Class rdf:ID="S-Shape">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Doubly-symmetric shapes produced in accordance with dimensional standards adopted in 1896 by the Association of American Steel Manufacturers for American Standard beam shapes.</rdfs:comment>
 <rdfs:subClassOf rdf:resource="#StandardSteelShape"/>
</owl:Class>
<owl:Class rdf:ID="Bridge">
 <rdfs:subClassOf rdf:resource="http://www.w3.org/2002/07/owl#Thing"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >A structure including supports erected over a depression or an obstruction, such as
```

```
water, highway, or railway, and having a track or passageway for carrying traffic or other moving loads, and having an opening measured along the center of the roadway of more than 20 feet (6.1 meters) between undercopings of abutments or spring lines of arches, or extreme ends of openings for multiple boxes; it may also include multiple pipes, where the clear distance between openings is less than half of the smaller contiguous opening.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Restriction>
    <owl:onProperty>
     <owl:ObjectProperty rdf:ID="hasType"/>
    </owl:onProperty>
    <owl:someValuesFrom>
     <owl:Class rdf:about="#BridgeType"/>
    </owl:someValuesFrom>
   </owl:Restriction>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:about="#SteelConnection">
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Connection"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="Pile">
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Foundation"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A long column driven deep into the ground to form part of a foundation or substructure.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="Deck">
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Superstructure"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >That portion of a bridge which provides direct support for vehicular and pedestrian traffic.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="Beam">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A linear structural member designed to span from one support to another.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Superstructure"/>
  </rdfs:subClassOf>
  <rdfs:subClassOf rdf:resource="#Girder"/>
```

```
</owl:Class>
<owl:Class rdf:about="#Foundation">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Different types of basis on which bridges are grounded</rdfs:comment>
 <rdfs:subClassOf rdf:resource="#Substructure"/>
</owl:Class>
<owl:Class rdf:ID="SegmentalBoxGirder">
 <rdfs:subClassOf rdf:resource="#Girder"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Girder constructed of individual pieces or segments which are collectively joined to
form the whole.</rdfs:comment>
</owl:Class>
<owl:Class rdf:ID="Box">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >A box is a rectangular prism. It has length, width, height, and volume.
</rdfs:comment>
 <rdfs:subClassOf rdf:resource="#StandardShape"/>
</owl:Class>
<owl:Class rdf:ID="UnreinforcedConcrete">
 <rdfs:subClassOf rdf:resource="#Concrete"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Concrete that has not been reinforced.</rdfs:comment>
</owl:Class>
<owl:Class rdf:ID="ChannelShape">
 <rdfs:subClassOf rdf:resource="#StandardSteelShape"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >The cross-section is in the shape of a capital C.</rdfs:comment>
</owl:Class>
<owl:Class rdf:ID="Tower">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >A pier or frame supporting the catenary cables of a suspension
bridge.</rdfs:comment>
 <rdfs:subClassOf>
  <owl:Class rdf:about="#Superstructure"/>
 </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:about="#EpoxyOverlay">
 <owl:disjointWith>
  <owl:Class rdf:about="#IntegralConcrete"/>
 </owl:disjointWith>
 <owl:disjointWith>
  <owl:Class rdf:about="#LatexConcrete"/>
 </owl:disjointWith>
 <owl:disjointWith rdf:resource="#Bituminous"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Any of various resins capable of forming tight, cross-linked polymer structures
```

```
characterized by toughness, strong adhesion, and corrosion resistance. Commonly
used as a two-part adhesive.</rdfs:comment>
  <owl:disjointWith>
   <owl:Class rdf:about="#MonolithicConcrete"/>
  </owl:disjointWith>
  <owl:disjointWith>
   <owl:Class rdf:about="#LowSlumpConcrete"/>
  </owl:disjointWith>
  <owl:disjointWith>
   <owl:Class rdf:about="#Gravel"/>
  </owl:disjointWith>
  <rdfs:subClassOf>
   <owl:Class rdf:about="#WearingSurface"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="Arched">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Bridge constructed with or in the form of an arch or arches.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:about="#BridgeType"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="SeatedBeam">
  <rdfs:subClassOf rdf:resource="#SteelConnection"/>
 </owl:Class>
 <owl:Class rdf:ID="Roller">
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Connection"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="Slab">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A flat beam, usually of reinforced concrete, which supports load by
flexure.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Superstructure"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="DeckArch">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Arch bridge with the deck above the arch.</rdfs:comment>
  <rdfs:subClassOf rdf:resource="#Arch"/>
 </owl:Class>
 <owl:Class rdf:ID="Stem">
  <rdfs:subClassOf rdf:resource="#Substructure"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
```

```
 >The vertical wall portion of an abutment retaining wall, or solid pier.</rdfs:comment>
</owl:Class>
<owl:Class rdf:about="#Connection">
 <rdfs:subClassOf rdf:resource="#AuxiliaryComponents"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >A link between two communicating structures.</rdfs:comment>
</owl:Class>
<owl:Class rdf:ID="RolledBeamGirder">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Girder with forms of rolled steel having "I", "H", "Z" or other cross sectional
shapes.</rdfs:comment>
 <rdfs:subClassOf rdf:resource="#Girder"/>
</owl:Class>
<owl:Class rdf:ID="Howe">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Bridge with a truss of the parallel chord type with a web system composed of vertical
(tension) rods at the panel points with an X pattern of diagonals.</rdfs:comment>
 <rdfs:subClassOf>
  <owl:Class rdf:about="#BridgeType"/>
 </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="Portal">
 <rdfs:subClassOf rdf:resource="#AuxiliaryComponents"/>
</owl:Class>
<owl:Class rdf:ID="M-Shape">
 <rdfs:subClassOf rdf:resource="#StandardSteelShape"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Doubly-symmetric shapes that cannot be classified as "W," "S," or "HP"
shapes.</rdfs:comment>
</owl:Class>
<owl:Class rdf:ID="DeckTruss">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >A truss which carries its deck on its top chord.</rdfs:comment>
 <rdfs:subClassOf>
  <owl:Class rdf:about="#Truss"/>
 </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="Pavement">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >The paved surface of a bridge.</rdfs:comment>
 <rdfs:subClassOf>
  <owl:Class rdf:about="#Superstructure"/>
 </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="Stringer">
 <rdfs:subClassOf>
```

```
   <owl:Class rdf:about="#Superstructure"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A longitudinal beam supporting the bridge deck.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:about="#WearingSurface">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >The surface of a roadway that is in direct contact with traffic and that resists the resulting abrading, crushing, or other disintegrating action.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Restriction>
    <owl:cardinality rdf:datatype="http://www.w3.org/2001/XMLSchema#int"
    >1</owl:cardinality>
    <owl:onProperty>
     <owl:FunctionalProperty rdf:ID="hasThickness"/>
    </owl:onProperty>
   </owl:Restriction>
  </rdfs:subClassOf>
  <rdfs:subClassOf rdf:resource="http://www.w3.org/2002/07/owl#Thing"/>
 </owl:Class>
 <owl:Class rdf:ID="Diaphragm">
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Superstructure"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A member placed within a member or superstructure system to distribute stresses and improve strength and rigidity.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="Parapet">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A low wall along the outmost edge of the roadway of a bridge to protect vehicles and pedestrians.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Restriction>
    <owl:onProperty>
     <owl:ObjectProperty rdf:ID="hasHeight"/>
    </owl:onProperty>
    <owl:cardinality rdf:datatype="http://www.w3.org/2001/XMLSchema#int"
    >1</owl:cardinality>
   </owl:Restriction>
  </rdfs:subClassOf>
  <rdfs:subClassOf>
   <owl:Restriction>
    <owl:cardinality rdf:datatype="http://www.w3.org/2001/XMLSchema#int"
    >1</owl:cardinality>
    <owl:onProperty>
```

```
     <owl:ObjectProperty rdf:about="#hasWidth"/>
    </owl:onProperty>
   </owl:Restriction>
  </rdfs:subClassOf>
  <rdfs:subClassOf>
   <owl:Restriction>
    <owl:onProperty>
     <owl:ObjectProperty rdf:ID="isMadeOf"/>
    </owl:onProperty>
    <owl:minCardinality rdf:datatype="http://www.w3.org/2001/XMLSchema#int"
    >1</owl:minCardinality>
   </owl:Restriction>
  </rdfs:subClassOf>
  <rdfs:subClassOf rdf:resource="#Safety"/>
 </owl:Class>
 <owl:Class rdf:about="#Pre-fabricated">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Bridges constructed in a factory, usually in modules or units, which is then assembled
where it is to be used.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:about="#BridgeType"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="Span">
  <rdfs:subClassOf>
   <owl:Restriction>
    <owl:maxCardinality rdf:datatype="http://www.w3.org/2001/XMLSchema#int"
    >1</owl:maxCardinality>
    <owl:onProperty>
     <owl:ObjectProperty rdf:ID="hasStartPosition"/>
    </owl:onProperty>
   </owl:Restriction>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  > The horizontal space between two supports of a structure. Also refers to the
structure itself. May be used as a noun or a verb.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Restriction>
    <owl:cardinality rdf:datatype="http://www.w3.org/2001/XMLSchema#int"
    >1</owl:cardinality>
    <owl:onProperty>
     <owl:FunctionalProperty rdf:ID="spanLength"/>
    </owl:onProperty>
   </owl:Restriction>
  </rdfs:subClassOf>
  <rdfs:subClassOf>
```

```
   <owl:Restriction>
    <owl:cardinality rdf:datatype="http://www.w3.org/2001/XMLSchema#int"
    >1</owl:cardinality>
    <owl:onProperty>
     <owl:DatatypeProperty rdf:ID="typeOfLengthMeasurement"/>
    </owl:onProperty>
   </owl:Restriction>
  </rdfs:subClassOf>
  <rdfs:subClassOf rdf:resource="http://www.w3.org/2002/07/owl#Thing"/>
  <rdfs:subClassOf>
   <owl:Restriction>
    <owl:maxCardinality rdf:datatype="http://www.w3.org/2001/XMLSchema#int"
    >1</owl:maxCardinality>
    <owl:onProperty>
     <owl:ObjectProperty rdf:ID="hasEndPosition"/>
    </owl:onProperty>
   </owl:Restriction>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="Moment">
  <rdfs:subClassOf rdf:resource="#SteelConnection"/>
 </owl:Class>
 <owl:Class rdf:ID="TrestleBent">
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Bent"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Bent with a long structure which does not have a predominantly larger
span.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="WarrenTruss">
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Truss"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A triangular truss consisting of sloping members between the top and bottom chords
and no verticals; members form the letter W.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="Wire">
  <rdfs:subClassOf rdf:resource="#AuxiliaryComponents"/>
 </owl:Class>
 <owl:Class rdf:ID="InTension">
  <rdfs:subClassOf rdf:resource="#SteelConnection"/>
 </owl:Class>
 <owl:Class rdf:ID="Asfalt">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
```

```
 >Black surface material made from mineral hydrocarbons containing
petroleum.</rdfs:comment>
  <rdfs:subClassOf rdf:resource="#Material"/>
 </owl:Class>
 <owl:Class rdf:ID="PostTensioned">
  <rdfs:subClassOf rdf:resource="#ReinforcedConcrete"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Concrete externally prestressed by a method in which the tendons are stressed after
the concrete has been cast.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:about="#InternallySealed">
  <owl:disjointWith rdf:resource="#OtherCoatedReinforcing"/>
  <owl:disjointWith rdf:resource="#CathodicProtection"/>
  <owl:disjointWith rdf:resource="#EpoxyCoatedReinforcing"/>
  <rdfs:subClassOf rdf:resource="#DeckProtection"/>
  <owl:disjointWith rdf:resource="#GalvanizedReinforcing"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Made free of cracks or other openings that allow the entry or passage of moisture
from the inside.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="Draw">
  <rdfs:subClassOf>
   <owl:Class rdf:ID="Movable"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A general term applied to a bridge over a navigable body of water having a movable
superstructure span of any type permitting the channel to be freed of its obstruction to
navigation.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:about="#Movable">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A bridge having one or more spans capable of being raised, turned, lifted, or slid from
its normal service location to provide for the passage of navigation.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:about="#BridgeType"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="CyllindricalBearing">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Bearing in the shape of a cyllinder.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Bearing"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="FiberReinforcedPolymer">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
```

>FRP, a general term for a composite that is reinforced with cloth, mat, strands, or any other fiber form and resin.</rdfs:comment>
<rdfs:subClassOf rdf:resource="#Material"/>
</owl:Class>
<owl:Class rdf:ID="Fender">
<rdfs:subClassOf rdf:resource="#AuxiliaryComponents"/>
</owl:Class>
<owl:Class rdf:ID="OpenSpandrelArch">
<rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
>Arch bridge with an open area above the extrados and below deck level. </rdfs:comment>
<rdfs:subClassOf rdf:resource="#Arch"/>
</owl:Class>
<owl:Class rdf:ID="RockerBearing">
<rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
>Bearing used where, due to limited space (e.g. narrow piers), the use of pot bearings is impossible.</rdfs:comment>
<rdfs:subClassOf>
<owl:Class rdf:about="#Bearing"/>
</rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="Cantilevered">
<rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
>A general term applying to a bridge having a superstructure utilizing cantilever design.</rdfs:comment>
<rdfs:subClassOf>
<owl:Class rdf:about="#BridgeType"/>
</rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="Scarf">
<rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
>Ends of the wooden strips are cut at a shallow angle to provide a large area for joining.</rdfs:comment>
<rdfs:subClassOf rdf:resource="#WoodConnection"/>
</owl:Class>
<owl:Class rdf:about="#LatexConcrete">
<rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
>Wearing surface of latex modified concrete on a prepared surface in accordance with specifications in the Specifications Book for Highway Construction (http://www.modot.org/business/standards_and_specs/documents/Sec0505.pdf)</rdfs:comment>
<owl:disjointWith>
<owl:Class rdf:about="#LowSlumpConcrete"/>
</owl:disjointWith>
<owl:disjointWith>
<owl:Class rdf:about="#IntegralConcrete"/>

```
  </owl:disjointWith>
  <owl:disjointWith rdf:resource="#Bituminous"/>
  <owl:disjointWith rdf:resource="#EpoxyOverlay"/>
  <rdfs:subClassOf rdf:resource="#WearingSurface"/>
  <owl:disjointWith>
   <owl:Class rdf:about="#Gravel"/>
  </owl:disjointWith>
  <owl:disjointWith>
   <owl:Class rdf:about="#MonolithicConcrete"/>
  </owl:disjointWith>
 </owl:Class>
 <owl:Class rdf:ID="FootingOnCaissons">
  <rdfs:subClassOf rdf:resource="#Foundation"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A bridge foundation, usually embedded in a riverbed by continuously digging out the
material within the bed, so that the caisson sinks.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="CrossFrame">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >When the frames are extending or lying across each other.</rdfs:comment>
  <rdfs:subClassOf rdf:resource="#Frame"/>
 </owl:Class>
 <owl:Class rdf:about="#GeographicLocation">
  <owl:disjointWith rdf:resource="#MeasuredUnit"/>
  <owl:disjointWith rdf:resource="#CartesianPoint"/>
  <rdfs:subClassOf rdf:resource="#Miscellaneous"/>
  <owl:disjointWith rdf:resource="#StationReference"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Geographic location given by a GPS.</rdfs:comment>
  <owl:disjointWith>
   <owl:Class rdf:about="#GeographicCoordinate"/>
  </owl:disjointWith>
  <owl:disjointWith>
   <owl:Class rdf:about="#OrganizationalPattern"/>
  </owl:disjointWith>
  <owl:disjointWith>
   <owl:Class rdf:about="#PossibleUnit"/>
  </owl:disjointWith>
 </owl:Class>
 <owl:Class rdf:ID="PileBent">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Bent with a long column driven deep into the ground to form part of a foundation or
substructure. </rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Bent"/>
  </rdfs:subClassOf>
```

```
 </owl:Class>
 <owl:Class rdf:ID="Hinge">
  <rdfs:subClassOf rdf:resource="#Substructure"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A point in a structure at which a member is free to rotate.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="Triangular">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A two-dimensional figure with three vertices and three sides which are straight line
segments.</rdfs:comment>
  <rdfs:subClassOf rdf:resource="#StandardShape"/>
 </owl:Class>
 <owl:Class rdf:ID="ThruArch">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Arch bridge with the deck below the arch.</rdfs:comment>
  <rdfs:subClassOf rdf:resource="#Arch"/>
 </owl:Class>
 <owl:Class rdf:about="#Truss">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A jointed structure made up of individual members arranged and connected usually in
a triangular pattern, so as to support longer spans.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Superstructure"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="Narrow">
  <rdfs:subClassOf>
   <owl:Class rdf:about="#BridgeType"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Bridge that is not wide.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="Steel">
  <rdfs:subClassOf rdf:resource="#Material"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >An alloy of iron, carbon, and various other elements and metals.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="KneeJoint">
  <rdfs:subClassOf rdf:resource="#Monolithic"/>
 </owl:Class>
 <owl:Class rdf:ID="Masonry">
  <rdfs:subClassOf rdf:resource="#Material"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >That portion of a structure composed of stone, brick or concrete block placed in
layers and in some cases cemented with mortar.</rdfs:comment>
 </owl:Class>
```

```
<owl:Class rdf:about="#PreformedFabric">
 <owl:disjointWith>
  <owl:Class rdf:about="#Built-up"/>
 </owl:disjointWith>
 <rdfs:subClassOf>
  <owl:Class rdf:about="#Membrane"/>
 </rdfs:subClassOf>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Comprises a layer of a mixture of bitumen, a linear monoalkenyl arene/conjugated
diene block copolymer and a branched monoalkenyl arene/conjugated diene block
copolymer.</rdfs:comment>
 <owl:disjointWith rdf:resource="#Epoxy"/>
</owl:Class>
<owl:Class rdf:ID="Glued">
 <rdfs:subClassOf rdf:resource="#WoodConnection"/>
</owl:Class>
<owl:Class rdf:ID="Culvert">
 <rdfs:subClassOf rdf:resource="#AuxiliaryComponents"/>
</owl:Class>
<owl:Class rdf:ID="Trestles">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Bridge with spans supported upon frame bents.</rdfs:comment>
 <rdfs:subClassOf>
  <owl:Class rdf:about="#BridgeType"/>
 </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="TimberDeck">
 <rdfs:subClassOf rdf:resource="#Deck"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Deck made of timber (wood).</rdfs:comment>
 <rdfs:subClassOf>
  <owl:Restriction>
   <owl:onProperty>
    <owl:ObjectProperty rdf:about="#isMadeOf"/>
   </owl:onProperty>
   <owl:someValuesFrom rdf:resource="#Timber"/>
  </owl:Restriction>
 </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="ApproachGuardrail">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >A safety feature element intended to redirect an errant vehicle - away from the
approach embankment.</rdfs:comment>
 <rdfs:subClassOf rdf:resource="#Safety"/>
</owl:Class>
<owl:Class rdf:ID="Eyebar">
```

```
  <rdfs:subClassOf>
   <owl:Class rdf:ID="PinConnected"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="Bascule">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A bridge over a waterway with one or two leaves which rotate from a horizontal to a near-vertical position, providing unlimited clear headway.</rdfs:comment>
  <rdfs:subClassOf rdf:resource="#Movable"/>
 </owl:Class>
 <owl:Class rdf:ID="GravityWall">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A retaining which is prevented from overturning its weight alone.</rdfs:comment>
  <rdfs:subClassOf rdf:resource="#Substructure"/>
 </owl:Class>
 <owl:Class rdf:ID="SwingSpan">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A movable bridge in which the span rotates in a horizontal plane on a pivot pier, to permit passage of marine traffic.</rdfs:comment>
  <rdfs:subClassOf rdf:resource="#Movable"/>
 </owl:Class>
 <owl:Class rdf:ID="Trussed">
  <rdfs:subClassOf>
   <owl:Class rdf:about="#BridgeType"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A bridge having a pair of trusses for a superstructure.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="Iron">
  <rdfs:subClassOf rdf:resource="#Material"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A metallic element used in cast or wrought iron and steel.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:about="#BridgeType">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Collection of different types of bridges.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="NonPrestressed">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Concrete that has not gone through pre or post stressing methods.</rdfs:comment>
  <rdfs:subClassOf rdf:resource="#ReinforcedConcrete"/>
 </owl:Class>
 <owl:Class rdf:ID="WeldedPlate">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Girder in which the assembled elements and members are united through fusion of metal.</rdfs:comment>
```

```
  <rdfs:subClassOf rdf:resource="#Girder"/>
 </owl:Class>
 <owl:Class rdf:ID="Welded">
  <rdfs:subClassOf rdf:resource="#Connection"/>
 </owl:Class>
 <owl:Class rdf:about="#Member">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Anything that belongs to a set or class of superstructures and substructures in a
bridge.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="Sidewalk">
  <rdfs:subClassOf>
   <owl:Restriction>
    <owl:cardinality rdf:datatype="http://www.w3.org/2001/XMLSchema#int"
    >1</owl:cardinality>
    <owl:onProperty>
     <owl:ObjectProperty rdf:about="#hasWidth"/>
    </owl:onProperty>
   </owl:Restriction>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >The portion of the bridge floor area serving pedestrian traffic only.</rdfs:comment>
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Superstructure"/>
  </rdfs:subClassOf>
  <rdfs:subClassOf>
   <owl:Restriction>
    <owl:cardinality rdf:datatype="http://www.w3.org/2001/XMLSchema#int"
    >1</owl:cardinality>
    <owl:onProperty>
     <owl:FunctionalProperty rdf:about="#polarOrientation"/>
    </owl:onProperty>
   </owl:Restriction>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="EndPlate">
  <rdfs:subClassOf rdf:resource="#SteelConnection"/>
 </owl:Class>
 <owl:Class rdf:ID="Railing">
  <rdfs:subClassOf>
   <owl:Restriction>
    <owl:cardinality rdf:datatype="http://www.w3.org/2001/XMLSchema#int"
    >1</owl:cardinality>
    <owl:onProperty>
     <owl:ObjectProperty rdf:about="#hasWidth"/>
    </owl:onProperty>
```

```
   </owl:Restriction>
  </rdfs:subClassOf>
  <rdfs:subClassOf>
   <owl:Restriction>
    <owl:onProperty>
     <owl:ObjectProperty rdf:about="#hasHeight"/>
    </owl:onProperty>
    <owl:cardinality rdf:datatype="http://www.w3.org/2001/XMLSchema#int"
    >1</owl:cardinality>
   </owl:Restriction>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A fence-like construction built at the outermost edge of the roadway or the sidewalk portion of a bridge to protect pedestrians and vehicles.</rdfs:comment>
  <rdfs:subClassOf rdf:resource="#Safety"/>
  <rdfs:subClassOf>
   <owl:Restriction>
    <owl:onProperty>
     <owl:ObjectProperty rdf:about="#isMadeOf"/>
    </owl:onProperty>
    <owl:minCardinality rdf:datatype="http://www.w3.org/2001/XMLSchema#int"
    >1</owl:minCardinality>
   </owl:Restriction>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="Skew">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Bridges where the superstructure is not perpendicular to the substructure, a skew angle is created. The skew angle is the acute angle between the alignment of the superstructure and the alignment of the substructure.</rdfs:comment>
  <rdfs:subClassOf rdf:resource="#BridgeType"/>
 </owl:Class>
 <owl:Class rdf:ID="Bracing">
  <rdfs:subClassOf>
   <owl:Restriction>
    <owl:onProperty>
     <owl:FunctionalProperty rdf:about="#hasRelativePosition"/>
    </owl:onProperty>
    <owl:cardinality rdf:datatype="http://www.w3.org/2001/XMLSchema#int"
    >1</owl:cardinality>
   </owl:Restriction>
  </rdfs:subClassOf>
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Superstructure"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
```

```
  >A system of secondary members that maintain the geometric configuration of primary members.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:about="#OrganizationalPattern">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Different patterns in which trusses can be designed.</rdfs:comment>
  <owl:disjointWith rdf:resource="#StationReference"/>
  <owl:disjointWith rdf:resource="#MeasuredUnit"/>
  <rdfs:subClassOf rdf:resource="#Miscellaneous"/>
  <owl:disjointWith rdf:resource="#GeographicLocation"/>
  <owl:disjointWith rdf:resource="#CartesianPoint"/>
  <owl:disjointWith>
   <owl:Class rdf:about="#GeographicCoordinate"/>
  </owl:disjointWith>
  <owl:equivalentClass>
   <owl:Class>
    <owl:oneOf rdf:parseType="Collection">
     <OrganizationalPattern rdf:ID="Lattice"/>
     <OrganizationalPattern rdf:ID="Panel"/>
     <OrganizationalPattern rdf:ID="Counterbrace"/>
     <OrganizationalPattern rdf:ID="Web"/>
     <OrganizationalPattern rdf:ID="Diagonal"/>
     <OrganizationalPattern rdf:ID="Bowstring"/>
    </owl:oneOf>
   </owl:Class>
  </owl:equivalentClass>
  <owl:disjointWith>
   <owl:Class rdf:about="#PossibleUnit"/>
  </owl:disjointWith>
 </owl:Class>
 <owl:Class rdf:ID="Station">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A ground position at which a geophysical instrument is located for an observation.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:about="#Superstructure">
  <rdfs:subClassOf rdf:resource="#Member"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >The portion of a bridge structure which carries the traffic load and passes that load to the substructure.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:about="#IntegralConcrete">
  <owl:disjointWith>
   <owl:Class rdf:about="#Gravel"/>
  </owl:disjointWith>
  <owl:disjointWith rdf:resource="#EpoxyOverlay"/>
```

```
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Separate non-modified layer of concrete added to structural deck.</rdfs:comment>
  <owl:disjointWith>
   <owl:Class rdf:about="#MonolithicConcrete"/>
  </owl:disjointWith>
  <owl:disjointWith rdf:resource="#LatexConcrete"/>
  <rdfs:subClassOf rdf:resource="#WearingSurface"/>
  <owl:disjointWith rdf:resource="#Bituminous"/>
  <owl:disjointWith>
   <owl:Class rdf:about="#LowSlumpConcrete"/>
  </owl:disjointWith>
 </owl:Class>
 <owl:Class rdf:ID="Abutment">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Part of a structure which supports the end of a span or accepts the thrust of an arch;
often supports and retains the approach embankment.</rdfs:comment>
  <rdfs:subClassOf rdf:resource="#Substructure"/>
 </owl:Class>
 <owl:Class rdf:ID="DeckPlateGirder">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A large I-shaped beam composed of a solid web plate with flange plates attached to
the web plate by flange angles or fillet welds.</rdfs:comment>
  <rdfs:subClassOf rdf:resource="#Girder"/>
 </owl:Class>
 <owl:Class rdf:about="#PinConnected">
  <rdfs:subClassOf rdf:resource="#Connection"/>
 </owl:Class>
 <owl:Class rdf:ID="Covered">
  <rdfs:subClassOf rdf:resource="#BridgeType"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >An indefinite term applied to a wooden bridge having its roadway protected by a roof
and enclosing sides.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:about="#Bent">
  <rdfs:subClassOf rdf:resource="#Substructure"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A rigid frame commonly made of reinforced concrete or steel which supports a
vertical load and is placed transerse to the length of a structure.</rdfs:comment>
  <owl:equivalentClass rdf:resource="#Frame"/>
 </owl:Class>
 <owl:Class rdf:ID="Soil">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Layer of minerals and organic matter, in thickness from centimetres to a metre or
more, on the land surface. Its main components are rock and mineral matter, organic
matter, water, and air. </rdfs:comment>
  <rdfs:subClassOf rdf:resource="#Material"/>
```

```xml
</owl:Class>
<owl:Class rdf:ID="ConcreteDeck">
 <rdfs:subClassOf rdf:resource="#Deck"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Deck made of concrete.</rdfs:comment>
 <rdfs:subClassOf>
  <owl:Restriction>
   <owl:someValuesFrom rdf:resource="#ConcreteDeckType"/>
   <owl:onProperty>
    <owl:ObjectProperty rdf:about="#hasType"/>
   </owl:onProperty>
  </owl:Restriction>
 </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="DrilledShaft">
 <rdfs:subClassOf rdf:resource="#Foundation"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >A vertical or nearly vertical drilled into the earth for bridge fixation.</rdfs:comment>
</owl:Class>
<owl:Class rdf:ID="GratingDeck">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Deck that has parallel or crossed bars blocking a passage but admitting
air.</rdfs:comment>
 <rdfs:subClassOf rdf:resource="#Deck"/>
</owl:Class>
<owl:Class rdf:ID="PonyPlateGirder">
 <rdfs:subClassOf rdf:resource="#Girder"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >A plate girder having insufficient height to use a top chord system of lateral
bracing.</rdfs:comment>
</owl:Class>
<owl:Class rdf:ID="Median">
 <rdfs:subClassOf rdf:resource="#Superstructure"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >A strip of land between opposing lanes of highway traffic.</rdfs:comment>
</owl:Class>
<owl:Class rdf:ID="LongSpan">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Bridges with typical span lenghts of 70m - 1,000m+.</rdfs:comment>
 <rdfs:subClassOf rdf:resource="#BridgeType"/>
</owl:Class>
<owl:Class rdf:about="#MonolithicConcrete">
 <owl:disjointWith rdf:resource="#EpoxyOverlay"/>
 <owl:disjointWith rdf:resource="#LatexConcrete"/>
 <owl:disjointWith>
  <owl:Class rdf:about="#Gravel"/>
```

```
  </owl:disjointWith>
  <owl:disjointWith rdf:resource="#Bituminous"/>
  <rdfs:subClassOf rdf:resource="#WearingSurface"/>
  <owl:disjointWith>
   <owl:Class rdf:about="#LowSlumpConcrete"/>
  </owl:disjointWith>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Concurrently placed with structural deck.</rdfs:comment>
  <owl:disjointWith rdf:resource="#IntegralConcrete"/>
 </owl:Class>
 <owl:Class rdf:about="#Membrane">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A very thin layer of tissue that covers the surface of a bridge
member.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="Bolt">
  <rdfs:subClassOf rdf:resource="#AuxiliaryComponents"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A mechanical fastener with machine threads at one end to receive a nut, and a
hexagonal head at the other end.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:about="#PossibleUnit">
  <owl:equivalentClass>
   <owl:Class>
    <owl:oneOf rdf:parseType="Collection">
     <PossibleUnit rdf:ID="Ampere"/>
     <PossibleUnit rdf:ID="Angstrom"/>
     <PossibleUnit rdf:ID="Btu"/>
     <PossibleUnit rdf:ID="Candela"/>
     <PossibleUnit rdf:ID="Degree"/>
     <PossibleUnit rdf:ID="Ksi"/>
     <PossibleUnit rdf:ID="Degree-Kelvin"/>
     <PossibleUnit rdf:ID="Degree-Rankine"/>
     <PossibleUnit rdf:ID="Cartesian"/>
     <PossibleUnit rdf:ID="Foot"/>
     <PossibleUnit rdf:ID="Hour"/>
     <PossibleUnit rdf:ID="Inch"/>
     <PossibleUnit rdf:ID="Joule"/>
     <PossibleUnit rdf:ID="Kilogram"/>
     <PossibleUnit rdf:ID="Kilometer"/>
     <PossibleUnit rdf:ID="Meter"/>
     <PossibleUnit rdf:ID="Mile"/>
     <PossibleUnit rdf:ID="Minute"/>
     <PossibleUnit rdf:ID="Mole"/>
     <PossibleUnit rdf:ID="Newton"/>
     <PossibleUnit rdf:ID="Pascal"/>
```

```
    <PossibleUnit rdf:ID="Pound-Force"/>
    <PossibleUnit rdf:ID="Pound-Mass"/>
    <PossibleUnit rdf:ID="Radian"/>
    <PossibleUnit rdf:ID="Second"/>
    <PossibleUnit rdf:ID="Slug"/>
    <PossibleUnit rdf:ID="Us-Cent"/>
    <PossibleUnit rdf:ID="Us-Dollar"/>
   </owl:oneOf>
  </owl:Class>
 </owl:equivalentClass>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >As seen at at Standard-Units ontology in
http://www.ksl.stanford.edu/htw/dme/thermal-kb-tour/standard-units.html
</rdfs:comment>
 <owl:disjointWith rdf:resource="#StationReference"/>
 <owl:disjointWith rdf:resource="#GeographicLocation"/>
 <owl:disjointWith rdf:resource="#CartesianPoint"/>
 <owl:disjointWith rdf:resource="#MeasuredUnit"/>
 <owl:disjointWith>
  <owl:Class rdf:about="#GeographicCoordinate"/>
 </owl:disjointWith>
 <owl:disjointWith rdf:resource="#OrganizationalPattern"/>
 <rdfs:subClassOf rdf:resource="#Miscellaneous"/>
</owl:Class>
<owl:Class rdf:about="#Hanger">
 <owl:equivalentClass rdf:resource="#Suspender"/>
 <rdfs:subClassOf rdf:resource="#Superstructure"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >A tension member serving to suspend an attached member.</rdfs:comment>
</owl:Class>
<owl:Class rdf:about="#Built-up">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >A built-up membrane is one made up of several components, usually glue-fixed, but
sometimes screwed, nailed, bolted or welded</rdfs:comment>
 <owl:disjointWith rdf:resource="#PreformedFabric"/>
 <owl:disjointWith rdf:resource="#Epoxy"/>
 <rdfs:subClassOf rdf:resource="#Membrane"/>
</owl:Class>
<owl:Class rdf:ID="WingWall">
 <rdfs:subClassOf rdf:resource="#Substructure"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >The retaining wall extension of an abutment intended to restrain and hold in place the
side slope material of an approach roadway embankment.</rdfs:comment>
</owl:Class>
<owl:Class rdf:ID="VerticalLift">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
```

```xml
  >A bridge in which the span moves up and down while remaining parallel to the roadway.</rdfs:comment>
  <rdfs:subClassOf rdf:resource="#Movable"/>
 </owl:Class>
 <owl:Class rdf:ID="ReinforcementConfiguration">
  <owl:equivalentClass>
   <owl:Class>
    <owl:oneOf rdf:parseType="Collection">
     <ReinforcementConfiguration rdf:ID="Longitudinal"/>
     <ReinforcementConfiguration rdf:ID="Transverse"/>
     <ReinforcementConfiguration rdf:ID="Curtain"/>
    </owl:oneOf>
   </owl:Class>
  </owl:equivalentClass>
  <rdfs:subClassOf rdf:resource="#Miscellaneous"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Different configurations in which reinforcement features can be configured.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="Cable-stayed">
  <rdfs:subClassOf rdf:resource="#Cantilevered"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A bridge in which the superstructure is directly supported by cables, or stays, passing over or attached to towers located at the main piers.</rdfs:comment>
 </owl:Class>
 <owl:Class rdf:ID="SphericalBearing">
  <rdfs:subClassOf>
   <owl:Class rdf:about="#Bearing"/>
  </rdfs:subClassOf>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Bearing that enables shifting and sliding on plane as well as on curved sliding surfaces. </rdfs:comment>
 </owl:Class>
 <owl:Class rdf:about="#Gravel">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A loose mixture of pebbles and rock fragments that are coarser than sand.</rdfs:comment>
  <owl:disjointWith rdf:resource="#IntegralConcrete"/>
  <rdfs:subClassOf rdf:resource="#WearingSurface"/>
  <owl:disjointWith rdf:resource="#MonolithicConcrete"/>
  <owl:disjointWith rdf:resource="#EpoxyOverlay"/>
  <owl:disjointWith>
   <owl:Class rdf:about="#LowSlumpConcrete"/>
  </owl:disjointWith>
  <owl:disjointWith rdf:resource="#Bituminous"/>
  <owl:disjointWith rdf:resource="#LatexConcrete"/>
```

```xml
</owl:Class>
<owl:Class rdf:ID="Stone">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >A lump or mass of hard consolidated mineral matter.</rdfs:comment>
 <rdfs:subClassOf rdf:resource="#Material"/>
</owl:Class>
<owl:Class rdf:ID="Chord">
 <rdfs:subClassOf>
  <owl:Restriction>
   <owl:onProperty>
    <owl:FunctionalProperty rdf:about="#hasRelativePosition"/>
   </owl:onProperty>
   <owl:cardinality rdf:datatype="http://www.w3.org/2001/XMLSchema#int"
   >1</owl:cardinality>
  </owl:Restriction>
 </rdfs:subClassOf>
 <rdfs:subClassOf rdf:resource="#Superstructure"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >A generally horizontal member of a truss.</rdfs:comment>
</owl:Class>
<owl:Class rdf:ID="Circular">
 <rdfs:subClassOf rdf:resource="#StandardShape"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >In the shape of a circle, round.</rdfs:comment>
</owl:Class>
<owl:Class rdf:ID="PrattTruss">
 <rdfs:subClassOf rdf:resource="#Truss"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >A truss with parallel chords and a web system composed of vertical posts with
diagonal ties inclined outward and upward from the bottom chord panel points toward
the ends of the truss; also known as N-truss.</rdfs:comment>
</owl:Class>
<owl:Class rdf:about="#Bearing">
 <rdfs:subClassOf rdf:resource="#Substructure"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 > A device at the ends of beams which is placed on top of a pier or abutment. The
ends of the beam rest on the bearing.</rdfs:comment>
</owl:Class>
<owl:Class rdf:ID="Rectangular">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >A quadrilateral polygon in which all four angles are right angles. </rdfs:comment>
 <rdfs:subClassOf rdf:resource="#StandardShape"/>
</owl:Class>
<owl:Class rdf:about="#GeographicCoordinate">
 <owl:disjointWith rdf:resource="#CartesianPoint"/>
 <rdfs:subClassOf rdf:resource="#Miscellaneous"/>
```

```
  <owl:disjointWith rdf:resource="#GeographicLocation"/>
  <owl:disjointWith rdf:resource="#PossibleUnit"/>
  <owl:disjointWith rdf:resource="#StationReference"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A set of numbers that designate a geographic location in a given reference system.</rdfs:comment>
  <owl:disjointWith rdf:resource="#OrganizationalPattern"/>
  <owl:disjointWith rdf:resource="#MeasuredUnit"/>
 </owl:Class>
 <owl:Class rdf:about="#LowSlumpConcrete">
  <owl:disjointWith rdf:resource="#Gravel"/>
  <rdfs:subClassOf rdf:resource="#WearingSurface"/>
  <owl:disjointWith rdf:resource="#Bituminous"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Wearing surface of low slump, dense concrete on a prepared surface in accordance with specifications in the Specifications Book for Highway Construction (http://www.modot.org/business/standards_and_specs/documents/Sec0505.pdf)</rdfs:comment>
  <owl:disjointWith rdf:resource="#IntegralConcrete"/>
  <owl:disjointWith rdf:resource="#EpoxyOverlay"/>
  <owl:disjointWith rdf:resource="#LatexConcrete"/>
  <owl:disjointWith rdf:resource="#MonolithicConcrete"/>
 </owl:Class>
 <owl:Class rdf:ID="Pier">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >A vertical structure which supports the ends of a multi-span superstructure at a location between abutments.</rdfs:comment>
  <rdfs:subClassOf rdf:resource="#Substructure"/>
 </owl:Class>
 <owl:Class rdf:ID="FramedBeam">
  <rdfs:subClassOf rdf:resource="#SteelConnection"/>
 </owl:Class>
 <owl:ObjectProperty rdf:ID="hasStressGrade">
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdfs:domain rdf:resource="#TimberDeck"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasModulusOfElasticity">
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdfs:domain rdf:resource="#Steel"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasThicknessOfPlates">
  <rdfs:domain rdf:resource="#WebSplice"/>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasDeadLoad">
```

```
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Identifies the dead load of a bridge.</rdfs:comment>
  <rdfs:domain rdf:resource="#Bridge"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="isReinforcedBy">
  <rdfs:domain>
   <owl:Class>
    <owl:unionOf rdf:parseType="Collection">
     <owl:Class rdf:about="#AuxiliaryComponents"/>
     <owl:Class rdf:about="#Bridge"/>
     <owl:Class rdf:about="#Member"/>
    </owl:unionOf>
   </owl:Class>
  </rdfs:domain>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Links a body to another body that reinforces it.</rdfs:comment>
  <rdfs:range rdf:resource="#ReinforcementConfiguration"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasOrganizationalPattern">
  <rdfs:domain>
   <owl:Class>
    <owl:unionOf rdf:parseType="Collection">
     <owl:Class rdf:about="#Member"/>
     <owl:Class rdf:about="#AuxiliaryComponents"/>
    </owl:unionOf>
   </owl:Class>
  </rdfs:domain>
  <rdfs:range rdf:resource="#OrganizationalPattern"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="supportProvidedBy">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Describe the structural element of the bridge that receives the weight of the utility
first.</rdfs:comment>
  <rdfs:domain rdf:resource="#Pipe"/>
  <rdfs:range rdf:resource="#Member"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasBottomFlangeThickness">
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdfs:domain rdf:resource="#Girder"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasSeconds">
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
  <rdfs:domain rdf:resource="#GeographicCoordinate"/>
```

```xml
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Identifies the seconds of a coordinate from a GPS instrument.</rdfs:comment>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasLongitude">
  <rdfs:domain rdf:resource="#GeographicLocation"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >World Longitude at reference point (most likely defined in legal description). Defined as integer values for degrees, minutes, seconds. Longitudes are measured relative to Greenwich as the prime meridian: longitudes west of Greenwich have positive values - from 0 till +180, longitudes east of Greenwich have negative values - from 0 till -180.</rdfs:comment>
  <rdfs:range rdf:resource="#GeographicCoordinate"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasBottomPlateThickness">
  <rdfs:domain rdf:resource="#WeldedPlate"/>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:about="#isMadeOf">
  <rdfs:range rdf:resource="#Material"/>
  <rdfs:domain>
   <owl:Class>
    <owl:unionOf rdf:parseType="Collection">
     <owl:Class rdf:about="#AuxiliaryComponents"/>
     <owl:Class rdf:about="#Bridge"/>
     <owl:Class rdf:about="#Member"/>
     <owl:Class rdf:about="#ReinforcementConfiguration"/>
    </owl:unionOf>
   </owl:Class>
  </rdfs:domain>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Links a body to the materials of which it was made.</rdfs:comment>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasDegrees">
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Identifies the degrees of a coordinate from a GPS instrument.</rdfs:comment>
  <rdfs:domain rdf:resource="#GeographicCoordinate"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasReferentialStation">
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Links to a station plus an offset to position an object.</rdfs:comment>
  <rdfs:range rdf:resource="#Station"/>
  <rdfs:domain rdf:resource="#StationReference"/>
```

```
&lt;/owl:ObjectProperty&gt;
&lt;owl:ObjectProperty rdf:ID="hasShearCapacityOfTheWeb"&gt;
 &lt;rdfs:range rdf:resource="#MeasuredUnit"/&gt;
 &lt;rdfs:domain rdf:resource="#Girder"/&gt;
&lt;/owl:ObjectProperty&gt;
&lt;owl:ObjectProperty rdf:ID="hasRise"&gt;
 &lt;rdfs:range rdf:resource="#MeasuredUnit"/&gt;
 &lt;rdfs:domain&gt;
  &lt;owl:Class&gt;
   &lt;owl:unionOf rdf:parseType="Collection"&gt;
    &lt;owl:Class rdf:about="#Bridge"/&gt;
    &lt;owl:Class rdf:about="#Member"/&gt;
   &lt;/owl:unionOf&gt;
  &lt;/owl:Class&gt;
 &lt;/rdfs:domain&gt;
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Identifies the rise of an object.&lt;/rdfs:comment&gt;
 &lt;rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/&gt;
&lt;/owl:ObjectProperty&gt;
&lt;owl:ObjectProperty rdf:ID="hasLiveLoad"&gt;
 &lt;rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/&gt;
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Identifies the live load of a bridge.&lt;/rdfs:comment&gt;
 &lt;rdfs:range rdf:resource="#MeasuredUnit"/&gt;
 &lt;rdfs:domain rdf:resource="#Bridge"/&gt;
&lt;/owl:ObjectProperty&gt;
&lt;owl:ObjectProperty rdf:ID="hasHeightOfPlates"&gt;
 &lt;rdfs:domain rdf:resource="#WebSplice"/&gt;
 &lt;rdfs:range rdf:resource="#WebSplice"/&gt;
&lt;/owl:ObjectProperty&gt;
&lt;owl:ObjectProperty rdf:ID="hasYoungModulus"&gt;
 &lt;rdfs:range rdf:resource="#MeasuredUnit"/&gt;
 &lt;rdfs:domain rdf:resource="#Material"/&gt;
&lt;/owl:ObjectProperty&gt;
&lt;owl:ObjectProperty rdf:ID="hasTypeOfReinforcement"&gt;
 &lt;rdfs:domain rdf:resource="#ReinforcedConcrete"/&gt;
&lt;/owl:ObjectProperty&gt;
&lt;owl:ObjectProperty rdf:ID="hasTopFlangeWidth"&gt;
 &lt;rdfs:range rdf:resource="#MeasuredUnit"/&gt;
 &lt;rdfs:domain rdf:resource="#Girder"/&gt;
&lt;/owl:ObjectProperty&gt;
&lt;owl:ObjectProperty rdf:ID="hasDryUnitWeight"&gt;
 &lt;rdfs:range rdf:resource="#MeasuredUnit"/&gt;
 &lt;rdfs:domain rdf:resource="#Soil"/&gt;
&lt;/owl:ObjectProperty&gt;
&lt;owl:ObjectProperty rdf:ID="hasShape"&gt;
```

```
  <rdfs:domain rdf:resource="#Member"/>
  <rdfs:range rdf:resource="#StandardShape"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="maximumPressure">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >If data is available, indicate the maximum bearing pressures.</rdfs:comment>
  <rdfs:domain rdf:resource="#Bearing"/>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasShearModulus">
  <rdfs:domain rdf:resource="#Material"/>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasPermeability">
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdfs:domain rdf:resource="#Soil"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasMedianType">
  <rdfs:domain rdf:resource="#Bridge"/>
  <rdfs:range rdf:resource="#MedianType"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Indicate if the median is non-existent, open or closed. The median is closed when the
area between the 2 roadways at the structure is bridged over and is capable of
supporting traffic.</rdfs:comment>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasCompressiveStrength">
  <rdfs:domain rdf:resource="#Concrete"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasMember">
  <rdfs:domain>
   <owl:Class>
    <owl:unionOf rdf:parseType="Collection">
     <owl:Class rdf:about="#Bridge"/>
     <owl:Class rdf:about="#Span"/>
     <owl:Class rdf:about="#Member"/>
    </owl:unionOf>
   </owl:Class>
  </rdfs:domain>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Links a bridge or a part of a bridge to one of its many different
members.</rdfs:comment>
  <rdfs:range rdf:resource="#Member"/>
 </owl:ObjectProperty>
```

```
 <owl:ObjectProperty rdf:ID="hasMainBarDepth">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Depth of the deepest grating bars that are being supported on the next level below
the grating.</rdfs:comment>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdfs:domain rdf:resource="#GratingDeck"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasYieldStrength">
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdfs:domain rdf:resource="#Steel"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasTopPlateThickness">
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdfs:domain rdf:resource="#WeldedPlate"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasDetourLength">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Indicate the actual length to the nearest kilometer of the detour length. The detour
length should represent the total additional travel for a vehicle which would result from
closing of the bridge.</rdfs:comment>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
  <rdfs:domain rdf:resource="#Bridge"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasBridgeEdgeToRailDistance">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Distance from the left edge of the bridge to the
inside face of the top portion of the rail for each track. For thru type of structures, use
the center line of the truss or girder as the edge of the bridge. For deck structures with
ties or some other type of track support, use the edge of this support.</rdfs:comment>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:about="#hasHeight">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >The vertical dimension of extension; distance from the base of an entity to the
top.</rdfs:comment>
  <rdfs:domain rdf:resource="#Member"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasAxisX">
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
  <rdfs:domain rdf:resource="#CartesianPoint"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
```

```
 >Identifies the point on the X axis.</rdfs:comment>
</owl:ObjectProperty>
<owl:ObjectProperty rdf:ID="isUsedFor">
 <rdfs:domain rdf:resource="#Bridge"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Identifies the usages of a bridge.</rdfs:comment>
</owl:ObjectProperty>
<owl:ObjectProperty rdf:ID="hasBridgeApproachAlignment">
 <rdfs:domain rdf:resource="#Bridge"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Notes whether the bridge is tangent or on a curve. If the bridge is on a curve, state the radius of the curve if plans are available for this information. On the older roads and bridges, a comparison between the alignment of the road should be made.</rdfs:comment>
 <rdfs:range rdf:resource="#MeasuredUnit"/>
</owl:ObjectProperty>
<owl:ObjectProperty rdf:ID="hasMinimumVerticalClearance">
 <rdfs:range rdf:resource="#MeasuredUnit"/>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
 <rdfs:domain rdf:resource="#Span"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Only the greatest of the "minimum clearances" for the two or more openings shall be coded regardless of the direction of travel.</rdfs:comment>
</owl:ObjectProperty>
<owl:ObjectProperty rdf:ID="hasWire">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Links a cable to specific wires.</rdfs:comment>
 <rdfs:domain rdf:resource="#Cable"/>
 <rdfs:range rdf:resource="#Wire"/>
</owl:ObjectProperty>
<owl:ObjectProperty rdf:ID="hasWebThickness">
 <rdfs:range rdf:resource="#Girder"/>
 <rdfs:domain rdf:resource="#Girder"/>
</owl:ObjectProperty>
<owl:ObjectProperty rdf:about="#hasEndPosition">
 <rdfs:range>
  <owl:Class>
   <owl:unionOf rdf:parseType="Collection">
    <owl:Class rdf:about="#CartesianPoint"/>
    <owl:Class rdf:about="#StationReference"/>
   </owl:unionOf>
  </owl:Class>
 </rdfs:range>
 <rdfs:domain rdf:resource="#Span"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Identifies the end position of point that characterizes a span.</rdfs:comment>
```

```xml
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasLatitude">
  <rdfs:domain rdf:resource="#GeographicLocation"/>
  <rdfs:range rdf:resource="#GeographicCoordinate"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >World Latitude at reference point (most likely defined in legal description). Defined as integer values for Degrees, minutes, seconds. Latitudes are measured relative to the equator, north of the equator by positive values - from 0 till +90, south of the equator by negative values - from 0 till -90.</rdfs:comment>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasMembrane">
  <rdfs:domain rdf:resource="#Deck"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Identifies membranes to protect the bridge deck.</rdfs:comment>
  <rdfs:range rdf:resource="#Membrane"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasMeanGrainSize">
  <rdfs:domain rdf:resource="#Soil"/>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasUnit">
  <rdfs:range rdf:resource="#PossibleUnit"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Identifies the unit of a given value.</rdfs:comment>
  <rdfs:domain rdf:resource="#MeasuredUnit"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:about="#hasType">
  <rdfs:range>
   <owl:Class>
    <owl:unionOf rdf:parseType="Collection">
     <owl:Class rdf:about="#BridgeType"/>
     <owl:Class rdf:about="#ConcreteDeckType"/>
    </owl:unionOf>
   </owl:Class>
  </rdfs:range>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Links a body with many different types of that body.</rdfs:comment>
  <rdfs:domain>
   <owl:Class>
    <owl:unionOf rdf:parseType="Collection">
     <owl:Class rdf:about="#Bridge"/>
     <owl:Class rdf:about="#ConcreteDeck"/>
    </owl:unionOf>
   </owl:Class>
```

```
  </rdfs:domain>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="isConnectedBy">
  <rdfs:domain rdf:resource="#Girder"/>
  <rdfs:range rdf:resource="#Connection"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:about="#hasStartPosition">
  <rdfs:range>
   <owl:Class>
    <owl:unionOf rdf:parseType="Collection">
     <owl:Class rdf:about="#StationReference"/>
     <owl:Class rdf:about="#CartesianPoint"/>
    </owl:unionOf>
   </owl:Class>
  </rdfs:range>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Identifies the start position of point that characterizes a span.</rdfs:comment>
  <rdfs:domain rdf:resource="#Span"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasDynamicViscosity">
  <rdfs:domain rdf:resource="#Material"/>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasSkewAngle">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >The skew angle is the angle between the centerline of a pier and a line normal to the
roadway centerline.</rdfs:comment>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
  <rdfs:domain rdf:resource="#Pier"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="capacity">
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >If data is available, indicate the pile capacities.</rdfs:comment>
  <rdfs:domain rdf:resource="#Pile"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasWearingSurface">
  <rdfs:range rdf:resource="#WearingSurface"/>
  <rdfs:domain rdf:resource="#Deck"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Information on the wearing surface of the bridge deck</rdfs:comment>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasMainBarSpacing">
  <rdfs:domain rdf:resource="#GratingDeck"/>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
```

```
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Center-to-center distance of the main bars.</rdfs:comment>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasTopFlangeThickness">
  <rdfs:domain rdf:resource="#Girder"/>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasRoadwayWidth">
  <rdfs:domain rdf:resource="#Bridge"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >The most restrictive of the clear width(s) between curbs, railings, or other restrictions
for the roadway on the bridge. </rdfs:comment>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasBottomFlangeWidth">
  <rdfs:domain rdf:resource="#Girder"/>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasSaturatedUnitWeight">
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdfs:domain rdf:resource="#Soil"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasShearStrength">
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdfs:domain rdf:resource="#Soil"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasDepth">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Extent downward or backward or inward.</rdfs:comment>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdfs:domain rdf:resource="#Deck"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasThermalExpansionCoefficient">
  <rdfs:domain rdf:resource="#Material"/>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:about="#hasWidth">
  <rdfs:domain>
   <owl:Class>
    <owl:unionOf rdf:parseType="Collection">
     <owl:Class rdf:about="#Member"/>
     <owl:Class rdf:about="#TimberDeck"/>
    </owl:unionOf>
   </owl:Class>
  </rdfs:domain>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
```

```
  >The extent of a body from side to side.</rdfs:comment>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasMainBarThickness">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Thickness of the main bars.</rdfs:comment>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdfs:domain rdf:resource="#GratingDeck"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasWebDepth">
  <rdfs:domain rdf:resource="#Girder"/>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasProtection">
  <rdfs:domain rdf:resource="#Deck"/>
  <rdfs:range rdf:resource="#DeckProtection"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Information on the protective system of the bridge deck.</rdfs:comment>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasWidthOfPlates">
  <rdfs:domain rdf:resource="#WebSplice"/>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasDiameter">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >The length of a straight line passing through the center of a circle and connecting two
points on the circumference.</rdfs:comment>
  <rdfs:domain rdf:resource="#Pipe"/>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
 </owl:ObjectProperty>
 <owl:ObjectProperty rdf:ID="hasAxisY">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Identifies the point on the Y axis.</rdfs:comment>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
  <rdfs:domain rdf:resource="#CartesianPoint"/>
 </owl:ObjectProperty>
 <owl:DatatypeProperty rdf:ID="hasNumberOfTopBars">
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#int"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Number of top bars per foot in the concrete deck.</rdfs:comment>
  <rdfs:domain rdf:resource="#ConcreteDeck"/>
 </owl:DatatypeProperty>
 <owl:DatatypeProperty rdf:ID="hasSoilType">
  <rdfs:domain rdf:resource="#Soil"/>
```

```xml
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="hasSaturation">
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#float"/>
 <rdfs:domain rdf:resource="#Soil"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="hasSite">
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Identifies the site or location of a bridge. (e.g. Niagara Falls, New York - Canada).</rdfs:comment>
 <rdfs:domain rdf:resource="#Bridge"/>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="hasSizeOfBottomBars">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Size of the bottom bars used in the slab.</rdfs:comment>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#int"/>
 <rdfs:domain rdf:resource="#ConcreteDeck"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="hasManufacturer">
 <rdfs:domain rdf:resource="#Member"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Identifies the manufacturers of a piece.</rdfs:comment>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="hasSpecificGravity">
 <rdfs:domain rdf:resource="#Soil"/>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#float"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="hasNumberOfArches">
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
 <rdfs:domain rdf:resource="#Arched"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Identifies the number of arches an arched bridge has.</rdfs:comment>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#int"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="conductsUtilityType">
 <rdfs:domain rdf:resource="#Pipe"/>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Identifies the material carried in the conduit or pipe, such as cable, fluid and gas.</rdfs:comment>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="hasHistory">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
```

```
 >Describes any important piece of information found in the bridge's history.</rdfs:comment>
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
  <rdfs:domain rdf:resource="#Bridge"/>
 </owl:DatatypeProperty>
 <owl:DatatypeProperty rdf:ID="hasSpanOver">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Describes the bodies a bridge spans over. (e.g. Golden State Strait, North Bay)</rdfs:comment>
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
  <rdfs:domain rdf:resource="#Bridge"/>
 </owl:DatatypeProperty>
 <owl:DatatypeProperty rdf:ID="hasVoidRatio">
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#float"/>
  <rdfs:domain rdf:resource="#Soil"/>
 </owl:DatatypeProperty>
 <owl:DatatypeProperty rdf:ID="hasWaterContent">
  <rdfs:domain rdf:resource="#Soil"/>
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#float"/>
 </owl:DatatypeProperty>
 <owl:DatatypeProperty rdf:ID="hasConsultingEngineer">
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
  <rdfs:domain rdf:resource="#Bridge"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Identifies the engineers who were consulted during the bridge's life cycle.</rdfs:comment>
 </owl:DatatypeProperty>
 <owl:DatatypeProperty rdf:ID="isLoadPathRedundant">
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#boolean"/>
  <rdfs:domain rdf:resource="#WebSplice"/>
 </owl:DatatypeProperty>
 <owl:DatatypeProperty rdf:ID="hasNumberOfLeaves">
  <rdfs:domain rdf:resource="#Steel"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Identifies the number of leaves a steel piece has.</rdfs:comment>
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#int"/>
 </owl:DatatypeProperty>
 <owl:DatatypeProperty rdf:ID="hasNumberOfCables">
  <rdfs:domain rdf:resource="#Suspension"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#int"/>
 </owl:DatatypeProperty>
 <owl:DatatypeProperty rdf:ID="hasSoilStructure">
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
  <rdfs:domain rdf:resource="#Soil"/>
 </owl:DatatypeProperty>
```

```
<owl:DatatypeProperty rdf:ID="hasRelativeDensity">
 <rdfs:domain rdf:resource="#Soil"/>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#float"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="hasNumberOfSpans">
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#int"/>
 <rdfs:domain rdf:resource="#Bridge"/>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="hasCoefficientOfUniformity">
 <rdfs:domain rdf:resource="#Soil"/>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:about="#typeOfLengthMeasurement">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Note whether the measurement of the length is center to center (c/c) or clear open
distance (clr) between piers, bents, or abutments.</rdfs:comment>
 <rdfs:domain rdf:resource="#Span"/>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="hasTollStatus">
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >The toll status of the structure is indicated by this item. e.g toll bridge; on toll road; on
free road.</rdfs:comment>
 <rdfs:domain rdf:resource="#Bridge"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="isHeatTreated">
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#boolean"/>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
 <rdfs:domain rdf:resource="#Steel"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="hasNumberOfStrands">
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
 <rdfs:domain rdf:resource="#Cable"/>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#int"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Identifies the number of strands in a cable.</rdfs:comment>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="hasPorosity">
 <rdfs:domain rdf:resource="#Soil"/>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#float"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="hasPoissonRatio">
 <rdfs:domain rdf:resource="#Material"/>
```

```
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#float"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="isCast">
 <rdfs:domain rdf:resource="#Iron"/>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#boolean"/>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="hasSizeOfTopBars">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Size of the top bars used in the slab.</rdfs:comment>
 <rdfs:domain rdf:resource="#ConcreteDeck"/>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#int"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="IntegerValue">
 <rdfs:domain rdf:resource="#MeasuredUnit"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Identifies data given as an integer value.</rdfs:comment>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#int"/>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="hasNumberOfStressCycles">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Number of stress cycles to which the splice is to be subjected.</rdfs:comment>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#int"/>
 <rdfs:domain rdf:resource="#WebSplice"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="hasPlaceOfCast">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Identifies if the concrete is cast-in-place or precast.</rdfs:comment>
 <rdfs:domain rdf:resource="#Concrete"/>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#FunctionalProperty"/>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="hasConstructionEngineer">
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Identifies the construction engineers of the bridge.</rdfs:comment>
 <rdfs:domain rdf:resource="#Bridge"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="hasChiefEngineer">
 <rdfs:domain rdf:resource="#Bridge"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Identifies the chief engineers of the bridge.</rdfs:comment>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="haspH">
```

```
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#float"/>
  <rdfs:domain rdf:resource="#Soil"/>
 </owl:DatatypeProperty>
 <owl:FunctionalProperty rdf:ID="isOrthotropic">
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#boolean"/>
  <rdfs:domain rdf:resource="#Material"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >The material is isotropic or orthotropic.</rdfs:comment>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
 </owl:FunctionalProperty>
 <owl:FunctionalProperty rdf:about="#hasRelativePosition">
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
  <rdfs:domain>
   <owl:Class>
    <owl:unionOf rdf:parseType="Collection">
     <owl:Class rdf:about="#Bracing"/>
     <owl:Class rdf:about="#Post"/>
     <owl:Class rdf:about="#Chord"/>
    </owl:unionOf>
   </owl:Class>
  </rdfs:domain>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Relative position such as intermediate, portal, lower, upper, end.</rdfs:comment>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
 </owl:FunctionalProperty>
 <owl:FunctionalProperty rdf:ID="hasMultiplierForInitialPosition">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Identifies number that will multiply the initial position of a station (e.g.
10,000).</rdfs:comment>
  <rdfs:domain rdf:resource="#Station"/>
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#int"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
 </owl:FunctionalProperty>
 <owl:FunctionalProperty rdf:ID="hasStructureNumber">
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
  <rdfs:domain rdf:resource="#Bridge"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Each agency should code the structure number according to its own internal
processing procedures. The structure number must be unique for each bridge within the
State, and once established should preferably never change for the life of the
bridge.</rdfs:comment>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
 </owl:FunctionalProperty>
 <owl:FunctionalProperty rdf:ID="isFlared">
  <rdfs:domain rdf:resource="#Bridge"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
```

```
 >Indicate if the structure is flared (i.e., the width of the structure
varies).</rdfs:comment>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#boolean"/>
 </owl:FunctionalProperty>
 <owl:FunctionalProperty rdf:ID="hasEstimatedTotalCost">
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdfs:domain rdf:resource="#Bridge"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Identifies how much a bridge was estimated to cost, in comparison with the actual
cost.</rdfs:comment>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#ObjectProperty"/>
 </owl:FunctionalProperty>
 <owl:FunctionalProperty rdf:ID="hasAxisZ">
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdfs:domain rdf:resource="#CartesianPoint"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Identifies the point on the Z axis.</rdfs:comment>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#ObjectProperty"/>
 </owl:FunctionalProperty>
 <owl:FunctionalProperty rdf:ID="isWeathering">
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#boolean"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
  <rdfs:domain rdf:resource="#Steel"/>
 </owl:FunctionalProperty>
 <owl:FunctionalProperty rdf:ID="hasInitialPosition">
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#ObjectProperty"/>
  <rdfs:domain rdf:resource="#Station"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Identifies the initial position of point that characterizes a station, without the
offset.</rdfs:comment>
 </owl:FunctionalProperty>
 <owl:FunctionalProperty rdf:about="#spanLength">
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdfs:domain rdf:resource="#Span"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#ObjectProperty"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Should be recorded to the nearest foot and it shall be measured along the centerline
of the bridge.</rdfs:comment>
 </owl:FunctionalProperty>
 <owl:FunctionalProperty rdf:ID="hasFloatValue">
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#float"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Identifies data given as a float value.</rdfs:comment>
```

```
 <rdfs:domain rdf:resource="#MeasuredUnit"/>
</owl:FunctionalProperty>
<owl:FunctionalProperty rdf:ID="hasWeightPerFoot">
 <rdfs:domain>
  <owl:Class>
   <owl:unionOf rdf:parseType="Collection">
    <owl:Class rdf:about="#Pipe"/>
    <owl:Class rdf:about="#RolledBeamGirder"/>
   </owl:unionOf>
  </owl:Class>
 </rdfs:domain>
 <rdfs:range rdf:resource="#MeasuredUnit"/>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#ObjectProperty"/>
</owl:FunctionalProperty>
<owl:FunctionalProperty rdf:ID="hasSupportDistance">
 <rdfs:range rdf:resource="#MeasuredUnit"/>
 <rdfs:domain rdf:resource="#Deck"/>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#ObjectProperty"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Center-to-center distance between the members supporting the deck.</rdfs:comment>
</owl:FunctionalProperty>
<owl:FunctionalProperty rdf:ID="hasNumberOfBottomBars">
 <rdfs:domain rdf:resource="#ConcreteDeck"/>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#int"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Number of bottom bars per foot in the concrete deck.</rdfs:comment>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
</owl:FunctionalProperty>
<owl:FunctionalProperty rdf:about="#hasThickness">
 <rdfs:domain>
  <owl:Class>
   <owl:unionOf rdf:parseType="Collection">
    <owl:Class rdf:about="#AuxiliaryComponents"/>
    <owl:Class rdf:about="#WearingSurface"/>
    <owl:Class rdf:about="#Member"/>
   </owl:unionOf>
  </owl:Class>
 </rdfs:domain>
 <rdfs:range rdf:resource="#MeasuredUnit"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Identifies how thick a given body is.</rdfs:comment>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#ObjectProperty"/>
</owl:FunctionalProperty>
<owl:FunctionalProperty rdf:ID="hasLength">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
```

```
  >This shall be the length of roadway which is supported on the bridge structure. The length should be measured back to back of backwalls of abutments or from paving notch to paving notch. Culvert lengths should be measured along the center line of roadway regardless of their depth below grade. Measurement should be made between inside faces of exterior walls. Tunnel length should be measured along the centerline of the roadway.</rdfs:comment>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdfs:domain rdf:resource="#Bridge"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#ObjectProperty"/>
 </owl:FunctionalProperty>
 <owl:FunctionalProperty rdf:ID="isComposite">
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#boolean"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
  <rdfs:domain rdf:resource="#Girder"/>
 </owl:FunctionalProperty>
 <owl:FunctionalProperty rdf:ID="hasElevation">
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Datum elevation relative to sea level.</rdfs:comment>
  <rdfs:domain rdf:resource="#GeographicLocation"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#ObjectProperty"/>
  <rdfs:range rdf:resource="#MeasuredUnit"/>
 </owl:FunctionalProperty>
 <owl:FunctionalProperty rdf:ID="hasGeographicLocation">
  <rdfs:range rdf:resource="#GeographicLocation"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#ObjectProperty"/>
  <rdfs:domain>
   <owl:Class>
    <owl:unionOf rdf:parseType="Collection">
     <owl:Class rdf:about="#Station"/>
     <owl:Class rdf:about="#Bridge"/>
    </owl:unionOf>
   </owl:Class>
  </rdfs:domain>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Identifies the geographic location of a body with the coordinates of a GPS.</rdfs:comment>
 </owl:FunctionalProperty>
 <owl:FunctionalProperty rdf:ID="hasStrength">
  <rdfs:domain>
   <owl:Class>
    <owl:unionOf rdf:parseType="Collection">
     <owl:Class rdf:about="#AuxiliaryComponents"/>
     <owl:Class rdf:about="#Member"/>
    </owl:unionOf>
   </owl:Class>
  </rdfs:domain>
```

```xml
 <rdfs:range rdf:resource="#MeasuredUnit"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >The ultimate strength of an entity.</rdfs:comment>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#ObjectProperty"/>
</owl:FunctionalProperty>
<owl:FunctionalProperty rdf:ID="hasNumberOfLanesUnder">
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
 <rdfs:domain rdf:resource="#Bridge"/>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#int"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Number of traffic lanes being crossed by the structure.</rdfs:comment>
</owl:FunctionalProperty>
<owl:FunctionalProperty rdf:ID="hasRampOnSpanNumber">
 <rdfs:domain rdf:resource="#Ramp"/>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#int"/>
</owl:FunctionalProperty>
<owl:FunctionalProperty rdf:ID="isAcceptable">
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#boolean"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Inspected feature meets currently acceptable standards.</rdfs:comment>
 <rdfs:domain rdf:resource="#Safety"/>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
</owl:FunctionalProperty>
<owl:FunctionalProperty rdf:ID="isContinuous">
 <rdfs:domain>
  <owl:Class>
   <owl:unionOf rdf:parseType="Collection">
    <owl:Class rdf:about="#Beam"/>
    <owl:Class rdf:about="#Arch"/>
    <owl:Class rdf:about="#Culvert"/>
    <owl:Class rdf:about="#Frame"/>
    <owl:Class rdf:about="#Girder"/>
    <owl:Class rdf:about="#Truss"/>
    <owl:Class rdf:about="#Slab"/>
   </owl:unionOf>
  </owl:Class>
 </rdfs:domain>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#boolean"/>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Whether the member is continuous or not.</rdfs:comment>
</owl:FunctionalProperty>
<owl:FunctionalProperty rdf:ID="hasLandCost">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Identifies how much the land to build the bridge cost.</rdfs:comment>
```

```xml
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#ObjectProperty"/>
 <rdfs:range rdf:resource="#MeasuredUnit"/>
 <rdfs:domain rdf:resource="#Bridge"/>
</owl:FunctionalProperty>
<owl:FunctionalProperty rdf:ID="hasMinutes">
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Identifies the minutes of a coordinate from a GPS instrument.</rdfs:comment>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#ObjectProperty"/>
 <rdfs:domain rdf:resource="#GeographicCoordinate"/>
 <rdfs:range rdf:resource="#MeasuredUnit"/>
</owl:FunctionalProperty>
<owl:FunctionalProperty rdf:ID="isHollow">
 <rdfs:domain>
  <owl:Class>
   <owl:unionOf rdf:parseType="Collection">
    <owl:Class rdf:about="#StandardShape"/>
    <owl:Class rdf:about="#GratingDeck"/>
   </owl:unionOf>
  </owl:Class>
 </rdfs:domain>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#boolean"/>
</owl:FunctionalProperty>
<owl:FunctionalProperty rdf:ID="hasWeight">
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#ObjectProperty"/>
 <rdfs:range rdf:resource="#MeasuredUnit"/>
 <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
 >Identifies the total weight of a body.</rdfs:comment>
 <rdfs:domain>
  <owl:Class>
   <owl:unionOf rdf:parseType="Collection">
    <owl:Class rdf:about="#AuxiliaryComponents"/>
    <owl:Class rdf:about="#Bridge"/>
    <owl:Class rdf:about="#Member"/>
   </owl:unionOf>
  </owl:Class>
 </rdfs:domain>
</owl:FunctionalProperty>
<owl:FunctionalProperty rdf:ID="hasBendingStrength">
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#ObjectProperty"/>
 <rdfs:range rdf:resource="#MeasuredUnit"/>
 <rdfs:domain rdf:resource="#Timber"/>
</owl:FunctionalProperty>
<owl:FunctionalProperty rdf:about="#polarOrientation">
 <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
 <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
```

```xml
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >State if it's North, South, East, or West.</rdfs:comment>
  <rdfs:domain>
   <owl:Class>
    <owl:unionOf rdf:parseType="Collection">
     <owl:Class rdf:about="#Curb"/>
     <owl:Class rdf:about="#Sidewalk"/>
    </owl:unionOf>
   </owl:Class>
  </rdfs:domain>
 </owl:FunctionalProperty>
 <owl:FunctionalProperty rdf:ID="isWrought">
  <rdfs:domain rdf:resource="#Iron"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#boolean"/>
 </owl:FunctionalProperty>
 <owl:FunctionalProperty rdf:ID="hasNumberOfWires">
  <rdfs:domain rdf:resource="#Cable"/>
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#int"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Identifies the number of wires in a cable.</rdfs:comment>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#DatatypeProperty"/>
 </owl:FunctionalProperty>
 <owl:FunctionalProperty rdf:ID="hasOffset">
  <rdfs:range rdf:resource="#MeasuredUnit"/>
  <rdfs:domain>
   <owl:Class>
    <owl:unionOf rdf:parseType="Collection">
     <owl:Class rdf:about="#Station"/>
     <owl:Class rdf:about="#StationReference"/>
    </owl:unionOf>
   </owl:Class>
  </rdfs:domain>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#ObjectProperty"/>
  <rdfs:comment rdf:datatype="http://www.w3.org/2001/XMLSchema#string"
  >Identifies what is the offset to be added to the starting position of a
station.</rdfs:comment>
 </owl:FunctionalProperty>
 <Pier rdf:ID="bridges_Individual_30"/>
 <OrganizationalPattern rdf:ID="Curved"/>
</rdf:RDF>

<!-- Created with Protege (with OWL Plugin 1.3, Build 225.4)

http://protege.stanford.edu -->
```

APPENDIX B. PAPER SUBMITTED TO TRB PROCEEDINGS, 2007

Ontology Engineering for Management of Data in the Transportation Domain

Gustavo Sudre, BS
Research Assistant
The University of Kansas – EECS Department

Samuel Hanson
Research Assistant
The University of Kansas – EECS Department

Adolfo Matamoros, PhD
Associate Professor
The University of Kansas – CEAE Department

Steve Graham, PhD
Assistant Professor
Dakota State University - Computer Science & Information Assurance

APPENDIX B ABSTRACT

This paper explores the use of the Semantic Web to address two major problems facing transportation agencies: the management of increasingly larger pools of information and the lack of interoperability between software agents used for the management of sub-sets of that information. An ontology was created to describe information in the domain of bridges following basic principles of ontology and software engineering. The ontology employed a modular structure intended to facilitate interoperability and reuse. The ontology was evaluated through Use Cases based on data and applications obtained from the Kansas Department of Transportation. It was found that the implementation of the bridge ontology presented significant benefits over traditional search and storage methods used by KDOT for the case studies that were analyzed.

B.1 Introduction

The management of large pools of information is becoming an increasingly complex problem facing Transportation Agencies. In the current state of practice data originating from different areas of related knowledge (domains) is stored and managed through multiple and often incompatible software agents. The lack of interoperability between agents makes it difficult, inefficient, and costly to store and retrieve information accurately. This interoperability problem can be addressed through the conceptualization of the knowledge in each domain, by establishing a common understanding of the knowledge being managed.

The development of ontologies is an effective solution for describing knowledge and the relationships that exist between elements of a domain, clarifying assumptions and establishing a shared understanding of terms and their relationships. For this reason ontologies can alleviate the interoperability problem within the agencies that develop and adopt them. However, unless some commonality is established, the interoperability problem will remain at a higher level. Furthermore, a significant investment of resources is needed for the development of robust ontologies, which is why there are significant advantages in creating them with the goal of reuse.

This paper provides background information on ontologies and the Semantic Web and discusses the process of developing an ontology to describe knowledge in the domain of bridges. A detailed description of the ontology is presented elsewhere *(1)*.

B.2 Project Goals

The first step in the development of the bridge ontology was to define the scope of the domain. One of the fundamental problems in ontology engineering is that knowledge in a specific field is related in multiple ways to knowledge in peripheral fields.

For this reason it is essential to define boundaries for a domain in order to make the development of an ontology a feasible task. The domain of bridges was chosen because it encompassed a significant portion of the information that is managed by the Kansas Department of Transportation (KDOT), which was the main sponsor of the project.

The methodology adopted to develop the bridge ontology was derived from various established methods for ontology engineering *(2)*. The project sought to create two different types of ontologies in order to learn about the interactions necessary to improve interoperability:

- Broad and shallow ontology: defines general concepts to be used by domain-specific ontologies.

- Narrow and deep ontology**:** defines a specific domain to a greater extent.

The bridge_record ontology was developed as a broad and shallow ontology with the goal of providing the semantic connections between the various elements that compose a bridge record. The record of a bridge contains several pieces of information such as inventory and personnel data, and it is crucial to identify and manage information about bridges. The bridge_parts ontology was developed as a narrow and deep ontology, and it contains definitions about the parts of a bridge and relationships between them. The bridge ontology encompasses both the bridge_record and bridge_parts ontologies. For example, if the bridge ontology is used to describe data about bridge repair, the bridge_record ontology is used to describe repair reports, while the bridge_parts ontology is used to organize information about the structural elements in a bridge that were repaired.

The classification of the two aforementioned ontologies was specific to the domain of information analyzed in this particular project, and may change depending on the scope of the domain. While the bridge_record ontology represented a broader domain than the bridge_parts ontology, this is not true when bridge_record ontology is placed in the context of the entire transportation domain. In that case, an ontology representing the transportation domain would be classified as a broad and shallow ontology, while the bridge_record ontology would be classified as a narrow and deep ontology. Likewise, the bridge_parts ontology would be classified as a broad and shallow ontology compared with narrower fields like types of materials or structural connections.

B.3 Background

Terms commonly used in the context of describing ontologies are presented in the following. Metadata is information about the data, such as author, date, topic, and computer program used to write the data. To illustrate, one can consider the old library cards as metadata about books. Likewise, ontologies can be considered metadata about domains.

Classes are used in ontologies to represent concepts within a domain. A class can have subclasses under it that define more specific concepts, making that class a superclass of its subclasses. Classes have properties that describe their features. To describe individuals in a certain class, instances are defined. For example, if the classes

“Male” and “Female” exist as subclasses under the class “Person”, then Paul would be an instance of the “Male” class and Kristy would be an instance of the “Female” class.

B.3.1 Ontology Applications

The following are goals commonly sought in the process of building ontologies *(3)*:

- To share common understanding of the structure of information among people or software agents. This is crucial because it helps agents, whether they are software or people, to communicate more effectively since they all have access to the same underlying base of information contained in the ontology.

- Enable the reuse of domain knowledge. An example of reuse would be if a group needed to represent time in their domain. If there is already a functional time ontology in existence, then the group could simply reuse this ontology, rather than spending time and other resources developing their own time ontology.

- Making explicit domain assumptions. In defining all the concepts in the scope of an ontology, the assumptions within a domain become explicit. Having explicit domain assumptions makes it easier to change them if knowledge about the domain changes and it makes it easier for users that may be unfamiliar with the domain to learn about it.

- Separate domain knowledge from the operational knowledge. This means that one can take the domain knowledge and apply it in different areas. An example is taking an ontology that covers information on bridges and applying it to the different areas of bridge design, bridge repair, and bridge management.

- Automated reasoning. Since ontologies define the terms and the relationships between them, they have the ability to return answers to queries about terms and relationships in the domain that they define.

B.3.2 The Semantic Web

Ontologies are useful tools to organize and model relationships between data. Because machines can sift through data faster than humans, the benefits of developing it would make sense to have software to interact with ontologies increase as the volume of information being managed increases. One of the main advantages goals of ontologies is that they proo vide an improved foundation for develop the future of the World Wide Web (WWW). In this vision, called the Semantic Web *(4)*, data can be annotated so that a less intelligent agent, such as a computer program, can retrieve data and determine its meaning based on its context *(5)*.

In the current state of practice, data available on the WWW is not well organized and Currently, there is no organization to the data available on the web and there is very little metadata associated with it to describe its meaningabout information. Some automated tools, such as the Google search engine *(6)*, analyze the content of a web site and attempt to extract information about the data. This method of retrieving information is less effective than the Semantic Web and it may lead to search results in which large amounts of irrelevant data are retrieved, or in which little information is found.

B.4 Related Work

Before starting to develop an ontology describing the bridge domain, it was important to investigate previous efforts towards organizing information in the transportation domain.

B.4.1 Library of Congress Classification and Dewey Decimal System

The Library of Congress Classification system (LCC) and the Dewey Decimal system are both widely used to organize different sorts of documents in libraries. The goal of observing these classification systems was to create a taxonomy based on their data, and then elaborate on the initial taxonomic tree in order to add properties intrinsic to the transportation domain. Two categories of the LCC were closely related to the scope of this project: HE – Transportation and Communications *(7)*, and TA – Civil Engineering *(8)*. The subcategories presented by both the LCC and Dewey Decimal systems, although useful, were found to be not comprehensive enough to properly describe the domain.

B.4.2 Transportation Research Thesaurus (TRT)

The TRT was one of the most complete sources of information found during this project. It contains a comprehensive tree of terms *(9)* related to the transportation domain, and covers all subjects related to the following transportation modes: air, land, water, space, and ground. The latter is covered more in-depth, and it was found to be particularly useful because it encompassed the domain of bridges.

The terms listed in this thesaurus and their organization were used to complement information previously collected from other sources *(1)*. Also, many times the hierarchy in the TRT did not agree with the data previously collected by the researchers. In those cases, the structure used in the TRT was given priority because it was compiled by a renowned entity (Transportation Research Board), and this is important towards the creation of a standard for the domain.

Although the TRT had a very comprehensive list of terms, it followed the parental relationships characteristic of thesauri. Thus, all other relationships that are intrinsic to the transportation domain still have to be added to these terms in order to produce an ontology.

B.4.3 Third-party Software

Third-party software for bridge design and bridge management was important to develop a comprehensive list of concepts necessary to describe bridge components. Because in most cases the software analyzed was proprietary, it was not always possible to review the manner in which the information was organized within the databases used by the programs. However, several classes and properties that were missing in the ontology were identified by analyzing input and output data, manuals, screenshots, and help files.

It was evident from this analysis that each program had a particular structure to organize and store bridge data, which causes interoperability problems. Even though these computer programs used essentially the same type of information, the transfer of information between them can be a complicated task. The following programs were reviewed during this information gathering stage:

- AASHTOWare® products *(10)*: the programs analyzed were Pontis, for Bridge Management, and Virtis/Opis, for bridge design and rating. The bridge concepts recognized by these programs are summarized by Thompson and Shepard *(11)*.

- BRASS™ Suite of Computer Programs *(12)*: comprehensive set of programs designed by the Wyoming Department of Transportation for bridge design and analysis.

- Pennsylvania Department of Transportation Engineering Programs *(13)*: broad set of software suited for bridge analysis, rating, and design.

B.4.4 TransXML

This project was created by the National Cooperative Highway Research Program to develop a set of eXtensible Markup Language (XML) schema for transportation applications. The main objectives of the project were to create broadly accepted public domain XML schemas for exchange of transportation data, and a framework for development, validation, dissemination, and extension of current and future schemas *(14)*.

Although the ultimate goal of the project was to encompass a broader set of schemas for all crucial transportation business areas, it initially focused on four areas essential for interoperability with the AASHTOWare software: survey and roadway design, transportation construction and materials, transportation safety, and highway bridge structures. Among these areas, the latter was of the most interest to this ontology development effort.

Integrating the results of the TransXML project to the bridge ontology was given strong consideration. However, after carefully studying the TransXML UML Description for Highway Bridge Structures *(15)* it was concluded that the TransXML project covered mostly the design and analysis of bridges. Areas within the scope of this project, such as inspection, inventory, history, finances, and personnel, were not represented in the

TransXML schema. Moreover, because the TransXML schema focused on describing data from pre-stressed I-Beams, and the manner in which the Geography Markup Language (GML) was used to describe geometric forms was unclear, the integration to the bridge ontology was halted. If the TransXML schema indeed becomes a standard in the industry, mapping the data model to the bridge_parts ontology is an attainable goal.

B.5 Bridge Ontology

The main purpose of the bridge ontology is was to improve the management and sharing of information about different types of bridges. The process of finding similar facts about bridges can be simplified by establishing relationships between data, which is a feature inherent to ontologies. Also, the use of ontologies allows capturing and sharing knowledge about bridges, and can be used to overcome interoperability problems.

B.5.1 Tools and Resources

The following sections describe the tools that were used in this project, and also identify the resources used to acquire the knowledge necessary to build the bridge ontology.

B.5.1.1 Languages for Representing Ontologies

XML is a flexible metadata language which is based on a small set of standard tags. One of the most significant features of XML is that it can be extended through user-defined tags constructed from the standard set *(16)*. However, user-defined tags must be explained to all agents that make use of an XML file in order to make these tags recognizable by the agents. Although this feature gives the language great flexibility, it is not sufficient to make the language well-suited to organize metadata. One of the areas of weakness of XML is scalability. In order for a language to be scalable, it should be able to manage information regardless of the amount. For instance, the order in which elements are listed in an XML file is important, and therefore it matters whether the name of a bridge is listed before its location. It is impractical to expect that these two concepts will always appear in this particular order, which limits the ability of a language such as XML to cope with large sets of data.

For the aforementioned reason the Resource Description Framework (RDF) *(17)* is more commonly used than XML for organizing metadata. RDF consists of triples of a subject, predicate, and object to describe data. The subject is always a Unique Resource Identifier (URI), which guarantees the uniqueness of information being described regardless of the order in which is presented. The object can be a literal (e.g. text strings, numbers), or another URI. It is important to notice that the predicates are also resources in order to assure their uniqueness.

Although both XML and RDF can be used to express basic relationships, such as "XYZ is a bridge in Kansas", the meaning of the relationship can only be expressed by using RDF. In other words, RDF can be used to express semantics about the "is a bridge in" property, which is necessary for further reasoning with this information. Furthermore, there is a semantic extension to RDF called RDF Schema (RDFS), which is basically a language for describing vocabularies in RDF *(18)*. Using RDFS it is possible to describe groups of related resources (such as classes, subclasses, and their properties) and the relationships among them.

Finally, the Web Ontology Language (OWL) incorporates elements from RDFS, and it is built on top of RDF (and therefore, XML). OWL is a very expressive language, which allows exact expressions of relationships between classes and properties, as well as other features such as inverse properties, equivalent classes, logical expressions, and cardinality of properties. It is a well-defined open standard, meaning that anyone has free access to the full language specification *(19)*. The fact that OWL has an open specification has contributed to this language becoming a widely-used standard for ontology development, and has lead to the development of many applications based on this language *(20)*.

The bridge ontology was implemented using two different OWL files *(21)*, one for each part of the ontology. This type of structure allows other developers to use either the bridge_parts or bridge_record ontologies for a different operational area, or to use the representation of a bridge record with different metadata to describe the parts of the bridge.

B.5.1.2 Protégé

Protégé *(22)* is an ontology development environment created at Stanford University which supports many ontology languages, including OWL, XML, and RDF. Figure B1 shows a representation of the bridge_parts ontology in Protégé. One of the advantages of Protégé is that it is written in the Java programming language which allows it to run in different platforms. Also, because of the structure of the program, it is relatively easy to develop extensions that provide new capabilities.

B.5.1.3 Knowledge Acquisition

Several sources *(23) (24) (25) (26) (27) (28)* were used to develop a list of concepts related to bridges. Using multiple sources was important to capture the different terminology used to describe bridge elements, and to verify that there was consensus in the meaning of specific concepts. While all sources were useful in this process, the AASHTO Manual for Condition Evaluation of Bridges *(29)* and the TexasDOT Bridge Inspection Manual *(30)* were particularly important in the development of the bridge_record ontology because these two documents addressed bridge management, inspection, and guidelines for storing such data.

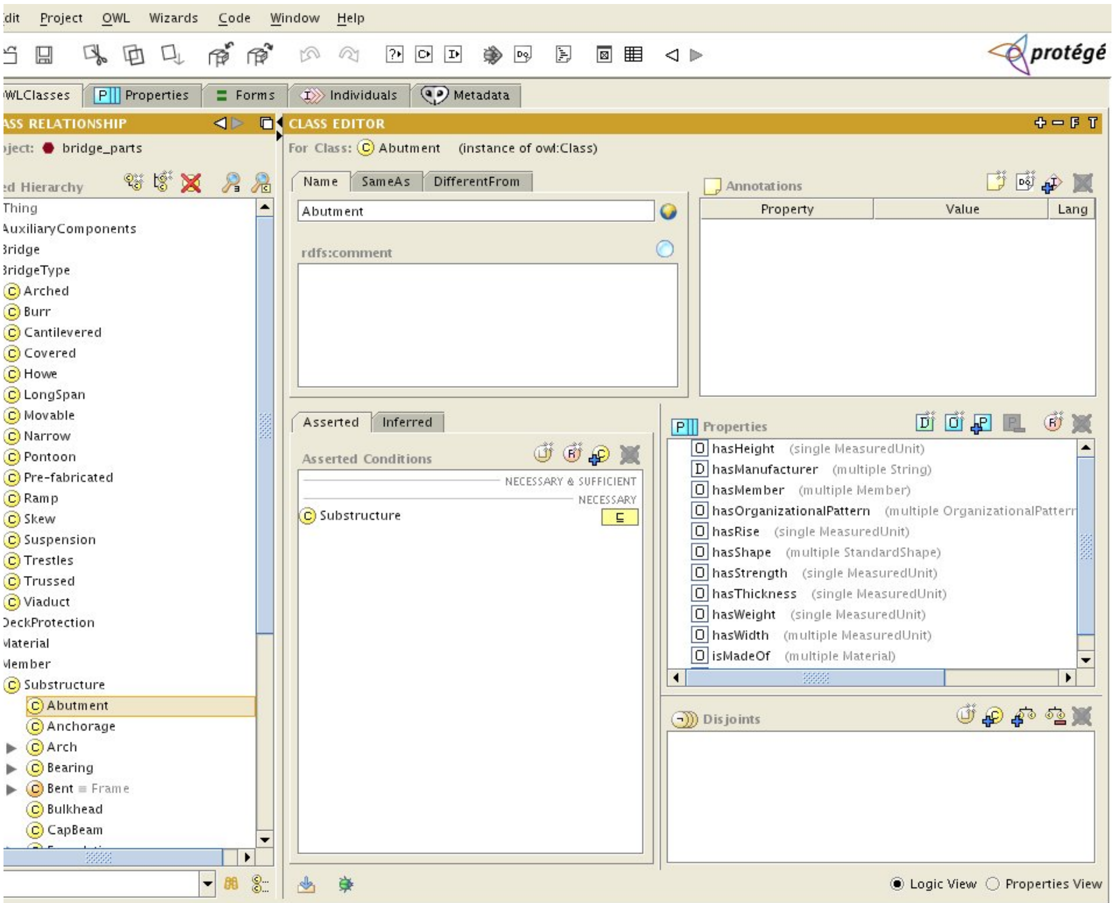

Figure B.1: Bridge Parts ontology represented in Protege

Although the knowledge acquisition process started with sources that were important to KDOT, one of the goals of the project was to develop an ontology that could be used by KDOT to interact with other entities. In addition to these sources, other online references *(31) (32) (33) (34) (35)* were used to complement the list of concepts to facilitate such interactions.

Another important source of information was the National Bridge Inventory Project, which is a collection of data from more than 600,000 bridges located on Interstate Highways, U.S. Highways, State and County Roads, and other routes of national significance *(36)*. Concepts originating from this source were deemed very important because of their significance to State Transportation Agencies and to the Federal Highway Administration *(37)*.

B.5.1.4 Ontology Gathering

The use of existing ontologies can be helpful to describe small parts of the domain being analyzed. Ontology reuse increases productivity by avoiding the need to "reinvent the wheel" and improving interoperability. Good examples of ontologies that can be reused are ontologies that describe commonly-used domains such as time, geometric shapes, and units of measure. The task of searching for existing ontologies has become easier since the development of specialized searching tools to browse the Internet for metadata:

- Swoogle *(38)*: project of the University of Maryland – Baltimore County that features searches by terms, annotated documents, and ontologies. It has a good database size, and it returns results ranked by an internal mechanism.

- Google *(5)*: this powerful Internet search engine can also be used to search for ontologies. Basic searches such as “people ontology” or “units ontology” can yield results with the usual accuracy for which Google is known. Moreover, many times the engine returns links to documents explaining how to use the ontology and describing all the features in it, which can help in understanding how the ontology was created and aid in a smoother merging process.

- Knowledge Zone *(39)*: This website was created by the developers of Protégé, and it is a repository of different ontologies organized by domain. It has ratings by users and reviews, which are very useful when looking for prior experience in merging ontologies. It currently does not have a very large database, but it has the potential to grow and become a widely-used repository of ontologies.

Certain details are important in the selection of ontologies to be re-used. First, the popularity of an ontology is a good indicator of how many people agree with that particular representation of the domain, which is a forward step towards reaching a standard in the area. Additionally, it is crucial to make sure that the new ontology represents the initial domain requirements. To illustrate, if early in the process it was agreed that the representation of a person should include his or her address and cellular phone number, it is evident that the chosen ontology to be merged should contain such information. Otherwise, more work will be required extend the ontology to fit the needs specified before. Finally, it is important to choose an ontology that can be easily expanded, so it can be extended to suit the needs of the project. Many times an ontology will be well-suited for reuse, but it lacks some information that is required by the project. Then, the ability to add data to the ontology without damaging its structure becomes a key factor in the decision of whether or not that particular ontology should be used.

B.5.2 Engineering of the Bridge Ontology

After the scope of the bridge ontology was defined, supporting domains were identified. These supporting domains consisted of areas (e.g. units of measure, coordinates) in which existing ontologies could be adopted with minor modifications in order to avoid duplicity of efforts. Following this step, classes and properties were created based on the knowledge acquired from the resources previously mentioned. Finally, the existing ontologies found online were integrated with the bridge ontology to cover the supporting domains.

B.5.2.1 Suggested Upper Merged Ontology (SUMO)

Among all the ontologies analyzed SUMO *(40)* was deemed the best alternative to represent the supporting domains. The SUMO ontology “[...] is limited to concepts that are generic, abstract, or philosophical, and hence are general enough to address (at a high level) a broad range of domain areas.” *(41).*

The efforts by the group that created SUMO also include a few ontologies devoted to more specific domains, such as government, economy, transportation and geography. The aforementioned ontologies are extensions of SUMO and use the Mid-Level Ontology (MILO) *(41)*, which is also available in OWL. MILO is intended to act as a bridge between the high-level abstractions of the SUMO and the low-level detail of the domain ontologies. The SUMO Ontology Browser *(42)* links common terms in the English language to classes and properties in the ontologies.

Because SUMO describes many different areas, it was used in the bridge ontology to represent almost all of its supporting domains, such as agents (person, organization), units, directions, and stationary artifacts. When the representation of the domain in SUMO was not detailed enough, or when it did not agree with the views of the developers for the particular domain, other ontologies were used to replace or even complement SUMO.

Another goal of this phase was to find an upper-level ontology to which the bridge ontology could be linked. SUMO provided an abstract representation of generic terms such as entity, physical entity, and abstract entity. The highest level classes of the bridge ontology were interpreted as an extension of SUMO, and these classes were defined as children of classes in SUMO *(43)*. Figure B2 shows how SUMO was integrated with the bridge ontology.

Although SUMO has a good description for the majority of the supporting domains of the bridge ontology, its representations are often very generic and demand some adjustments and extensions before fulfilling all the requirements previously envisioned. For this reason other ontologies were sought to either completely replace specific sub-domains of SUMO, extend them, or at least provide insight on how to expand SUMO to better suit the bridge ontology.

B.5.2.2 Other Supporting Domains

The following ontologies and data schemas were studied to expand or replace specific sub-domains of SUMO:

- Dublin Core Metadata Initiative (DCMI) *(44)*: this project was developed to provide a standard set of metadata fields (e.g. author, subject, and language) which can be used to describe many kinds of resources. It is often used to describe documents in a business or research setting, but the fields are applicable to many types of resources, such as literature, visual artwork, or music. Each effort to implement the DCMI must decide which of these terms are useful in describing the given resources. In the bridge ontology, the DCMI was used to describe bridge-related documents, such as reports, structural drawings, pictures, and other data files.

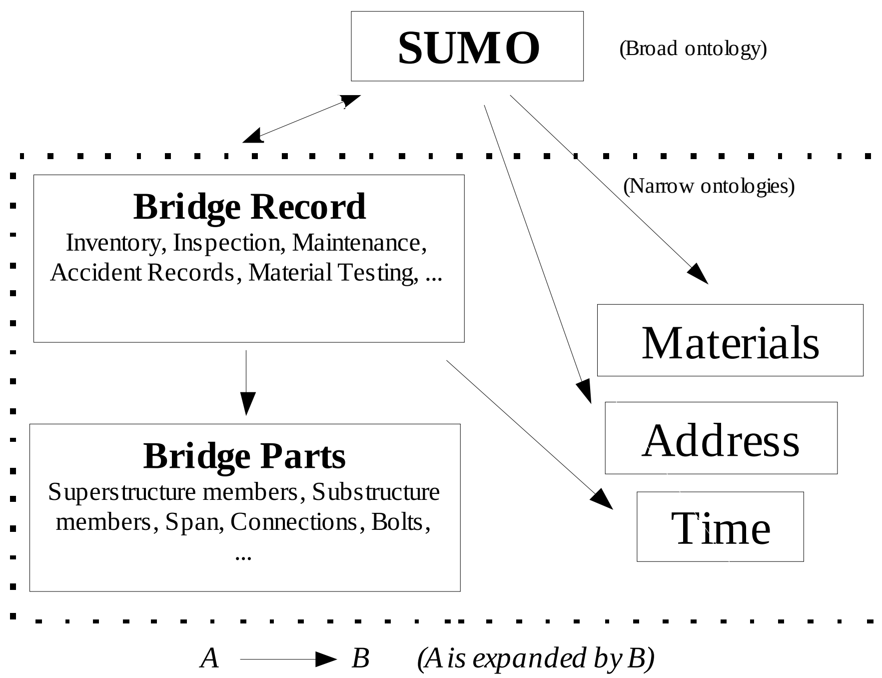

Figure B.2: Integration of SUMO, bridge, and bridge parts ontologies and supporting domains

Industry Foundation Classes (IFCs) *(45)*: the IFCs were created to provide a single platform with which all members of the construction and facilities management industries could exchange data more effectively. The entire IFCs data schema was not imported into the bridge ontology because of its size and amount of unrelated information. Instead, it was decided to replicate the representation of certain auxiliary domains, leaving off unnecessary classes and properties. Some of the sub-domains that were replicated were units of measure, agents, and GPS location.

- Materials: It was necessary to represent the properties of different materials used in bridge construction and repair, such as steel and concrete. In order to represent this sub-domain, a small part of an ontology previously developed for a different research project *(46)* was used.

Other ontologies and data schemas were identified for future expansion and improvement of the bridge ontology. EngMath *(47)* is an ontology that describes units for the engineering domain, and it includes features such as conversion parameters. For the location, geometry, and coordinate sub-domains, the Geographic Information Systems standard ontologies *(48)* and GML *(49)* can be used to provide a more detailed representation. Finally, MILO can be used to provide a finer integration with SUMO, and the Time ontology *(50)* can be used to extend the capabilities of SUMO in the time domain.

The advantages of ontology reuse have been described in the previous. It is also important to note that merging ontologies makes it more difficult to develop well-mapped and tightly-integrated ontologies. For example, if the metadata field "author" from the DCMI is used as an annotation and not properly mapped to other related classes, it will not be possible to associate the name of an author with an instance of the class Person, which causes duplicity of the data.

B.5.3 Evaluation

While concepts related to bridges and the relationships among them were defined in the bridge ontology, the ontology itself does not hold any actual data about bridges. For this reason, it was essential to identify agents and sources of information about bridges that could be used in combination with the bridge ontology. Verifying that the information contained in these sources is representable by the ontology is an important step prior to the development of new agents that can make use of the ontology.

Three main sources of information were identified to populate the ontology:

- KDOT Project Portal *(51)*: This website has detailed information about all the on-going and scheduled KDOT projects. Bridge repair projects were of particular interest because each project listing included a description of the bridge being repaired and other relevant data about the project, such as costs and personnel. This information is ideal for testing the completeness of the bridge_parts and the bridge_record ontologies.

- Accident Reports *(52)*: The Kansas Highway Patrol maintains an online crash log that frequently mentions the names of bridges. This is another important source to analyze the different manners in which bridges can be identified by people with expertise in areas other than bridge design, management, or repair.

- Newspapers: Information about bridges cited in newspaper articles was of interest because descriptions are similar to those used by ordinary citizens and government agencies. For example, the newspaper Lawrence Journal-World *(53)* has a section titled Commuter Report, in which bridges that are under repair are listed according to their location so that citizens can avoid the construction areas. Through this source it was possible to contrast the approach a customer would have to describe a bridge (the same one used by the newspaper) to what would actually be listed in a KDOT bridge database.

Figure B3 shows a description of the location of a bridge extracted from the KDOT Project Portal *(51)* and its mapping to classes of the bridge ontology.

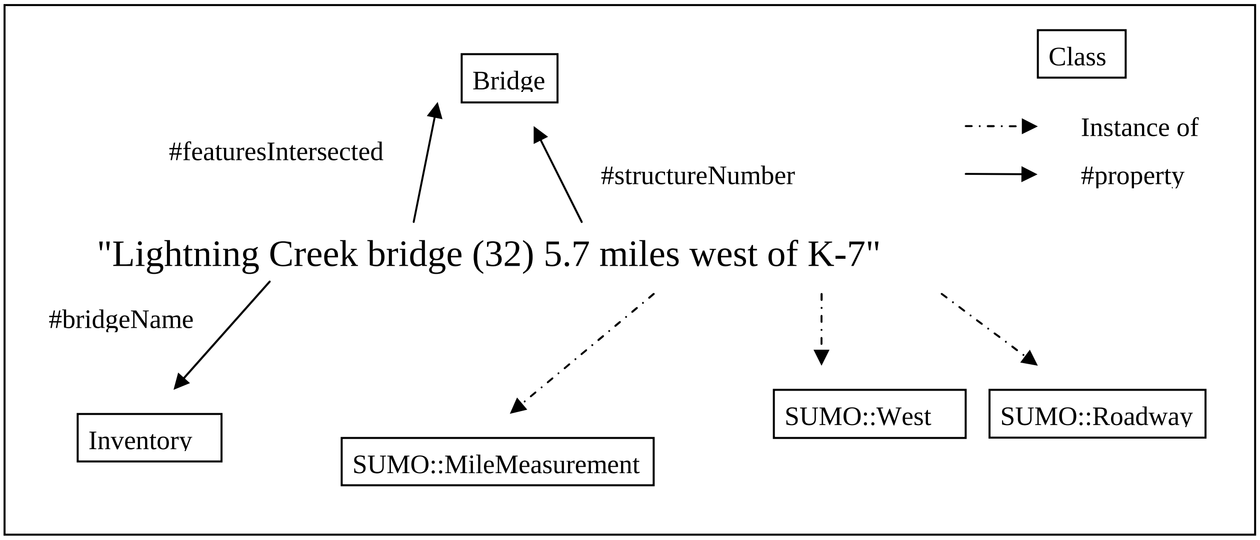

Figure B.3: Mapping a description of the location of a bridge to the classes in the ontology

Use cases constitute an important technique to test the ontology and evaluate the advantages it offers for management of information. A use case is a detailed description of a single activity (in a business process) in which one can identify inputs, outputs, constraints, and interactions. The use cases for the bridge ontology were developed considering the types of information searches conducted by KDOT, and also the types of searches that KDOT would like to be able to perform. Another criterion used to develop use cases was that the information retrieved be obtained from at least two different databases managed by KDOT. This section describes two of the theoretical cases the group created to validate the bridge ontology.

B.5.3.1 "Which bridge?" Use Case

This situation may arise when a customer specifies a bridge in an unknown fashion, and then expects more information about the bridge being queried. The current approach is to use the information provided by the costumer as parameters of a search. For example, suppose the customer is looking for more information about a "two-span bridge on I-70 at mile X", but the data about this same bridge describes it as a "prestressed concrete bridge Y miles west of Lawrence".

The first problem one can notice is the representation of distance and location in the database, which poses a serious challenge because of the lack of consistency. Also, there are many different ways to describe the properties of a bridge, and the usual string based description, without standardized semantics, does not contain the semantic information necessary to allow the mapping between different descriptions.

If the text about a bridge is annotated with metadata, then a reasoner could be used to draw conclusions about that data and possibly yield better results than a simple keyword search. For example, since the distances are instances of a length measurement, they can be converted according to the unit being used. Also, a reasoner could identify that mile X is Y miles away from Lawrence, and hence conclude that the bridge described by the customer is the same as the one in the database. Finally, since Concrete is a subclass of Materials, it will inherit many properties that can be used for further reasoning.

B.5.3.2 "John Smith" Use Case

In this scenario, the customer is seeking all the maintenance records for bridges in which John Smith was part of the design team and also a senior engineer for the project. The most straight-forward method to perform this search would be to start a keyword search in the database using words that describe the situation, such as "John Smith maintenance report design team senior engineer".

Although this search might return several results, these may not necessarily match the request issued by the customer. To illustrate, it is difficult to locate the specific John Smith in question. Furthermore, it is not possible to guarantee that John Smith is part of the design team, as the search may also yield documents in which the term “design team” is mentioned in addition to the other keywords listed above. Likewise, there is no assurance that the document retrieved is a maintenance record, or if it only refers to such record. Finally, was John Smith the senior engineer or is someone else listed as the senior engineer?

Again, metadata annotation would make reasoning possible in this situation. The John Smith the customer is looking for would have the same unique ID throughout the database, and also the same instance of the class Person, which would be linked to all the documents he wrote. Also, the reasoner might be able to eliminate records where John Smith is not listed as a member of the design team or as the senior engineer, given that the ontology provides such properties. Then, if a company is responsible for the design or maintenance of the bridge, the reasoner can check if John Smith is a designer or senior engineer in that company. If John Smith was the main designer for the organization XYZ, the reasoner will know that “John Smith” and “main designer of XYZ” are the same, so it will return documents marked as written by both. Finally, individuals with graduation dates after the construction of the bridge could be eliminated by the reasoner.

B.6 Conclusions

The bridge ontology was created based on multiple sources of knowledge with the goal of making it capable of representing knowledge held by different groups, and reusable in other projects. It was found that interoperability and reusability improved by dividing the ontology into modular parts, and by adopting existing ontologies to characterize the supporting domains. Although the Semantic Web helped to address interoperability problems between different software agents, the adoption of widely-used standards in the different sub-domains would present significant benefits in terms of efficiency and cost. This because the use of different ontologies describing a domain by small groups of users leads to interoperability problems that can only be resolved though an extensive mapping effort.

In the process of developing the bridge ontology the difficulties of creating a tightly integrated and re-usable ontology became evident. It was found that in order to achieve improved performance over traditional search methods and avoid multiplicity of data it was important to properly map all building blocks of the ontology.

It was found also that the implementation of the bridge ontology presented significant benefits over traditional search and storage method used by KDOT for the case studies that were analyzed. Consequently, the use of the Semantic Web to manage data in the transportation domain can bring about significant benefits in terms of interoperability and improved efficiency in the management of data.

Finally, it was found that in order to successfully develop an ontology representing a large domain it was essential to have a well-defined scope and to take advantage as much as possible of ontology reuse. Because the process of ontology development usually involves integrating knowledge from different areas, it is essential to focus on describing terms that are needed, so that the outcome is a relatively small but functional and well-integrated ontology. Peripheral domains can be added as extensions according to need. Attempting a comprehensive description of the entire domain at once can be overwhelming and result in a poorly-written and poorly-integrated ontology.

K - TRAN

KANSAS TRANSPORTATION RESEARCH
AND
NEW - DEVELOPMENTS PROGRAM

A COOPERATIVE TRANSPORTATION RESEARCH PROGRAM BETWEEN:

KANSAS DEPARTMENT OF TRANSPORTATION

THE UNIVERSITY OF KANSAS

KANSAS STATE UNIVERSITY