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An Ontology-Based Standard for Transportation Planning

Megan KATSUMI [a,1] and Mark FOX [b]
[a] *University of Toronto Transportation Research Institute, University of Toronto, Canada*
[b] *Mechanical & Industrial Engineering, University of Toronto, Canada*

Abstract. Transportation planning is concerned with the development of infrastructure, definition of policies, and other activities based on a plan to meet future transportation needs. Transportation planning activities must consider a range of factors such as land use and land value, capacity of the transportation network, and public safety. The analyses performed in support of transportation planning activities must therefore utilize and combine a wide range of information. In order to effectively perform these analyses the data must be correctly combined. This requires a clear understanding of the terms used to describe the data, as well as how they relate to one another; the semantic integration of this data is just one of several clear applications for ontologies in the transportation planning domain. In this paper, we make the case for an ontology-based standard to support transportation planning. Toward this, we present a suite of ontologies which is currently proposed as a standard for transportation planning data. We give an overview of the ontology's contents, highlighting some key concepts, and describing the intended use of the standard.

Keywords. ontology, standards, transportation, planning, urban informatics

1. Introduction

The importance of standards is well-recognized in many areas of transportation such as Intelligent Transportation Systems (ITS), however standards are decidedly less prevalent in the area of transportation planning. Despite this, we observe that transportation planning stands to benefit considerably from the implementation and adoption of standards. Standards for transportation planning would support the integration of collected data thereby making data more easily accessible and reusable. This would also ensure that data used in a particular analysis could easily be reused by other researchers to better understand and analyse results obtained throughout the community. Similarly, a standard representation of simulation models and their output would serve both sharing and reuse of models between research groups, but would support a better understanding and evaluation of the model results. While transportation planning activities make use of existing

[1]Corresponding Author: Megan Katsumi, University of Toronto, 5 King's College Rd. Toronto, ON M5S 3G8, Canada; E-mail: katsumi@mie.utoronto.ca.

integration efforts, what is truly needed is a standard specifically targeted to the domain of transportation planning.

In this paper we motivate the need for an ontology-based standard for transportation planning. We provide an outline of the requirements for such a standard, and subsequently present the Transportation Planning Suite of Ontologies (TPSO), a set of ontologies designed to address these requirements.

2. Motivation

Standards for transportation data are traditionally specified as data models. They rely on detailed documentation, or tools such as UML in order to convey the intended use of the standard. Unfortunately even in the most detailed efforts, these approaches are unable to completely eliminate ambiguity. This ambiguity undermines the efforts of the standards, as it leaves room for misinterpretation and thus misuse of the standards. It also poses a challenge for the task of identifying correspondences with other standards. Instead, we propose the use of ontologies as a mechanism for the specification of standards, in particular for the specification of a standard for transportation planning data. The use of an ontology enables an explicit specification of semantics, thereby removing the risk of ambiguity in the standard. In addition, the representation supports a more precise mapping with other standards, as the mappings themselves may be defined using the vocabulary of the ontology in the same formal logic.

3. Related Work

The transportation planning standard described here is distinct from existing standard efforts both in terms of its formalism and its scope. Many existing standards in the transportation domain are focused on very specific components of transportation data; for example GML [1] which focuses only on geographic information. Those standards that do have a broader scope are focused on standardizing operational transportation data and activities; for example, Transmodel [2] focuses on capturing public transport data. While there is certainly overlap between these topics, no standard precisely captures the scope required for transportation planning. Furthermore, none of the existing standards are formalized with a well-defined semantics, so the work described here is novel in that sense as well. While there is a considerable body of work that looks at applying ontologies within the transportation domain (a detailed survey is presented in [3]), at the time of this writing no efforts have addressed transportation planning data.

4. Requirements for a Transportation Planning Standard

The goal of the standard is to capture the concepts underlying data that are relevant for transportation planning. Not only do these entities include travel activities, they include various aspects of the urban system. The concepts required for this may be divided into three categories: land use, agents, and infrastructure. Other aspects of transportation planning, such as surveys and simulations are out of scope. The purpose of the standard is to facilitate the consistent representation of data regarding the concepts involved in transportation planning. Representation of the use and provenance of this data are important but would be most effectively addressed in specialized standards, such as a standard for the representation of simulation data.

4.1. Land Use

The classification of land use is a fundamental aspect of transportation planning. Historical studies and simulations investigate the relationship between land use and transportation behaviour in order to support decision making. The capture of land use information requires the representation of parcels of land and their associated classification(s). Different classifications may be used, according to various systems. In addition to these classification systems, individual buildings and parking areas and the locations that they occupy must be represented in order to capture land use at a more detailed level of granularity.

4.2. Agents

Another important aspect of transportation planning is the representation of behaviour in the urban domain. Data is collected and generated regarding travel behaviour in the urban system to answer important questions regarding the travel demand and capacity within a system. This includes changes in the demographics of the population and the resulting impact on travel behaviour. A standard for transportation planning must support the representation of agents in order to capture this behaviour of interest. This includes concepts such as persons and the trips they take, but also more detailed attributes such as their occupations and the households they are members of.

4.3. Infrastructure

A final key area of transportation planning that must be considered is infrastructure. The transportation infrastructure provides the context required for a more complete representation of travel activities. At its core, this amounts to a representation of the transportation system such that trips from one point to another may be distinguished by the paths travelled. Consideration of various modes, such as walking, driving, and public transit must also be considered. A standard for transportation planning must support the representation of this system and the various modes it supports. This includes vehicles and public transit, as well as various attributes of the transportation network: costs associated with travel, attributes of the various links in the network such as allowed modes, speed detected from sensors and so on.

5. Ontologies for a Transportation Planning Standard

The goal of the TPSO is to serve as a specification for a standard for transportation planning data. The use of an ontology to specify the standard will facilitate interoperability as it provides a vocabulary that data may be encoded in or mapped to, for example via Ontology-Based Data Access as presented in [4]. The formal semantics of the TPSO may also be leveraged to support verification of the data via consistency checking. It will also augment the TPSO as a standard, making the terms and their relation to one-another explicit. Finally, the TPSO is also intended to support the identification of mappings with other standards; ontology alignments may be specified in order to precisely identify the relationship between the TPSO and other ontologies, and even data standards lacking a formal semantics may be interpreted by the TPSO with the specification of mappings much like those R2RML models defined for relational data.

The TPSO includes ontologies to define the range of concepts involved in transportation planning activities. The ontology design was initially driven by the data consumed and produced by transportation planning modules developed at the UofT Transportation Research Institute [5], and in use by the City of Toronto and other cities in the Greater Toronto Area. This initial ontology was then refined by reviewing the transportation planning literature and feedback and data provided by subject matter experts from the transportation planning domain. The ontology was tested for consistency and evaluated based on how well it captured and communicated data across the sub-ontologies.

The division of the ontologies was designed based on groupings of concepts that could be semantically self-sufficient. To date, the TPSO focuses solely on the transportation of people as opposed to goods, however industrial transportation (i.e. freight) is an important factor that should be considered in transportation planning activities and will be included in future extensions of the TPSO.

OWL2 is the proposed representation language for the formalization of the TPSO. Primarily, this decision is owing to its role as the *de facto* standard for the Semantic Web, and the resulting popularity and available tool support. Using OWL2 ensures that the standard will be supported by Semantic Web technologies, such as Ontology-Based Data Access tools and triple stores. Nevertheless, we acknowledge that there are other advantages, increased expressivity in particular, that may motivate the use of other logical languages such as first-order logic. This will be a point of discussion for future work.

Where possible, the TPSO has reused existing ontologies to promote interoperability with other data sets. The Time [2], iContact [3], GeoSPARQL [4], LBCS [6], SSN [5], and Organization [6] ontologies have been reused via imports, and select terms have been reused from schema.org, the Units of Measure Ontology [7]. While the reuse of existing ontologies will facilitate some interoperability, we anticipate the eventual need for ontology alignments to be identified with other work in overlapping domains.

5.1. Foundations

Beyond the domain-specific subjects that are clearly identified the requirements, there are fundamental concepts that are necessary to formulate an accurate representation of the domain. These concepts are defined in a set of *foundational* ontologies, so-named because they provide a reusable foundation for the development of other ontologies in the transportation domain. This will become clear in the sections that follow as we will describe how the foundational ontologies are reused in various ways in order to capture the required domain-specific concepts. The clear definition and uncoupling of the founda-

[2] `https://www.w3.org/TR/owl-time/`
[3] `http://ontology.eil.utoronto.ca/icontact.owl`
[4] `http://www.opengis.net/ont/geosparql`
[5] `https://www.w3.org/TR/vocab-ssn/`
[6] `http://ontology.eil.utoronto.ca/tove/organization.owl`

tional concepts makes the fundamental commitments of the TPSO clear and accessible to potential adopters. It also ensures interoperability and consistency in the representation of key concepts such as time and location.

The TPSO defines eight ontologies to define the following foundational concepts: time[7], mereology[8], spatial location[9], units of measure[10], change[11], activities[12], recurring events[13], resources[14], and observations[15]. Although this collection of ontologies resonates strongly with the concepts often associated with the so-called upper ontologies, it is important to emphasize that it is not the intent of this work to present these ontologies as an upper ontology.

Rather than commit to a particular upper ontology, this collection of ontologies was identified through a domain-first approach wherein only concepts that were identified as foundational or generic in the context of transportation planning are included in the foundational ontologies. These were reused from existing ontologies where possible, and otherwise developed from-scratch. Upper ontologies were found to operate at a level of abstraction that was too high for direct use in this ontology. It is our position that this design decision achieves a clearer presentation of the scope and semantics of the ontology by avoiding the inclusion of unnecessary, high-level concepts.

A key commitment that is made in the foundational ontology is the representation of change over time. Many of the concepts identified in the urban system ontologies are subject to change. For example, a Vehicle will have one location at one time, and another location at a later time; it may have only one passenger at one time, and four passengers at a later time. The Change Ontology serves as to facilitate a consistent approach to formalizing change over time throughout the TPSO. The Change Ontology adopts an approach similar to 4-D perspective was proposed by [8], based on the design pattern presented by [9]. The 4-D view was chosen as it was found to provide a more natural representation in OWL, in contrast with the 3-D view which requires the use of the so-called N-ary relations approach [10]. The differences between the two approaches are discussed in greater detail in [9]. The ontology introduces the division of concepts that are subject to change into invariant and variant classes; we refer to these as TimeVaryingConcept and Manifestation classes, respectively. By distinguishing between these class types and recognizing the properties that are (and aren't) subject to change, the ontology supports the capture of both the static and dynamic aspects of a particular entity. A class that is subject to change is defined as a type of TimeVaryingConcept (e.g. Vehicle may be a subclass of TimeVaryingConcept). The TimeVaryingConcept itself is invariant and defined by properties that do not change over time. As per [11], we view TimeVaryingConcepts as perdurants (things that occur over time, i.e. processes). A TimeVaryingConcept has Manifestations that demonstrate their changing (variant) properties over time. Different types (subclasses) of TimeVaryingConcept may be defined based on the Manifestations that are part of them.

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[7] http://ontology.eil.utoronto.ca/icity/Time/
[8] http://ontology.eil.utoronto.ca/icity/Mereology/
[9] http://ontology.eil.utoronto.ca/icity/SpatialLoc/
[10] http://ontology.eil.utoronto.ca/icity/OM/
[11] http://ontology.eil.utoronto.ca/icity/Change/
[12] http://ontology.eil.utoronto.ca/icity/Activity/
[13] http://ontology.eil.utoronto.ca/icity/RecurringEvent/
[14] http://ontology.eil.utoronto.ca/icity/Resource/
[15] http://ontology.eil.utoronto.ca/icity/Observations/

5.2. *Land Use*

The TPSO defines three ontologies to capture the concepts of land use required for transportation planning: the Land Use Classification, Building, and Parking ontologies.

5.2.1. *Land Use Classification*[16]

The Land Use Ontology provides the necessary concepts to describe a particular classification(s) applied to some parcel of land. Currently, the Land Use Ontology includes classifications from Land-Based Classification Standards (LBCS), Canada Land Use Monitoring Plan (CLUMP), and Agriculture and Agri-Food Canada (AAFC); it may easily be extended to capture other classification systems as required. A goal of future work will be to define the classifications in greater detail such that any relationships between classifications in different systems may be inferred. The Land Use Ontology imports the Spatial Location ontology; in particular, a Parcel is defined as a type of spatial Feature. Parcels have some location which may be described as a geometry, they may also be related to other parcels (or arbitrary spatial Features) by the spatial relations such as containment, contact, overlaps, and so on.

5.2.2. *Building*[17]

The Building ontology defines the concepts to capture information about individual buildings, thus describing land use from a different perspective and at a finer level of granularity than typical land use classifications. The Building Ontology also reuses the Spatial Location ontology in order to capture the location of a building. While we expect the address of a building to remain constant its exact location may change over time, as in the case of a remodelling or extension. The possibility is supported by the Building Ontology, which also reuses the Change Ontology and captures the location as a variant property. Other attributes of a building are captured for transportation planning purposes, such as the type of building, units contained in a building, their monetary value, and so on. The Mereology Ontology is used to capture the disaggregate parts of a building, and the Units of Measure Ontology is required to capture attributes required for land value considerations, such as sale prices and square footage.

5.2.3. *Parking*[18]

Like the Building Ontology, the Parking Ontology allows for a representation of land use at a finer level of detail. In addition to characterising land use, the representation of parking facilities is important for studies considering travel activities as parking often contributes to the route and modes chosen to journey to a particular destination. Various aspects of parking are addressed in the ontology; beyond the location of a parking facility, the ontology captures concepts related to its policies such as a price and/or allowable periods. The ontology also uses the Mereology Ontology in order to describe a decomposition of parking facilities into parking areas. This is needed in order to capture cases where groups of parking spaces may have different policies within the same lot. Some studies may also require a representation of parking areas at an individual level in order to capture parking use and availability.

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[16] `http://ontology.eil.utoronto.ca/icity/LandUse`
[17] `http://ontology.eil.utoronto.ca/icity/Building`
[18] `http://ontology.eil.utoronto.ca/icity/Parking`

5.3. Agents in Transportation Planning

In the context of transportation planning, the key agents of interest are persons, households and organizations. The behaviour of each of these agents may be of interest for certain analyses and studies. Travel behaviour is of major importance, though other activities such as job changes (joining or leaving organizations) and household changes (joining or leaving a household) are also relevant. The TPSO defines five ontologies to capture the required concepts for agents in transportation planning: the Person, Household, Organization, Contact, and Trip ontologies.

5.3.1. Person[19]

Persons are key agents in transportation planning. It is the combination of decisions of persons in the population that result in changes to travel behaviour. For example, consider a person's decision to change places of employment. Among other things, this change will likely impact their daily travel behaviour. The Person Ontology enables the representation of persons and their attributes of interest. Factors such as a person's age, income, and place of residence are defined as properties of a person. The Change Ontology is used to specify which attributes may change over time (e.g. income), and which attributes are constant (e.g. date of birth).

5.3.2. Household[20]

The behaviour of a household may be represented by the collective activities of its members. The Household Ontology supports the representation of Households, Families, and Dwelling Units - all of which are distinct, though closely related concepts. This ontology is described in greater detail in Section 6.

5.3.3. Organization[21]

Organizations provide another source of influence on the behaviour in the urban system. An organization is defined broadly as some group of individuals, typically having some shared goal(s). Organizations such as schools and businesses are particularly important in transportation planning as they determine regular travel patterns for much of the population. The Organization Ontology introduces the concepts of Students and Employees who are members of certain types of Organizations. Using the Spatial Location ontology, the Organization ontology captures the location of a person's work or school. The Change Ontology is used to support the representation of variable attributes of an organization, such as its location and members.

5.3.4. Contact[22]

Contact information is relevant for a range of concepts in the transportation domain. For example, a building may have some associated address, similarly a person or an organization may have some contact address (or phone number, email address, and so

[19] `http://ontology.eil.utoronto.ca/icity/Person`
[20] `http://ontology.eil.utoronto.ca/icity/Household`
[21] `http://ontology.eil.utoronto.ca/icity/Organization`
[22] `http://ontology.eil.utoronto.ca/icity/Contact`

on). Note that a person's contact address may differ from their place of residence. Rather than define these attributes separately for persons, organizations, and so on, it makes sense to capture the general concepts assocated with contact information in a separate ontology. The iContact ontology[23], is reused to provide the core concepts necessary to define this type of information. The Contact Ontology extends this representation and uses concepts from the Spatial Location ontology in order to associate an address with a location. It also uses the Recurring Event Ontology to introduce a more specific definition of hours of operation (introduced in iContact) as a specialization of a RecurringEvent.

5.3.5. Trip[24]

Apart from activities that change the demographics of the population, trips are one of the most important activities performed by agents from the perspective of transportation planning. The Trip Ontology leverages the Activity and Person ontologies to define the concept of a Trip as is a kind of Activity wherein a Person(s) is transported from one location to another via some mode(s). As with activities, trips may have participants; they may also be described with specializations of the has participant property to capture drivers and passengers. The Trip Ontology also introduces the concepts of a Trip Segment and a Tour. Trip Segments allow for the division of a Trip into smaller parts, whereas a Tour represents a collection of Trips that begins and ends at the same location. Ontologies that describe the Urban Infrastructure (in the following section) are also utilized to capture the path that a trip takes in the context of the transportation network (road or rail lines, for example).

5.4. The Urban Infrastructure

Representation of the urban infrastructure and its attributes is an important requirement in order to provide context for transportation planning activities. The TPSO defines five ontologies to capture the required concepts: the Transportation System, Public Transit, Vehicle, Travel Cost, and Trip Cost ontologies.

5.4.1. Transportation System[25]

In the planning domain, the transportation planning system is a socio-technical system in the sense that it combines user behaviour with the physical aspects of the transportation. The term transportation system refers to a subset of the "transportation planning system", composed of an abstract transportation network and the physical assets that implement it.

The Transportation System Ontology models the transportation network separately from the physical infrastructure. The constraints on the flow of traffic are something that is *applied* to the physical infrastructure – the two are seen as distinct concepts. Although some constraints may be consequences of the physical infrastructure, such as flow constraints imposed by the size of the lane that an arc accesses, this is a specific relationship that is captured as opposed to conflating the two types of concepts. For example, there is nothing to stop a vehicle from going the wrong way on a road, except for the flow

[23] `http://ontology.eil.utoronto.ca/icontact.owl`
[24] `http://ontology.eil.utoronto.ca/icity/Trip`
[25] `http://ontology.eil.utoronto.ca/icity/TransportationSystem`

of traffic that is imposed on the system (and these constraints may change with time). This results in the identification of two key concepts: the Transportation Network (directed graphs that represent the possible flow of traffic), and the Transportation Complex (physical features where transportation occurs).

A Transportation Network is made up of Arcs and Nodes. Both Nodes and Arcs may have implicit locations based on the infrastructure they access, however unlike the infrastructure classes, Nodes and Arcs are not Spatial Things. These parts of the Transportation Network are tied to the physical infrastructure by relating an Arc to a Transportation Complex (some road segment or rail, for example) that it "accesses". The Change ontology is reused to represent the changes that may occur to nodes, arcs, and physical aspects of the transportation network. The Transportation System Ontology also extends the Observations ontology in order to define system-specific concepts regarding the observations of interest that may be made about the system. For example, loop detectors are defined as sensors that are used to observe traffic flow metrics.

5.4.2. Public Transit[26]

The Public Transit Ontology provides a representation of transit agencies and the services they provide. The Route is a key concept in this domain; the Transportation System ontology is used to describe Routes in detail based on the paths in the transportation network. The Transit ontology also provides a representation for route schedules and, using the Trips ontology, individual transit trips. This allows for the representation of the actual trips of transit vehicles on particular routes, as well as the trips taken by people via transit (i.e. on multiple segments of some routes).

5.4.3. Vehicle[27]

The Vehicle Ontology enables a representation of various types of vehicles that enable transit. Using the Change Ontology, the Vehicle Ontology distinguishes between static and variable vehicle attributes. Static attributes include characteristics such as their capacity, vintage. Variable attributes include characteristics such as location, which is captured using the Spatial Location Ontology.

5.4.4. Travel Cost[28]

The Travel Cost Ontology uses the Transportation System Ontology to introduce the concept of costs associated with accessing and travelling in some transportation network(s). These may take the form of direct costs such as tolls and fares. There may also be non-monetary costs associated with travel such as pollution and travel time. Costs are associated with Network access, but also with individual Arcs. The ontology supports a representation of travel costs that may vary depending on mode of access and time of day. It is important to clarify that Travel Costs define the costs associated with accessing the transportation system; a travel cost is a property of an arc or its network. These costs are distinguished from other costs that are dependent on situational factors such as time of day, or age of traveller. These costs vary between individual trips and are captured by the Trip Costs Ontology (described subsequently).

[26] `http://ontology.eil.utoronto.ca/icity/PublicTransit`
[27] `http://ontology.eil.utoronto.ca/icity/Vehicle`
[28] `http://ontology.eil.utoronto.ca/icity/TravelCost`

5.4.5. Trip Cost[29]

In contrast with travel costs, the Trip Cost Ontology defines costs that are specific to a particular trip. Using the Trip ontology, the Trip Cost ontology introduces the concept of a cost that is related to a Trip, Trip Segment, or Tour. These Trip Costs may take the form of direct costs such as those presented in the Travel Cost Ontology, but there may also be non-monetary costs associated with travel over different arcs such as pollution and travel time. Trip Costs capture these indirect costs that may vary between individual trips.

6. Households: A Deep Dive

Rather than attempt present all of the axioms of the TPSO in detail in a single paper we opt to take a closer look at one of the key ontologies in the TPSO: the Household Ontology. The aim of this section is to provide a more detailed example of the breadth and depth of the TPSO.

The Household Ontology introduces three key concepts: households, dwelling units, and families. A Household is considered to be a group of people who reside at the same place. A Household may or may not be comprised of Persons from the same Family, and some Persons may be members of multiple Households (as is the case for children of a divorce with shared custody). A Household's membership may vary without affecting its identity. However, the dwelling that is occupied by a Household may not change; it is part of the identify of the household. In the context of transportation planning, if a person moves to a new residence, this is considered to be a new household – even if the members of the household remain unchanged. In order to capture these changes, we reuse concepts from the Change ontology (prefixed *c*:) to define two distinct perdurant and manifestation types of Household. As described in [9], this also involves the introduction of definitions to ensure that Household perdurants have only Household objects as manifestations, and that there must exist some such manifestations; a similar constraint holds for the inverse relationship. The Person ontology (prefixed *p*:) is reused to provide the semantics for the Person class.

$$HouseholdPD \sqsubseteq c{:}TimeVaryingEntity \tag{1}$$

$$HouseholdPD \equiv \exists c{:}hasManifestation.Household \sqcap \forall c{:}hasManifestation.Household \tag{2}$$

$$HouseholdPD \sqsubseteq = 1 occupies.DwellingUnit \tag{3}$$

$$Household \sqsubseteq c{:}Manifestation \tag{4}$$

$$Household \equiv \exists c{:}manifestationOf.HouseholdPD \sqcap \forall c{:}manifestationOf.HouseholdPD \tag{5}$$

$$Household \sqsubseteq \exists hasHouseholdMember.p{:}Person \sqcap \forall hasHouseholdMember.p{:}Person \tag{6}$$

[29] `http://ontology.eil.utoronto.ca/icity/TripCost`

Dwelling Units are Building Units that are occupied by Households. The Building Ontology (prefixed *b*:) is reused to introduce the notion of a Building Unit. The main distinction between a Building Unit and a Dwelling Unit is that a Building Unit may exist without being occupied. The location of a Dwelling Unit is part of its identity, however other attributes such as its occupants and its value are subject to change. The Spatial Location ontology (prefixed *sloc*:) is used to capture the location, and the Units of Measure ontology (prefixed *om*:) is used to capture the monetary value of a unit. As with the other classes, this is represented using the TimeVaryingEntity and Manifestation classes from the Change ontology, as follows:

$$DwellingUnitPD \sqsubseteq c{:}TimeVaryingEntity \tag{7}$$

$$DwellingUnitPD \equiv \exists c{:}hasManifestation.DwellingUnit \sqcap \forall c{:}hasManifestation.DwellingUnit \tag{8}$$

$$DwellingUnitPD \sqsubseteq b{:}BuildingPD \tag{9}$$

$$DwellingUnitPD \sqsubseteq \forall sloc{:}hasLocation.sloc{:}Feature \tag{10}$$

$$DwellingUnit \sqsubseteq c{:}Manifestation \tag{11}$$

$$DwellingUnit \equiv \exists c{:}manifestationOf.DwellingUnitPD \sqcap \forall c{:}manifestationOf.DwellingUnitPD \tag{12}$$

$$DwellingUnit \sqsubseteq b{:}Building \tag{13}$$

$$DwellingUnit \sqsubseteq = 1 occupiedBy.Household \tag{14}$$

$$DwellingUnit \sqsubseteq \forall hasValue.om{:}MonetaryValue \tag{15}$$

The basic definition of a Family is simply a group of persons who are related to one another. The rationale is that this concept may be extended with more specific subclasses of Family (e.g. immediate family or extended family) as required. Similar to the above concepts, in the Household Ontology a Family is defined using variant and invariant classes to capture the possible changes in membership. Although it is possible to capture the intended semantics of a ‘related to’ property that holds between two people, this property cannot be used to fully define Family as something for which all of its family members are related to one another. This is one of several examples where it was not possible to completely capture the detailed semantics of the domain in OWL. It is the goal of the TPSO to specify the semantics as precisely as possible within OWL; the limitations that are encountered and their potential consequences will be carefully re-examined in future stages of this work.

Households play a major role in transportation planning in determining the demand for transportation over the planning horizon. The planning community puts significant effort into developing and validating household-based demand models. These demand models determine how households evolve over time, (for example: births, deaths, children moving out) in order to generate the trips that members of a household take on a given day. For example, the decision to drive depends not only on the time of day and destination, it depends on the travel of other members of the household. Another household member may already be using the only available vehicle, or may require a ride somewhere thereby impacting the resulting trip itself. Despite this, there is no widely accepted definition of a household. This means that what is identified as a household in one data set may differ from the semantics of a household used in some other analysis. The Household Ontology introduces the fundamental terms that are necessary to define a Household. These terms may then be used to align and distinguish between the varied interpretations of a Household.

7. Conclusion

This paper motivates the need for ontology-based standards for transportation planning and provides an overview an artefact designed to address this need: the TPSO. The TPSO reuses a significant number of existing ontologies to better facilitate semantic interoperability. Its design was motivated by transportation planning work encountered in the iCity-ORF project [5], and it is evidence of the breadth and depth required to represent the data used in the transportation planning domain.

Future work includes the continued refinement of the TPSO ontologies, as well as the development of a first-order logic version or selected first-order logic extensions. As noted in the discussion of the Household Ontology, some detailed semantics are beyond the expressive abilities of OWL. Rather than concealing this semantics in the ontology's documentation, the development of formal, detailed extensions that capture this semantics is desired. This will serve as an unambiguous reference to support the semantics of the TPSO standard, and may also be used to provide support for advanced reasoning tasks.

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