iCity Transportation Planning Suite of Ontologies

*Megan Katsumi*

*Postdoctoral Fellow*

*Enterprise Integration Lab*

*Mechanical and Industrial Engineering*

*University of Toronto*

*Mark Fox*

*Distinguished Professor of Urban Systems Engineering*

*Professor of Industrial Engineering and Computer Science*

*Director of the Centre for Social Services Engineering*

*University of Toronto*

*Version 1.2*

*Last Updated: September 19, 2019*

[1 Purpose 4](#_Toc22804586)

[2 Scope 4](#_Toc22804587)

[3 Role of the Ontology 4](#_Toc22804588)

[4 Development Approach 5](#_Toc22804589)

[5 Requirements 6](#_Toc22804590)

[5.1 Motivating Scenario: Land Use and Transportation Simulation 7](#_Toc22804591)

[5.2 Motivating Scenario: Transit Research 8](#_Toc22804592)

[5.3 Motivating Scenario: Smart Parking Applications 8](#_Toc22804593)

[5.4 Motivating Scenario: ATIS via IT-SoS 9](#_Toc22804594)

[5.5 Motivating Scenario: ArcGIS Query Support 9](#_Toc22804595)

[6 Urban System Characteristics and Behaviour 9](#_Toc22804596)

[6.1 Foundational Ontologies 10](#_Toc22804597)

[6.1.1 Location Ontology 10](#_Toc22804598)

[6.1.2 Time Ontology 13](#_Toc22804599)

[6.1.3 Change Ontology 16](#_Toc22804600)

[6.1.4 Activity Ontology 19](#_Toc22804601)

[6.1.5 Recurring Event ontology 26](#_Toc22804602)

[6.1.6 Resource Ontology 31](#_Toc22804603)

[6.1.1 The Ontology 32](#_Toc22804604)

[6.1.2 An Example 33](#_Toc22804605)

[6.1.3 Mereology Ontology 34](#_Toc22804606)

[6.1.4 Ontology of Units of Measure 37](#_Toc22804607)

[6.1.5 Observations Ontology 42](#_Toc22804608)

[6.2 Contact Ontology 45](#_Toc22804609)

[6.3 Person Ontology 46](#_Toc22804610)

[6.4 Household Ontology 47](#_Toc22804611)

[6.5 Organization Ontology 49](#_Toc22804612)

[6.6 Building Ontology 53](#_Toc22804613)

[6.7 Vehicle Ontology 55](#_Toc22804614)

[6.8 Transportation System Ontology 57](#_Toc22804615)

[6.8.1 Travel Costs 65](#_Toc22804616)

[6.9 Parking Ontology 66](#_Toc22804617)

[6.10 Public Transit Ontology 70](#_Toc22804618)

[6.11 Land Use Ontology 74](#_Toc22804619)

[6.12 Trip Ontology 78](#_Toc22804620)

[6.12.1 Trip Costs 80](#_Toc22804621)

[6.13 Urban System Ontology 80](#_Toc22804622)

[7 Extra-logical Design Practices 83](#_Toc22804623)

[8 Evaluation 83](#_Toc22804624)

[8.1 Consistency 83](#_Toc22804625)

[8.2 Competency 84](#_Toc22804626)

[8.3 Application 84](#_Toc22804627)

[9 Applications 84](#_Toc22804628)

[9.1 iCity Ontology for ATIS in the IT-SoS Framework (to revise based on revisions to project 1.2) 85](#_Toc22804629)

[9.1.1 Project 1.2: IT-SoS Architecture 85](#_Toc22804630)

[9.1.2 ATIS Case Study 87](#_Toc22804631)

[9.2 Analysis of TTC Data for Bus Bridging Study 90](#_Toc22804632)

[9.3 Organization of Travel Model Data 90](#_Toc22804633)

[9.4 iCity Ontology for Urban Simulation Results 90](#_Toc22804634)

[10 Integration with ArcGIS 91](#_Toc22804635)

[11 Workflows (in progress) 91](#_Toc22804636)

[11.1 Data Mapping 91](#_Toc22804637)

[11.1.1 Alternative approaches 91](#_Toc22804638)

[11.1.2 Basic data mapping/import workflow with Karma and Virtuoso: 92](#_Toc22804639)

[11.1.3 Repeat Data Mappings 93](#_Toc22804640)

[11.1.4 Offline Batch Mapping 93](#_Toc22804641)

[11.2 Data Storage 94](#_Toc22804642)

[11.2.1 Upload to triplestore 94](#_Toc22804643)

[12 Future Work 95](#_Toc22804644)

[12.1 Extensions to the Urban System Ontology 95](#_Toc22804645)

[12.2 Extensions for iCity Applications 95](#_Toc22804646)

[12.2.1 Data Collection 96](#_Toc22804647)

[12.2.2 Simulation of Urban Systems 97](#_Toc22804648)

[12.3 Evaluation 98](#_Toc22804649)

[12.4 Implementation 98](#_Toc22804650)

[12.5 Research 98](#_Toc22804651)

[13 Summary of Changes from Previous Version 98](#_Toc22804652)

[Acknowledgements 100](#_Toc22804653)

[Bibliography 101](#_Toc22804654)

# Purpose

The purpose of this document is to present the current release of the iCity ontologies. Complementary HTML documentation is automatically generated for each ontology from its OWL file using Widoco[[1]](#footnote-1); in a web browser, each iCity ontology IRI dereferences to this documentation.

# Scope

The iCity ontologies define the concepts required to represent the urban system and its behaviour, as informed by work undertaken by the iCity-ORF project teams.

This report includes documentation of the contents of the iCity ontology, along with recommendations for its implementation and maintenance, and examples of its application in the iCity-ORF project. The intended semantics of the ontology’s concepts are described in natural language, followed by an overview of the axioms that capture, or in some cases approximate, this semantics. The iCity is made up of sub-ontologies that are axiomatized in OWL 2 (Grau, et al., 2008). This report does not go into detail addressing the concepts defined in reused, external ontologies, except where necessary to describe concepts introduced in the iCity ontologies. The reader is referred to the original documentation for these ontologies as required.

# Role of the Ontology

All of the projects within iCity-ORF are situated in the urban domain, therefore it is not surprising to find many common concepts between them. As such, it stands to reason that some integration between the different applications should be possible. For example, if data is collected about the population, it should be usable by various simulations such as ILUTE [1], but also by the projects developing analysis tools, such as the smart parking application. Unfortunately, there is also ambiguity in how different concepts are used; the same concept may be defined differently in different applications. This provides a challenge not only for integration of the iCity applications, but for shareability and reuse of results: if the knowledge generated by iCity is not defined sufficiently, it will be difficult for any other researchers to understand and leverage it.

The key purpose of the iCity Ontology is to address these challenges of data integration and reuse. The iCity ontology provides a common set of terms with which data can be stored and accessed. The ontology will resolve any ambiguities and disagreements between terms by defining a common set of concepts that completely captures the domain, with agreed-upon definitions. In the case that two applications attribute a different meaning to the same term, the result will be two distinct terms with distinct, precisely defined meanings. In this way we can recognize these differences and clearly identify the relationships between different concepts. The ontology will be used to organize and describe data within the iCity project. It may also be used to support the publishing or sharing data with the research community.

The resulting artifact, often referred to as the *knowledge base* will take the form of a triple-store(s), created by mapping data from the iCity applications to the agreed-upon terminology defined in the iCity ontology. In future work, an alternative architecture may be explored wherein some or all of the data is maintained in its original location, such as a relational database, and accessed via mappings to the ontology. The high-level architecture for the ontology’s implementation in the context of the iCity project, is illustrated in Figure 1.

Another purpose of the ontology is to support automated reasoning. Owing to the formal logic that the ontology is encoded in, its axioms are capable of supporting data validation and inference of the information stored in the knowledge base.

The precise and formal nature of the ontology will support the use of services such as inference and data validation. Based on the definitions, we may be able to infer new information that was not originally part of the knowledge base. Data validation is supported as a result of the consistency-checking mechanism. We also hope that identification of relationships may serve to uncover synergies between the projects, by illustrating how data from one project may serve to inform the work of another.



Figure 1: iCity Knowledge Base High-Level Architecture

The sections that follow introduce the ontology required achieve this, in particular, to define the urban system. Beyond this basic architecture, the iCity Ontology may be implemented to support specific applications. Examples of this are discussed in further detail in Section 8.

# Development Approach

The ontologies presented in this report have been developed based on the guidelines for ontology development set out by both [2] and [3]. This combined approach may be described in terms of the following six activities, the outcomes of which are outlined in subsequent sections of this report.

1. Requirements gather: developing a clear understanding of the domain and required scope of the ontology. This activity is facilitated with the identification of motivating scenarios and eventually made more precise with the specification of Competency Questions. Competency Questions are queries that the ontology should be capable of representing and answering and may be thought of as analogous to functional requirements in Software Engineering.
2. Reuse: where possible, ontologies that were suitable for reuse to (partially) satisfied the requirements were identified. We also considered the reuse of existing vocabularies as appropriate.
3. Ontology Design: the definition of classes, the class hierarchy, and properties was tightly linked and iterative, rather than sequential as described by [2]. These terms were identified with a combined approach: bottom-up design from the required datasets, and top-down from the areas recognized as important to the domain. The reference to “facets” and “slots” by [2] can be interpreted as the task of defining axioms (primarily subsumption and equivalence, but also pertaining to object property characteristics) that relate the classes and properties with one-another.
4. Defining instances: the definition of instances was accomplished with the specification (and materialization) of R2RML mappings from existing data sources to the ontology. This process is described in greater detail later in the report.
5. Evaluation: the task of evaluation is an important step that is addressed in several ways in this project:
   1. *Consistency*: The ontologies shall be classified using an automated reasoner to demonstrate consistency of the definitions and absence of unsatisfiable classes.
   2. *Competency:* The ontologies shall be assessed against the Competency Questions specified in the Requirements stage.
   3. *Application:* The ontology shall be applied in a variety of case studies to serve as a concrete demonstration of its viability as a solution for several of the motivating scenarios. This will also illustrate the adequacy of the ontology to support mappings from relevant data sources (described previously).

# Requirements

In an effort to clarify the domain and scope of an ontology for transportation planning, interviews were conducted and relevant documents were reviewed to reveal required competency areas in two key knowledge categories, outlined in Table 1. The major concepts identified in this effort would eventually form many of the individual ontologies that the iCity TPSO is built from.

Table : Key competency requirements.

|  |  |
| --- | --- |
| **Knowledge Category** | **Competency Areas** |
| Urban System Characteristics | * Population:   + People   + Households   + Jobs   + Schedules   + Means of travel * Land Use   + Types of land use   + Occupied space * Transportation   + Road networks   + Transit networks   + Transportation modes and characteristics of (e.g. access points)   + Transportation vehicles and characteristics (e.g. capacity, speed, accessible routes/networks) |
| Urban System Behaviour | * Demographic Update: changes to population (people, household structures) * Labour Market: changes to job situations * Housing Market: changes to housing situations * Auto Ownership: changes to auto ownership * Activity-Based Daily Travel: activity schedules and associated travel * Transportation Emissions & Dispersed Pollution Concentrations * Transportation events: scheduled trips, failures, scheduled maintenance |

Delving deeper into the requirements for each research group, several motivating scenarios were identified. For each scenario, relevant data sets and competency questions were identified. The identification of relevant data sets served as a particularly useful source of requirements. Since data collection is a major task in transportation planning, the datasets provided a means of motivating the required scope and level of detail. The resulting ontology could then be assessed in terms of its ability to represent the competency questions as well as the information in the datasets.

**Note: Requirements beyond motivating scenarios**

The motivating scenarios provided precise, testable requirements and opportunities to apply the ontology in practice. However, scope of the resulting ontology extends considerably beyond the requirements dictated by the motivating scenarios and this should be addressed. This broader scope results from the subject matter interviews conducted with subject-matter experts, and the sample data that was provided at this stage. The motivating scenarios that were explored in greater detail were selected based on pragmatic criteria such as data availability, the stage of the various research projects. There exist many additional motivating scenarios, both within and beyond the iCity-ORF project that this ontology is intended to support. This should be explored in future work.

## Motivating Scenario: Land Use and Transportation Simulation

Reviewing the results of large-scale simulations, such as those generated by the ILUTE and TASHA [reference] models, can be challenging. The ontology can be used to capture the output and support question-answering to explore the results. Maintaining the data that serves as input to these simulations also poses a challenge for researchers. The ontology may be used to capture and relate historical data to improve access for researchers.

CQ1-1: What trips originated from/ended in a given zone?

CQ1-2: What is the occupation breakdown of the travelers whose trips originated/ended in a given zone?

CQ1-3: What were the purposes of the trips that originated/ended in a given zone?

CQ1-4: In a particular time period, how many trips originated/ended in a given zone?

CQ1-5: What were the transportation mode(s) taken by trips that originated/ended in a given zone?

CQ1-6: Who are the members of a particular household?

CQ1-7: What trips were performed, by which members of a particular household?

CQ1-8: What were the purposes of the trips performed by members of a particular household?

CQ1-9: What is the age, sex, and occupation of the traveler who performed a particular trip?

CQ1-10: What land use classification is associated with a particular parcel?

## Motivating Scenario: Transit Research

Transit research activities will often involve collecting, integrating, data from various sources. For example, researchers may need to combine data from various parts of the transit system to assess how some failure event, for example on a streetcar line, may impact nearby bus routes. Even assessing data about a single transit route may require the integration of various datasets, such as data describing the route itself, data describing the actual behavior of vehicles on the route, data on the vehicle’s characteristics, and perhaps contextual information such as ridership. The ontology may be employed to facilitate the integration of transit, thereby supporting easier access to information of interest.

In the iCity-ORF project, two areas of transit research were strategies to prevent streetcar bunching, and transit resilience strategies (so-called “bus bridging” where buses are re-routed to serve as shuttle buses in order to delays on the subway lines). As an initial step toward supporting these research areas, we elected to focus on supporting the transit resilience strategy project. This required support for queries to support the detection buses that had been re-routed as shuttle buses. This information could then be used to further analyze the bus bridging strategy and assess its impact on the network.

CQ2-1: What date and time has a subway incident occurred?

CQ2-2: What are the locations of buses from a particular station after the occurrence of a subway incident?

CQ2-3: Are any buses located more than a certain distance from their assigned route at a given point in time?

## Motivating Scenario: Smart Parking Applications

Through a tripartite research agreement on transportation and smart cities, a forward-looking motivating scenario for the Chinese University of Hong Kong (CUHK) was identified. Researchers at the CUHK have been investigating the potential for smart parking applications, especially in the context of electric vehicles. Providing parking information to drivers, whether real-time or static, is useful in helping them to locate a suitable parking spot. The question of suitability is complicated for drivers of electric vehicles, as they may require a parking location with access to a particular type of charger. Researchers at the CUHK were investigating the potential for such smart parking applications, and identified an opportunity to use ontologies to facilitate the access and integration of the required data. Based on the envisioned use cases and the currently available data, the following set of competency questions was identified:

CQ3-1 What is the address of the parking lot P?

CQ3-2 What is the capacity of parking lot P?

CQ3-3 Is it accessible by disabled people, and if so how many parking lots are for disabled vehicles?

CQ3-4 Is there a height limit for vehicles for a parking lot P?

CQ3-5 What are the geographic coordinates for parking lot P?

CQ3-6 What building is a particular parking lot located in?

CQ3-7 Is a particular parking lot open to the public at a given time?

CQ3-8 How much does it cost to park in a particular parking lot?

CQ3-9 What types of payment are accepted at a particular parking lot?

CQ3-10 How many parking spots are designated for electric vehicles in a particular parking lot?

CQ3-11 What types of electric vehicle chargers are available in a particular parking lot?

Opportunities for additional competency questions were identified as possibilities for future work, as more data sources become available.

## Motivating Scenario: ATIS via IT-SoS

ITS tools require integration of many heterogeneous data sources. Adaptability is challenging for traditional ITS frameworks due to the overhead to integrate new and changing data sources. The IT-SoS architecture proposed by [ref Elshenawy] can leverage the ontology to support data integration.

In general, the range of queries required to support the IT-SoS architecture will vary greatly as a function of the ITS application(s) to be supported. In the iCity-ORF project (1.2), the IT-SoS architecture was demonstrated by way of the Advanced Traveler Information System (ATIS). To support this implementation, the iCity ontology was required to answer competency questions regarding the traffic status on various road segments in the transportation network.

CQ4-1: What TTI\_Max values have been observed at some date/time?

CQ4-2: What is the TTI\_Max value at some location?

CQ4-3: What is the TTI\_Max value at some location, at some date/time?

Where TTI\_Max refers to the Maximum Transportation Travel Index, a measurement used to indicate traffic conditions by way of a comparison of the observed rate of travel to the maximum throughput speed on a road segment.

## Motivating Scenario: ArcGIS Query Support

ESRI Canada provides geospatial information system (GIS) solutions used for transportation research, urban planning, and a variety of other applications. They provide users with a wealth of data and powerful tools for visualization and analysis. However, the task of query formulation and revision can be challenging, in particular for less experienced users. These difficulties may be addressed with use of an ontology to formalize the terms of interest and provide a single interface with which complex queries may be formulated. Streamlined access to the geospatial data in ArcGIS will support all users, and may be particularly valuable for use cases for ongoing work on NextGen-911 services. There are added benefits to such an approach as the same ontology used to support data access may also serve as a specification of recent standardization efforts by the Canadian Transportation Infostructure (CTI).

CQ5-1: TBD

# Urban System Characteristics and Behaviour

In the urban system, we recognize the following key concepts that must be defined:

* Person
* Organization
* Household
* Building
* Parking
* Vehicle
* Transportation Networks
* Transit
* Land Use
* Travel

The semantics of each of these concepts will be defined by a generic ontology. These generic ontologies will then be used in the iCity ontology to define the urban system and its behaviour; its population, land use, transportation infrastructure, and the travel that occurs within it. This representation may then be extended to capture the individual iCity applications so that they may be integrated with one another and sufficiently well-defined so as to be shareable and reproducible with the research community. Foundational Ontologies will be also required in order to define the core concepts that apply across the transportation domain. These will be introduced first, followed by the presentation of each generic ontology in more detail. Where warranted, we provide a brief description of the domain and role of the ontology prior to describing its classes and their properties.

## Foundational Ontologies

In addition to the concepts that are specific to an urban system, there exist foundational concepts that are required to fully define the domain. In particular, the foundational ontology captures the concepts of time, space, change, activities, and resources; each concept is defined its own sub-ontology.

### Location Ontology

*http://ontology.eil.utoronto.ca/icity/SpatialLoc.owl*

To effectively capture the location of some object, several concepts must be introduced. First, a distinction must be made between the object and its location. Objects have some location, that is the region in space – a so-called spatial feature – that they occupy. The ontology must not only support a representation of these concepts, but a representation of relationships between spatial features. In particular, topological relationships are important as they allow for the identification of how one area in space is situated relative to another. For example, is one area contained in another? Are two areas disconnected?

Finally, to precisely describe the location of an object in space, some notion of geometry is required. This is important to represent the quantitative aspects of the feature, which may be represented as a point or perhaps some other area such as a polygon or a line.

#### The Ontology

The Spatial Location ontology reuses and extends the GeoSPARQL [4] standard to specify the concepts of interest. GeoSPARQL specifies the required vocabulary of spatial relations. It is particularly attractive as it has been published as a standard by the OGC; in addition, its defined relations are implemented, to various extents, as functions for querying spatial data by some knowledge base tools.

The ontology represents the location of objects using two key classes: Feature and Geometry, as shown in Table 2. A Feature is a spatial object, as opposed to a Geometry which is a more abstract object that may be used to describe the shape of some spatial object(s). The key properties, shown in Table 3, are largely made up of topological relations between Feature objects. In addition, the ontology specifies the property hasLocation to capture the relationship between non-spatial objects (e.g., train station) and the spatial locations they occupy. Similarly, the associatedLocation is introduced to capture the association of some non-spatial object to a particular location. For example, a train station may occupy a fairly large spatial location but be associated with a particular point.

In order to capture the quantitative geospatial information, spatial features may be associated with geometry objects, via the hasGeometry property. These geometries may then be encoded with coordinate information through the specification of WKT (well-known text) values with the data property asWKT. The default reference system for the coordinate values is assumed to be WGS84. While the GeoSPARQL specification allows for the identification of alternate reference systems, captured as IRIs and concatenated with the coordinates, it should be noted that current support is not widespread or standardized, therefore automated translation between these systems should not be assumed.

Table : Key classes in the Location Ontology

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| geo:Feature | rdf:subClassOf | geo:SpatialObject |
| geo:Geometry | rdf:subClassOf | geo:SpatialObject |

Table : Key properties in the Location Ontology

|  |  |  |
| --- | --- | --- |
| Property | Characteristic | Value (if applicable) |
| geo:sfEquals | Domain and Range | geo:SpatialObject |
| geo:sfDisjoint | Domain and Range | geo:SpatialObject |
| geo:sfIntersects | Domain and Range | geo:SpatialObject |
| geo:sfTouches | Domain and Range | geo:SpatialObject |
| geo:sfWithin | Domain and Range | geo:SpatialObject |
| geo:sfContains | Domain and Range | geo:SpatialObject |
| geo:sfOverlaps | Domain and Range | geo:SpatialObject |
| geo:sfCrosses | Domain and Range | geo:SpatialObject |
| geo:hasGeometry | Domain | geo:Feature |
| geo:hasGeometry | Range | geo:Geometry |
| hasLocation | Range | geo:Feature |
| associatedLocation | Range | geo:Feature |
| geo:asWKT | Range | geo:wktLiteral |
| as\_nDLatLon | Domain | geo:Geometry |
| Range | <http://franz.com/ns/allegrograph/5.0/geo/nd#_lat_la_-9.+1_+9.+1_+1.-4_+1.-1_lon_lo_-1.8+2_+1.8+2_+1.-4>[[2]](#footnote-2) |

#### An Example

For example, consider the location of a vehicle. A vehicle may be located at a person’s home or work. Similarly, a transit vehicle may be located at some station, maintenance yard, or at some point on a particular transit route. The Spatial Feature where the vehicle is located may be represented by some geometry (e.g. a point), and may have relationships of interest with other spatial features. For example, the location of the vehicle may be contained in some other spatial feature (corresponding to a traffic zone, for example). The resulting representation is illustrated in **Error! Reference source not found.**.



Figure : An example representation of a location information for a vehicle.

#### Future Work

The GeoSPARQL standard supports the identification of alternate coordinate reference systems, captured as IRIs and concatenated with the coordinates. However, support for translation between these systems is limited. Future work should address this in greater detail.

**Reused Ontologies:**

1. GeoSPARQL: http://www.opengis.net/ont/geosparql#

### Time Ontology

[*http://ontology.eil.utoronto.ca/icity/Time.owl*](http://ontology.eil.utoronto.ca/icity/Time.owl)

The concept of time is so pervasive that its definition is often taken for granted. In order to define an ontology for time, the objects of interest must be identified. What are the *things* that will be described? In general, three approaches to a representation of time have been identified: point-based, interval-based, and mixed. In a point-based representation, the objects of interest are timepoints. The passing of time is described as an ordering over time points, and periods of time may be represented as a series of timepoints. In an interval-based representation the objects of interest are time intervals, whereas the mixed representation includes both timepoints and time intervals. Key to all of these representations is that there is an ordering that holds over these time objects. We must be able to describe whether a time object is before another, and in the case of time intervals we must be able to describe other relationships such as whether one interval is contained in or overlaps with another.

#### The Ontology

Time is a concept that is fundamental, not only to transportation planning, but many other domains. For this reason, it is not surprising that a well-established ontology of time already exists, published as a W3C standard [5] and originally presented in work by [6] . This representation is reused directly, however rather than import the ontology directly into the transportation planning ontology, the time ontology is imported by a transportation-specific time ontology. This is done for two reasons: (1) It allows for the application of an organizational structure to the terms defined in the ontology; all classes are defined as subclasses of a TimeOntologyThing, similarly all object properties are subproperties of a TimeOntologyProperty, and likewise with data properties. These classes are superficial, but allow us to precisely organize the terms. This provides an added level of clarity in cases with large ontologies where multiple ontologies are imported. (2) In addition, it provides the flexibility for possible extensions to the time ontology in the iCity TPSO, while maintaining a clear relationship to the Time Ontology that is the W3C standard. In other words, any additions or changes may be made by defining new concepts in the transportation-specific time ontology, and *relating them* (e.g. via the subclass relation) to concepts in the W3C’s Time Ontology standard. These new concepts will be clearly identifiable their IRI.

The Time Ontology adopts a mixed representation of time, including both time instant and time interval classes. Definitions of the key classes and properties in the Time ontology are depicted in Table 4.

Table : Key classes in the Time Ontology

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| time:TemporalEntity | EquivalentClass | time:Instant and time:Interval |
| time:before | only time:TemporalEntity |
| time:after | only time:TemporalEntity |
| time:hasBeginning | only time:Instant |
| time:hasEnding | only time:Instant |
| time:hasDuration | only time:Duration |
| time:Instant | subClassOf | time:TemporalEntity |
| time:inside | only time:Interval |
| time:inTimePosition | max 1 time:TimePosition |
| time:inXSDDateTimeStamp | max 1 xsd:DateTimeStamp |
| time:Interval | subClassOf | time:TemporalEntity |
| time:meets | only time:Interval |
| time:overlaps | only time:Interval |
| time:starts | only time:Interval |
| time:finishes | only time:Interval |
| time:during | only time:Interval |
| time:equals | only time:Interval |
| time:DateTimeDescription | time:day | max 1 rdfs:Literal |
| time:dayOfWeek | max 1 owl:Thing |
| time:dayOfYear | max 1 rdfs:Literal |
| time:hour | max 1 rdfs:Literal |
| time:minute | max 1 rdfs:Literal |
| time:month | max 1 rdfs:Literal |
| time:second | max 1 rdfs:Literal |

#### An Example

Returning to the example of representation of a vehicle. Should we wish to represent an instant in time at which the vehicle exists, relative to some earlier time before the vehicle exists, this would involve the introduction of two Instant objects that could be related via the before property. Should the data be available, the instants could be further described with the date-time stamp using the inXSDDateTime data property, or using the inDateTime property to relate the instants to a DateTimeDescription object.

Alternatively, we might know the interval but the not the precise instant. If specific data were known regarding the date and time of these interval, say that it began at 09:22 EST on June 19, 2019 and ended at 11:33 EST on July 12, 2019, this could be specified using the inXSDDateTime data property. In this case, the instant might simply be described as being in the interval using the inside property. This example representation is depicted in Figure 3: Example use of the Time Ontology.



Figure : Example use of the Time Ontology

**Reused Ontologies:**

* time: W3C Time Ontology[[3]](#footnote-3) originally presented by (Hobbs & Pan, 2004)

### Change Ontology

*http://ontology.eil.utoronto.ca/icity/Change.owl*

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. Similarly, many attributes of Persons, Households, and even Transportation Networks are subject to change.

Change over time plays a role in many domains, and is by no means a new research topic. In fact, several approaches for capturing change in OWL have been proposed [7],[8]. Despite these solutions, we have found that Semantic Web practitioners currently lack clear and precise methods for how to apply these approaches to capture change at a domain level, whether reusing an ontology that does not account for change over time or developing an ontology from scratch. The Change Ontology serves as a clear guide to support a consistent approach to formalizing how things change over time throughout the iCity TPSO.

#### The Ontology

An approach to representing changing properties, or *fluents*,that leverages the 4-dimensionalist perspective was proposed by [7]. We adopt a similar approach, based on the design pattern presented in [9], requiring the division of classes that are subject to change into two parts: invariant and variant parts of the concept; 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 [8], we treat 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. The key classes and properties of the ontology are outlined in 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. Similarly, many attributes of Persons, Households, and even Transportation Networks are subject to change.

Change over time plays a role in many domains, and is by no means a new research topic. In fact, several approaches for capturing change in OWL have been proposed [10],[11]. Despite these solutions, we have found that Semantic Web practitioners currently lack clear and precise methods for how to apply these approaches to capture change at a domain level, whether reusing an ontology that does not account for change over time or developing an ontology from scratch. The Change Ontology serves as a clear guide to support a consistent approach to formalizing how things change over time throughout the iCity TPSO.

Table 5: Key classes in the Change Ontology

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| TimeVaryingConcept | disjointWith | time: TemporalEntity and Manifestation |
| existsAt | exactly 1 time:Interval |
| hasManifestation | only Manifestation |
| equivalentClass | hasManifestation some Manifestation and hasManifestation only Manifestation |
| Manifestation | disjointWith | TimeVaryingConcept and time: TemporalEntity |
| equivalentClass | manifestationOf some TimeVaryingConcept and manifestationOf only TimeVaryingConcept |
| manifestationOf | only TimeVaryingConcept |
| existsAt | exactly 1 time:TemporalEntity |

Table 6: Key properties in the Change Ontology

|  |  |  |
| --- | --- | --- |
| Property | Characteristic | Value (if applicable) |
| hasManifestation | inverseOf | manifestationOf |
| Inverse Functional | - |
| manifestationOf | Functional | - |
| existsAt | Ranges | time:TemporalEntity |

|  |  |  |
| --- | --- | --- |
| Property | Characteristic | Value (if applicable) |
| hasManifestation | inverseOf | manifestationOf |
| Inverse Functional | - |
| manifestationOf | Functional | - |
| existsAt | Ranges | time:TemporalEntity |

#### An Example

A key question to answer in the representation of changing objects is what properties may be subject to change, as opposed to other properties which have values that are part of the object’s identity. The vehicle identifier (VIN) is a unique identifier for a vehicle that is assigned by the manufacturer and remains constant throughout a vehicle’s lifetime. Therefore, the VIN should be a property of the TimeVaryingConcept (a class typically denoted with “PD” [[4]](#footnote-4), for example VehiclePD) object. On the other hand, a vehicle’s location may change over time. Therefore, the location should a property of the Manifestation object (a member of the Vehicle class). Note that the Change Ontology has implications not only on how instance data is represented, but also on how domain-specific classes are defined. This example representation is depicted in Figure 4. The individual “veh1t1” represents a manifestation of the individual vehicle “veh1”; in other words, veh1t1 captures a snapshot of veh1 in time. While veh1 has a single VIN for its entire existence, its location will change over time. Therefore, it is related to a series of individual manifestations (veh1t1 and others) that capture changing properties, such as location. When the location changes, this will be represented by another individual manifestation of veh1. Not captured in the diagram is the fact that each manifestation exists during some point or interval in time and thus may be related to a different temporal entity.



Figure : Example use of the Change Ontology

**Reused Ontologies:**

* iCity-Time

### Activity Ontology

*http://ontology.eil.utoronto.ca/icity/Activity.owl*

The concept of activities arises in several cases in the domain of transportation planning. Of particular importance are the trip activities that contribute to the demand on a transportation system, and the routine activities that motivate these trips. Trips are defined more precisely in an extension of the activity ontology, however both types of activities share the same foundational semantics. In the most general sense, activities may be thought of things that happen; events that occur (scheduled or not) or actions that are performed by some agent. It is not only the activity but the time of its occurrence and any things that are participants in some way that are involved in the description of an activity. Finally, central to understanding an activity, and thus central to its definition, is the effect it has or should have on the world.

#### The Ontology

There are many OWL ontologies that in some way address the concept of activities, however most are lacking with respect to the basic representation requirements. The Activity Ontology adopts the Activity Specification design pattern that was presented by [10] as a solution to address these limitations. The proposed solution adopts a view of causality similar to the Event Calculus [11], employing the concept of manifestations to describe the states (fluents) that hold before and after an activity. The representation of activity specifications is based on the activity clusters introduced by Fox, Sathi, and colleagues [12, 13].

A precursor to the TOVE [14] and PSL [15] activity ontologies, an activity cluster provides a basic structure for representing activity specifications. Illustrated in Figure 5, it consists of an activity connected to an enabling and caused state, each of which may be a state tree that defines complex states via decomposition into conjunctions and disjunctions of states.



Figure 5: A generic activity cluster

It is important to clarify that in this approach an activity is interpreted as a class of occurrences, in contrast other approaches where activities are separate entities that are related to occurrences via an *occurrence of* relation. This decision was motivated by several pragmatic factors: in many cases it is sufficient to capture information regarding individual activities (i.e. occurrences or events). These activities may be categorized via different subclasses of “Activity”, but there is no need to associate them with a single activity type entity, unless we wish to characterize the activity type itself. The capability for this more complex formalization is supported, should it be required, by the Recurring Event ontology (presented below). Dividing these representations into two separate ontologies allows users of this representation the discretion to only include what they need. In addition, much of the semantics that relate activity types and occurrences – as defined in PSL for example – is not expressible in OWL. There would be little value in forcing such an ontology in OWL, which would only superficially capture the intended semantics. Instead, the Activity Ontology works within the limitations of OWL to capture the concepts of activities, their composition, preconditions and effects, and ordering. The key terms are described below:

An Activity describes something that occurs in the domain. It may have precondition and/or effect states, and may be further decomposed into subactivities. An Activity may be enabled by or cause some State~~s~~. An enabling/causing state is a generalization of a precondition/effect; an Activity is enabled by or causes some State if it has a subactivity with a precondition or effect (respectively) of that State. An Activity occurs at some point in time or over some interval, and space, and may have some participants. Finally, though it is not possible to fully define the semantics in OWL, some notion of an ordering on activity occurrences must be captured in some cases. To address this, the properties: “occursBefore” and “occursDirectlyBefore” are introduced in the Activity ontology.

While we cannot fully define this semantics of an ordering over occurrences in OWL, we can leverage the start and end times of an activity to describe the occursBefore property using object property chaining:

* An activity occursBefore another if its endOf instant is before the beginOf instant of the other activity: endOf o before o inverse (beginOf) -> occursBefore. The occursBefore relation is also defined as transitive.
* An activity occursDirectlyBefore another if it occursAt an interval that meets the interval of the other activity; this can be captured similarly with object property chaining: occursAt o intervalMeets o inverse(occursAt) -> occursDirectlyBefore.

A state refers to a subclass of manifestations, as defined in the Change Ontology. It may be an immediate precondition or effect of some Activity, or more generally it may enable or be caused by some Activity (in which case, it might be a direct precondition or effect of some subactivity of the activity). A state may be complex and refer to some combination of classes of manifestations.

* A State may be either non-terminal or terminal. A terminal state has no child states, and therefore refers directly to a class of manifestations, whereas a non-terminal state has child states, which may define some classes of manifestations, or further define some other complex state types. A state type cannot be both non-terminal and terminal.
* A terminal state has cannot be decomposed, in other words it has no substates. It corresponds to a particular class of manifestations. A terminal state is achieved at some time if and only if there exists a manifestation within its defined classification, that exists at that time.
* A non-terminal state may be conjunctive or disjunctive. Naturally, a conjunctive state is defined by the conjunction of its child state, whereas a disjunctive state is defined by the disjunction of its child states. A state cannot be both conjunctive and disjunctive.

Conjunctive and disjunctive states, which *do* have substates, are achieved at some time if their decomposition of state is achieved.

Note that in this representation the decomposition of (*decomp\_of*) property is not a transitive relation, it only refers to the direct children of a non-terminal state. A more general relation that *is* transitive is the substate relation.

The key classes that formalize these concepts are summarized in Table 7 and illustrated in Figure 6.

Table : Key classes in the Activity Ontology

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| Activity | hasSubactivity | only Activity |
| hasPrecondition | only State |
| enabledBy | only State |
| hasEffect | only State |
| causes | only State |
| occursAt | some time:Interval |
| beginOf | some time:Instant |
| endOf | some time:Instant |
| spatial\_loc:hasLocation | only spatial\_loc:SpatialFeature |
| hasParticipant | only change:Manifestation |
| occursBefore | only Activity |
| occursDirectlyBefore | only Activity |
| State | preconditionOf | only Activity |
| enables | only Activity |
| effectOf | only Activity |
| causedBy | only Activity |
| achievedAt | only time:TemporalEntity |
| TerminalState | subClassOf | State |
| disjointWith | NonTerminalState |
| subClassOf | change:Manifestation and (preconditionOf some Activity or effectOf some Activity) |
| hasDecomp | exactly 0 StateType |
| NonTerminalState | subClassOf | State |
| disjointWtih | TerminalState |
| hasDecomp | only State and min 2 State |
| hasSubstate | only State |
| ConjunctiveState | subClassOf | NonTerminalState |
| disjointWith | DisjunctiveState |
| DisjunctiveState | subClassOf | NonTerminalState |
| disjointWith | ConjunctiveState |



Figure : Relationship between key classes in the Activity Ontology

#### An Example

As an example, consider the activity of driving to work. This activity occurs before the activity of working; axioms at the class-level could be added to state that all instances (occurrences) of the DriveToWork activity occur before some instances (occurrences) of the Work activity, though such statements may be too strong in some cases. There are also certain preconditions and effects of the activity that might be important to represent. For example, an effect of the DriveToWork activity is that both the driver and the car are at work. This could be represented as a complex, Conjunctive State. This state may then be decomposed into more precise sub-states that capture the intended semantics using concepts from other parts of the iCity TPSO. This example formalization of the DriveToWork activity is illustrated in Figure 7. Note that the activity DriveToWork might also be decomposed into subactivities (e.g. parts of the trip) as required. When the resulting Activity and State subclasses are instantiated, additional details regarding a particular occurrence of an activity may be added. For example, the location of the person and vehicle may be specified thus providing additional detail on the state before the particular activity occurrence. This is depicted in Figure 8.



Figure : Example formalization of the DriveToWorkActivity



Figure : Example use of the Activity Ontology

#### Future Work

As noted, this represented is influenced by earlier work on Activities in the TOVE ontologies. However, this ontology does not directly reuse the more recent OWL version of the TOVE Activity ontology released by the Enterprise Integration Laboratory[[5]](#footnote-5). Future work should address this by attempting to either revise and converge these ontologies or to formalize the relationship between the two.

**Reused Ontologies:**

* Change Ontology
* Location Ontology

### Recurring Event ontology

*http://ontology.eil.utoronto.ca/icity/RecurringEvent*

A specification of recurring events, in particular those that are defined according to calendar dates (e.g. every Monday, every March), is required to capture information regarding hours of operation, road restrictions, restrictions on parking policies, and so on. A recurring event is a means of describing scenarios where some activity is scheduled to recur at some regular interval. It is important to note that recurring events such as scheduled transit trips and operating hours represent planned or usual occurrences. For example, while a business may be open at some recurring intervals, it's possible that given some exceptional circumstances (e.g power failure) they may not be open during the predefined days and times.

#### The Ontology

The design of this ontology was inspired by previous work on an ontology for city services[[6]](#footnote-6) for the Global City Indicator (GCI) Ontology [16], however due to incompatibilities in the scope and semantics of the GCI ontology we do not directly reuse it in the iCity TPSO. The GCI Ontology defines recurring events specifically as “Service” events, whereas the transportation requires a more general notion of recurring events. The GCI Ontology employs the concept of a time interval to capture when some event recurs, however we observe that this is misleading as recurring events will occur at *multiple* intervals in time. In the iCity TPSO, we opt for a more precise representation that identifies the individual occurrences (that occur at a particular time interval) of some recurring event.

The Recurring Event Ontology adopts the following representation of recurring events: daily, weekly, and monthly recurring events (and their related properties) are defined, however the ontology may be extended with similar definitions of other type of recurring events, as required. This approach is based on the GCI Ontology work and adapted to provide a more suitable and complete representation of recurring events for the transportation domain.

An instance of a recurring event corresponds to a class of activities (e.g., all of the occurrences of a Tuesday, all of the occurrences of the weekly waste pickup). The intuition is that the occurrences of a recurring event are all the same type of activity. What defines a recurring event is a combination of the activity type (e.g. a transit trip from point A to point B or the provision of a service) and the frequency at which it recurs.

The ontology captures the associated activity type with the *hasOccurrence* property that relates recurring events to activities. Classes of recurring events may be captured by identifying their associated classes of Activities, while individual recurring events may be associated with one or more instances of an activity.

The Recurring Event ontology reuses the Activity ontology, as the concept of an activity is central to the notion of a recurring event: the activities are the recurrences. It is important to note that while the concept of Activity defined in the Activity ontology and is necessary for the definition of a RecurringEvent, it is *not* the case that the concept of RecurringEvents is required for the definition of an Activity. This allows the iCity TPSO to maintain a simpler representation of events in cases where the notion of recurrence not be required.

Recurring events are also identified based on the regular interval at which they occur; this is captured using some combination of the hasTime, dayOfWeek, hasMonth, and dayOfMonth properties. Using these properties, the ontology supports definitions of specializations of the RecurringEvent class. In particular, subclasses for daily, weekly, monthly, and yearly recurring events are defined; other classes of recurring events may be defined similarly, as required.

* A DailyRecurringEvent occurs every day. It has a maximum of one associated time – the start time. Typically, a daily recurring event will occur at the same time every day, however there may be no commitment to a recurring start time for the event, in which case no start time is specified. A DailyEvent does not necessarily have a recurring end time (this would require a constant duration), therefore this is not part of the definition (although it is possible to specify).
* A WeeklyRecurringEvent recurs regularly on the same day of the week, as specified by the schema:dayOfWeek property.
* A MonthlyRecurringEvent recurs regularly on the same day of each month, as specified by the dayOfMonth data property. Note that there is often ambiguity regarding the semantics of a monthly recurring event: in this formalization, a MonthlyRecurringEvent is any event that recurs regularly on the same *day* of each month; other interpretations sometimes consider events that recur on the same day of week, or first or last day, in which case the day of month will vary. Such a representation is not included in this ontology, but could be captured in an extension.
* A YearlyRecurringEvent recurs regularly on the same day of the same month, as specified by the hasMonth and dayOfMonth properties. As with MonthlyRecurringEvent, there may be ambiguity regarding the semantics of a yearly recurring event, however this formalization captures only the notion of an event that recurs on the same day of the same month (e.g. a birthday).

Exceptions to recurring events may also be defined. For example, a business may normally operate on Monday-Friday, except for public holidays. Exceptions may also be defined on *specific* dates (e.g. June 23, 2018), for example due to construction. If applicable, exceptions may be defined for recurring events with the recursExcept property. Conversely, so-called exceptions may involve an additional, unusual occurrences. This is captured with the recursAddition property.

As with an Activity, a RecurringEvent may be decomposed/decomposed into simpler/more complex RecurringEvents to support varying levels of granularity. This decomposition may be specified with the hasSubRecurringEvent property. The key classes in the Recurring Event Ontology are summarized in Table 8 and illustrated in Figure 9.

Table : Key classes in the Recurring Event Ontology

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| RecurringEvent | hasOccurrence | only activity:Activity |
| spatial\_loc:associatedLocation | only spatial\_loc:Feature |
| hasSubRecurringEvent | only rec:RecurringEvent |
| startTime | only xsd:time |
| endTime | only xsd:time |
| schema:dayOfWeek | only DayOfWeek |
| endDayOfWeek | only DayOfWeek |
| hasMonth | only Month |
| endMonth | only Month |
| dayOfMonth | only rdfs:Literal |
| endDayOfMonth | only rdfs:Literal |
| beginsRecurring | only time:TemporalEntity |
| endsRecurring | only time:TemporalEntity |
| recursExcept | only time:TemporalEntity or DayOfWeek |
| recursAddition | only time:TemporalEntity or DayOfWeek |
| DailyRecurringEvent | subclassOf | RecurringEvent |
| startTime | max 1 xsd:time |
| WeeklyRecurringEvent | subclassOf | RecurringEvent |
| schema:dayOfWeek | exactly 1 DayOfWeek |
| MonthlyRecurringEvent | subclassOf | RecurringEvent |
| dayOfMonth | exactly 1 rdfs:Literal |
| YearlyRecurringEvent | subclassOf | RecurringEvent |
| hasMonth | exactly 1 Month |
| dayOfMonth | exactly 1 rdfs:Literal |



Figure : Basic structure of the Recurring Event Ontology

#### An Example

As an example, consider the representation of scheduled transit trips. The Activity Ontology may be used to define classes of Transit Trip activities, and these classes may be instantiated with instances that correspond to individual occurrences of these trips, however in order to capture the schedule – i.e. that some trip occurs every day at 08:00am – the notion of a recurring event is required. A class of recurring events that captures scheduled bus trips may be defined as having only BusTrip activities as occurrences. Instances of the ScheduledBusTrip class may include recurring events with different start times, perhaps corresponding to different routes or different routes on the same trip. An individual scheduled bus trip with a start time of 08:00am corresponds to multiple occurrences. As daily recurring event, we can expect there will be a corresponding occurrence of the bus trip activity every day, thus an individual recurring event (an instance of a scheduled bus trip) will correspond to multiple instances of a particular activity type (a bus trip). The Recurring Event object provides information on the way in which the activity recurs (e.g. daily at 08:00am). This example is illustrated in Figure 10.



Figure : Example use of the RecurringEvent Ontology

#### Future work

* Address the relationship between a Recurring (Service) Event and an Event (Activity) in more detail. Based on the properties of a recurring event, additional constraints on its occurrences (related activities) may be inferred.
* Additional temporal constraints may be specified to describe the relationship between a Recurring Event and its sub-Recurring Events: the sub-Recurring Events may only recur during the times at which the Recurring Event recurs.
* An ordering relationship over sub-Recurring Events may be useful in future implementations, however this is not currently captured or required.

**Reused Ontologies**

* Activity Ontology

### Resource Ontology

*http://ontology.eil.utoronto.ca/icity/Resource.owl*

Resources are an important aspect of activities; they often capture important preconditions and effects of activities. In the context of transportation planning, resources such as vehicles, income, and transit passes will impact travel behaviour. The representation of resources is also important for tasks related to asset management; for example, transit vehicles and their scheduled maintenance and failure rates are important factors for predicting the performance of the transit system.

### The Ontology

The Resource Ontology provides a generic representation of resources that contain core properties generic across all transportation uses. We take the view presented in the TOVE model [17] that "*...being a resource is not an innate property of an object but a property that is derived from the role the object plays with respect to an activity*". In this sense, Resources are a class of Manifestations; a Resource is a manifestation of some *other* perdurant class in the ontology when it plays the role of Resource for some Activity. For example, an instance of a Vehicle, (a manifestation of some VehiclePD) may also be an instance of a Resource, whereas some other instance of a Vehicle, (some later manifestation of the same VehiclePD) may not be a Resource, or it may be a *different* type of Resource. For example, when the Vehicle is used for transportation, it is one type of resource, but when it is being used for scrap metal, it is a different type. This definition of a resource is dependent on its participation in an activity, thus the Resource ontology reuses the Activity ontology.

A Resource may have some Location, amount or availability, according to the definition of the Manifestation or TimeVaryingEntity. In addition, it may have some associated location and may have some owner. As with the precondition and effect properties defined in the Activity Ontology, the decomposition of an activity must be considered: there are atomic-level relationships of consumption and use, but also more general relationships based on inheritance through composition. For example, if Activity A has subactivity B, then a resource used by Activity B is also used by Activity A.

For additional detail, a Resource maybe classified according to more specific resource types. A Resource may *either* be a Divisible Resource or a Non-Divisible Resource, but not both. As the names indicate, a Divisible Resource may be divided for use or consumption between multiple activities at any point in time, whereas a Non-Divisible Resource may only be used for a single activity at once – even if it isn’t fully utilized. Continuing our example, a Vehicle used for transportation is non-divisible but if used for scrap then it is divisible. The key classes in the ontology are summarized in Table 9.

Various other types (subclasses) of Resource may be defined as required. A Resource Type may be used by or consumed by some Activity; the specification of the Resource Type defines the quantity of a particular resource that will be used or consumed by a particular activity. If some resource type is used by an activity, then when the activity occurs, there must be some resource of that type that is (partially) not available. If a resource type is consumed by an activity, then the resource and the entity it is a manifestation of (partially) cease to exist by the end of the occurrence.

Table : Key classes in the Resource Ontology

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| Resource | subClassOf | change:Manifestation |
| change:existsAt | exactly 1 TemporalEntity |
| spatial\_loc:hasLocation | only spatial\_loc:SpatialFeature |
| hasCapacity | only om:CapacitySize |
| capacityInUse | only om:CapacitySize |
| activity:participatesIn | min 1 activity:Activity |
| usedInOccurrence | only activity:Activity |
| consumedInOccurrence | only activity:Activity |
| DivisibleResource | subClassOf | Resource |
| disjointWith | NonDivisibleResource |
| hasAvailableCapacity | only om:CapacitySize |
| NonDivisibleResource | subClassOf | Resource |
| disjointWith | DivisibleResource |
| usedBy | exactly 1 activity:Activity |

### An Example

Consider the representation of a vehicle as an example. A Vehicle might be used as a non-divisible resource for transportation, and then later as a divisible resource for some metal recycling process. While these examples might refer to the same car over the span of its lifetime, each one in fact refers to a different manifestation of the car, and hence a different resource. The resources differ in their divisibility because each one is defined with respect to a different activity (e.g. travel, versus metal recycling). A divisible resource may be used by or consumed by more than one activity, whereas a non-divisible resource may only be used by one activity (i.e. the object may only be used by one activity at a time). This example is illustrated in Figure 11



Figure : Example use of the Resource Ontology

#### Future Work

The current representation is very general and simplistic. Future versions will likely need to expand on the types of resources as well as their relationship between activities.

**Reused Ontologies:**

* iCity Activity Ontology

### Mereology Ontology

*http://ontology.eil.utoronto.ca/icity/Mereology.owl*

Notions of parthood are ubiquitous in and beyond the transportation domain. While sometimes conflated, there are clear distinctions which can be made between different types of parthood and similar relations. The mereology ontology goes beyond classical mereology and is intended to capture any generic part-whole relations of interest; thus far, the ontology focuses on the part-of, contained-in, and component-of relations, attempting to make the distinctions between them explicit. These distinctions may be best explained with the use of examples. An item may be *contained in* my car, but that does not make it a *component of* my car. For example, we may wish to describe passengers or cargo being *contained in* a vehicle, but this relation must be distinguished from the parts and components that make up a vehicle. Similarly, the front of my car is intuitively a part of my car, but not a component of my car. While we may define components of a vehicle, different zone systems (wards, postal codes) are not components, but proper parts of larger areas.

#### The Ontology

The Mereology Ontology introduces the following different relations as object properties: proper-part-of, component-of, and contained-in. A more detailed analysis reveals clear, ontological distinctions between each of these relations that may formalized clearly with a set of first-order logic axioms. This analysis, presented in [18] also identifies the expressive limitations of OWL, which prevent a complete representation of this semantics, and discussed the various possible approximations. It is important to consider what should be captured, and what distinctions should be made in the introduction of properties, in contrast with what is actually expressible in the logic. Since we cannot completely capture the required semantics in OWL, some trade-off(s) is required for any partial specification, (e.g. OWL only allows the specification of transitivity for simple object properties).

The difficulty with such an approximation is that the resulting theory defines a semantics for something else entirely. Inherently, some semantics are omitted, which may not be required for one application but may be important for another. For example, if transitivity is a key aspect of some required reasoning, then perhaps a parthood relation would be defined as transitive, and some omissions would be made with respect to the formalization other restrictions (e.g. cardinality) that should be applied to the parthood relation. Certainly, the use of approximations will be required in some cases, for example in order to support some desired reasoning problems. However, precisely which axiomatization is most suitable will vary between different usage scenarios. The Mereology Ontology therefore omits a detailed, partial axiomatization in favour of an under-axiomatized specification of the key relations, in order to avoid prescribing one trade-off over another. This leaves the commitment open-ended and variable to suit individual applications’ needs. The key properties are summarized in Table 10.

This ontology defines the general properties such that the commonality between domain-specific part-of relations may be captured, and more detailed semantics may be defined in extensions of the properties. This creates a means of indicating the intended semantics of a relation by identifying the *type* of parthood that it is intended to capture, while allowing for the specification of different partial approximations of the semantics (and possibly also specializations of this semantics), as required. For example, a notion of parthood arises in the description of a building and the units it is divided into. In this case, this relationship may be identified as a sort of hasComponent relation; a new property ‘hasBuildingUnit’ may be identified then as a subPropertyOf hasComponent. We are free to assess, for the ‘hasBuildingUnit’ relation, which approximations of the component-of relation are the most suitable. The approximation chosen for one type of parthood relation does not constrain the choice of approximation for another.

Table : Key properties in the Mereology Ontology

|  |  |  |
| --- | --- | --- |
| Property | Characteristic | Value (if applicable) |
| properPartOf | inverseOf | hasProperPart |
| hasProperPart | inverseOf | properPartOf |
| componentOf | subPropertyOf | properPartOf |
| inverseOf | hasComponent |
| hasComponent | subPropertyOf | hasProperPart |
| inverseOf | componentOf |
| immediateComponentOf | subPropertyOf | componentOf |
| containedIn | inverseOf | contains |
| contains | inverseOf | containedIn |
| immediatelyContainedIn | subPropertyOf | containedIn |

#### An Example

For example, consider the representation of various parts in a vehicle. This is a component-of type property, therefore a property ‘hasVehicleComponent’ as a sub-property of the ‘hasComponent’ property. Like hasComponent, hasVehicleComponent should be both transitive and irreflexive. However, owing to the restriction on non-simple object properties in OWL, it is not possible to capture both characteristics. In the context of a vehicle’s component decomposition, it is likely the case that transitivity of the property may be more important than its irreflexivity. Therefore, the subproperty hasVehicleComponent may be approximated as being transitive while maintaining the under-axiomatized definition of hasComponent. On the other hand, it may be the case that for component relation for Buildings and BuildingUnits the anti-symmetry of the property is the most important aspect to capture. The hasBuildingUnit property may be approximated as anti-symmetric rather than transitive, thus allowing for different trade-offs to be made to capture the component-hood relationship in different domains. This example is illustrated in Figure 12.



Figure : Example use of the Mereology Ontology

#### Future work

In addition to the aforementioned work by [ref Bittner & Donnelly], various approaches to the partial capture of these mereological relationships in OWL have been proposed that may be used to extend the ontology presented here, such as in [https://www.w3.org/2001/sw/BestPractices/OEP/SimplePartWhole/], and also in top-level ontologies such as [ref BFO]. Future revisions may benefit from considering the relationship between these ontologies and other OWL formalisms.

* Extend to capture multidimensional mereotopological relations as in CODI
* Map the relations to GeoSPARQL properties
* Extend with a first-order formalization or mereology

### Ontology of Units of Measure

*http://ontology.eil.utoronto.ca/icity/OM.owl*

Units of measure are an important concept due to the observational nature of data collection for transportation planning. In particular, it is important to capture the relationship between some quantity and the unit of measure it is described with. This allows for a representation in which the same individual quantity may be associated with several values, according to different units of measurement.

#### The Ontology

The Ontology of Units of Measure provides a structured vocabulary to describe, among other things, the different values (measures) that we associate to given quantities. This allows us to provide greater detail regarding specific measurements that are defined in the ontology. Rather than simply have a simple data property to describe the length of some road segment as "10 m", with the units of measure ontology we are able to describe the nature of the quantity (i.e. length), its value as a Measure (10 m), and also describe the unit that the measure's numerical value is given in (e.g. meters). Key concepts are reused from the Units of Measure ontology defined by [19]. The full Units of Measure ontology is not imported here as it is quite large and includes many concepts that are out of scope for transportation planning. Existing concepts may be added from the original ontology or this ontology may be extended as to capture new units of measure as required. The Units of Measure Ontology was chosen for reuse to maintain consistency with other ontology-based standards efforts in the smart cities domain, in particular the ISO standard in development for smart city indicators [20].

Quantities, units, and/or measures that are defined using domain-specific concepts (e.g. vehicles, lanes) are defined by reusing and extending the units of measure ontology in the relevant ontologies, such that the necessary concepts may be captured and the foundational ontology is not complicated with domain-specific concepts. The key classes used in the definition of quantities and measures are summarized in Table 11.

Table : Key classes in the Units of Measure Ontology

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| om-2:Quantity | om-2:hasValue | only om-2:Measure |
| om-2:Measure | om-2:hasUnit | only om-2:Unit |
| om-2:Speed\_unit | subClassOf | om-2:Unit |
| om-2:Amount\_of\_money\_unit | subClassOf | om-2:Unit |
| ... | subClassOf | om-2:Unit |
| MonetaryValue | subClassOf | om-2:Measure |
| hasRelativeYear | exactly 1 xsd:gYear |
| om-2:hasUnit | only om-2:Amount\_of\_money\_unit |
| ValueOfMoney | subClassOf | om-2:Quantity |
| subClassOf | om-2:AmountOfMoney |
| om-2:hasValue | only MonetaryValue |

#### An Example

For example, consider the representation of the speed of a Vehicle, and a particular point in time. The Vehicle’s speedometer may indicate a speed of 62 mph, whereas the speed observed by some radar gun or loop detector may record a speed of 100 km/h. Both values represent the same quantity but use different units of measure. Using the Units of Measure Ontology, the two distinct values and their units of measure may be captured and associated with a single instance of the vehicle’s speed, as illustrated in Figure 13.



Figure : Example use of the Units of Measure Ontology.

**A note on populations and cardinality:**

In order to represent populations, we reuse the following classes from the GCI-Foundation ontology: gci:PopulationSize, gci:PopulationSizeMeasure, and gci:CardinalityUnit. Refer to the working paper on the GCI Ontology for more details on this approach. The meaning of population is general here, while it may define a population of residents within some zone, it may also be used to describe the population of vehicles occupying some stretch of the road network.

The quantity of interest (population size being measured/described) is defined as gci:Population\_Size, a subclass of Quantity. Population\_Size has some unit of measure (a cardinality unit), and has\_value some Population\_Measure (with an associated numeric value). The elements associated with a population quantity are captured through the defined\_by property that relates a Population to some class of objects. For example, consider the measurement of the number of cars on some road segment, we could specify: Population\_Size and cardinalityOf only (Population and definedBy only (Vehicle)). The defining population might be even more precisely captured for a given Road Segment, X, as depicted in Figure 14: definedBy only (Vehicle and onSegment value X). These specializations are defined, as required, within the relevant module; for example, a vehicle population would be defined in a module that contains the required concepts of vehicles and road segments. The units of measure ontology captures only the core concepts of Population Size, Population Measure, Cardinality Unit, and Population, as depicted in **Error! Reference source not found.**. Capacity and its associated quantity and measure are defined similar to population.



Figure 14: Specialization of populations.

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| om-2:Quantity | om-2:hasValue | only om-2:Measure |
| om-2:Measure | om-2:hasUnit | only om-2:Unit |
| om-2:Length\_unit | subClassOf | om-2:Unit |
| om-2:Mass\_unit | subClassOf | om-2:Unit |
| om-2:Area\_unit | subClassOf | om-2:Unit |
| om-2:Acceleration\_unit | subClassOf | om-2:Unit |
| om-2:Volume\_unit | subClassOf | om-2:Unit |
| om-2:Speed\_unit | subClassOf | om-2:Unit |
| om-2:Amount\_of\_money\_unit | subClassOf | om-2:Unit |
| Geo\_Position\_unit | subClassOf | om-2:Unit |
| gci:Cardinality\_unit | subClassOf | om-2:Unit |
| om-2:UnitDivision | subClassOf | om-2:Unit |
| Cardinality\_unit\_per\_time | subClassOf | om-2:UnitDivision |
| om-2:hasNumerator | only gci:Cardinality\_unit |
| om-2:hasDenominator | only om-2:TimeUnit |
| ... | subClassOf | om-2:Unit\_of\_measure |
| MonetaryValue | subClassOf | om-2:Measure |
| hasRelativeYear | exactly 1 xsd:gYear |
| om-2:hasUnit | only om-2:Amount\_of\_money\_unit |
| gci:Population\_measure | subClassOf | om-2:Measure |
| subClassOf | CardinalityMeasure |
| CardinalityMeasure | subClassOf | om-2:Measure |
| hasUnit | only gci:Cardinality\_unit |
| ValueOfMoney | subClassOf | om-2:Quantity |
| subClassOf | om-2:AmountOfMoney |
| om-2:hasValue | only MonetaryValue |
| om-2:Length | subClassOf | om-2:Quantity |
| om-2:hasValue | only (om-2:Measure and om-2:hasUnit only om-2:Length\_unit) |
| gci:PopulationSize | subClassOf | om-2:Quantity |
| om-2:hasValue | only gci:Population\_measure |
| gci:cardinalityOf | exactly 1 gci:Population |
| CapacitySize | subClassOf | om-2:Quantity |
| om-2:hasValue | only gci:Cardinality\_measure |
| gci:cardinalityOf | exactly 1 Capacity |
| CapacityRate | subclassOf | om-2:Quantity |
| om-2:hasValue | only (om-2:hasUnit only CardinalityUnitPerTime) |
| gci:cardinality\_of | exactly 1 Capacity |
| om-2:Mass | subClassOf | om-2:Quantity |
| om-2:hasValue | only (om-2:hasUnit only om-2:Mass\_unit) |
| om-2:Area | subClassOf | om-2:Quantity |
| om-2:hasValue | only (om-2:hasUnit only om-2:Area\_unit) |
| om-2:Volume | subClassOf | om-2:Quantity |
| om-2:hasValue | only (om-2:hasUnit only om-2:Volume\_unit) |
| om-2:Acceleration | subClassOf | om-2:Quantity |
| om-2:hasValue | only (om-2:hasUnit only om-2:Acceleration\_unit) |
| om-2:Speed | subClassOf | om-2:Quantity |
| om-2:hasValue | only (om-2:hasUnit only om-2:Speed\_unit) |

|  |  |  |
| --- | --- | --- |
| Property | Characteristic | Value (if applicable) |
| om-2:hasBaseUnit | domain | om-2:System\_of\_units |
| om-2:hasBaseUnit | range | om-2:Unit |
| om-2:hasDenominator | domain | om-2:UnitDivision |
| om-2:hasDenominator | range | om-2:Unit |
| om-2:hasNumerator | domain | om-2:UnitDivision |
| om-2:hasNumerator | domain | om-2:Unit |
| om-2:hasAggregateFunction | domain | om-2:Quantity |
| range | om-2:function |
| aggregateOf | domain | om-2:Quantity |
| aggregateOver | domain | om-2:Quantity |

#### Future work

Future extensions should consider whether it is more accurate to describe the position coordinates as quantities that are measured in degrees *that are relative to a geodetic datum* (e.g. NAD83), as it is important that we are able to distinguish between different position systems. In particular, WGS84 and NAD83, which were originally nearly equal are now considerably different (depending on the area) due to changes that have occurred to the earth since 1984. Note that <http://data.ign.fr/def/ignf/20150505.en.htm> may be a relevant ontology.

**Reused Ontologies:**

* (term reuse) Ontology of Units of Measure 2.0[[7]](#footnote-7)
* Global City Indicators Foundation Ontology[[8]](#footnote-8)

### Observations Ontology

*http://ontology.eil.utoronto.ca/icity/Observations*

In the iCity TPSO, the Observations ontology is included with the Foundational Ontologies due to the importance of data collection for transportation planning activities. Data collection efforts take various forms – whether through surveys, the use of sensors, or manual observation. With growing access to the Internet of Things, data from available sensors will continue to expand, likely to include observations about persons, vehicles, and so on. It is important to not only capture the data that is gathered, but the source of the observations.

#### The Ontology

The Observations ontology reuses the SSN (Semantic Sensor Network) ontology[[9]](#footnote-9), a W3C recommendation that has been widely adopted to represent sensors and their observations. It is this widespread use which has motivated the adoption of the SSN ontology to capture sensors and their observations in the domain of transportation planning. The SSN Ontology defines a Sensor as a device that makes some observation, and may be triggered by some stimulus. An Observation has some feature of interest – the thing whose property is being detected by the sensor. An observation observes some ObservableProperty. A phenomenon time (i.e. the time at which the property was demonstrated) and result time may be associated with a particular observation.

The Observations Ontology generalizes concepts from the SSN Ontology and expands the representation to include observations collected without the use of a sensor. To achieve this, the concept of an Observer is introduced; an Observer is a generalization of a Sensor and could also include concepts such as Persons or Surveys. The key concepts are summarized in Table 12.

The SSN ontology does not make any commitments as to whether instances of ssn:Property should be generic (e.g. ex:temperature) or specific to the feature of interest (e.g. ex:mybodytemperature); current documentation suggests that this is a choice for the modeler. On the other hand, the iCity TPSO prescribes a definition of instances of ssn:Property at a generic level; this enables the querying of sensors that observe some property (e.g. vehicle presence) regardless of the location. This is useful as there may be different kinds of sensors that observe the same properties (e.g. loop detectors vs Bluetooth sensors) and while they might not share the exact feature of interest, they may be in close enough proximity to be related and so a property indicating their similarity is desirable.

Table : Key classes in the Observations Ontology

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| Observation | observedBy | only Observer |
| Observer | inverse(observedBy) | only Observation |
| sosa:Sensor | subclassOf | Observer |
| sosa:madeObservation | only sosa:Observation |
| sosa:observes | only sosa:ObservableProperty |
| ssn:detects | only ssn:Stimulus |
| sosa:Observation | subclassOf | Observation |
| sosa:madeBySensor | exactly 1 sosa:Sensor |
| sosa:hasFeatureOfInterest | exactly 1 owl:Thing and only sosa:FeatureOfInterest |
| sosa:hasResult | exactly 1 owl:Thing and only sosa:Result |
| sosa:observedProperty | exactly 1 owl:Thing and only sosa:ObservableProperty |
| sosa:phenomenonTime | exactly 1 owl:Thing |
| sosa:resultTime | exactly 1 rdfs:Literal |
| ssn:wasOriginatedBy | exactly 1 owl:Thing and only ssn:Stimulus |
| sosa:ObservableProperty | subClassOf | ssn:Property |
| inverse ('is proxy for') | only ssn:Stimulus |
| inverse ('observed property') | only sosa:Observation |
| sosa:'is observed by' | only sosa:Sensor |
| sosa:FeatureOfInterest | ssn:'has property' | min 1 owl:Thing and ssn:Property |
| sosa:Result | sosa:'is result of' | min 1 owl:Thing |

#### An Example

As an example, consider the representation of a loop detector and its observations on the road network. The Observations ontology may be extended to capture the class of Loop Detector sensors. For a particular Loop Detector, we may specify that it makes some observation at a particular time, and that the result of this observation is some Vehicle Volume on the RoadSegment of interest (i.e. the segment being observed). The same observation may be associated with multiple results. In the case of the loop detector this might include not only vehicle volume, but also average vehicle speed. This example is illustrated in Figure 15. Note that the Units of Measure ontology also plays a role in capturing the observed values.



Figure 15: Example use of the Observations Ontology.

#### Future work

Add logic to relate the values of observable property, observation, feature of interest, and result: the observable property indicates how (by what property) the result relates to the feature of interest; e.g. the location of the loop detector indicates the identity of the feature of interest of its observations.

**Reused Ontologies:**

* W3C SSN Ontology

## Contact Ontology

*http://ontology.eil.utoronto.ca/icity/Contact*

**Namespace: contact**

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, etc). Note that a person’s contact address may differ from their place of residence. The iContact ontology is reused to provide the core concepts necessary to define this type of information. The Contact ontology uses concepts from the spatial location ontology in order to associate an address with a location. It also introduces a more specific definition of hours of operation as a specialization of the RecurringEvent class.

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| contact:Address | hasStreetNumber | exactly 1 xsd:nonNegativeInteger |
| hasStreet | only xsd:string |
| hasCity | exactly 1 schema:city |
| … |  |
| spatialloc:hasLocation | exactly 1 geo:Feature |
| subClassOf | iContact:Address |
| contact:HoursOfOperation | subClassOf | icontact:HoursOfOperation |
| subClassOf | rec:RecurringEvent |

**Reused Ontologies:**

* iContact: <http://ontology.eil.utoronto.ca/icontact.owl>
* iCity Spatial Location: [*http://ontology.eil.utoronto.ca/icity/SpatialLoc/*](https://w3id.org/icity/SpatialLoc/)

**Future Work:**

In future extensions it may be useful to consider the addition of properties such as the time zone (time:TimeZone) associated with an address, as well as the primary language of correspondence.

## Person Ontology

*http://ontology.eil.utoronto.ca/icity/Person*

**Namespace: person**

* Person: A Person may have a **unique identifier**.  
  A Person has a **date of birth**, and may have a **date of death**.  
  A Person has a **mother** and **father**, and may have a **spouse** and/or **child**(ren). Note that we define the parent relation as the legal relation as opposed to biological. This property may be specialized and restricted, for example hasBiologicalMother: exactly 1 Person.  
  A Person may **have** some **Job** and associated **Income**.  
  A Person has an **address** of residence and may have other contact information such as **E-mail**, **phone number**, etcetera.  
  A Person has some age and exactly 1 sex, and sex may be one of only male or female. The definition of sex is distinct from that of a person’s gender: “Sex refers to sex assigned at birth. Sex is typically assigned based on a person's reproductive system and other physical characteristics.”[[10]](#footnote-10) Future extensions may incorporate a representation of gender, should it be required.  
  A person has some Age may or may not be a licensed driver.

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| PersonPD | subclassOf | change:TimeVaryingConcept |
| equivalentClass | change:hasManifestation some Person and change:hasManifestation only Person |
| change:existsAt | exactly 1 time:Interval |
| hasPersonID | only PersonId |
| schema:birthDate | exactly 1 time:Instant |
| hasSex | exactly 1 Sex |
| schema:deathDate | max 1 time:Instant |
| Person | equivalentClass | change:manifestationOf some PersonPD and change:manifestationOf only PersonPD |
| subclassOf | change:Manifestation |
| change:existsAt | exactly 1 time:TemporalEntity |
| hasAge | exactly 1 om:duration |
| isLicensedDriver | exactly 1 xsd:boolean |
| schema:parent | only Person |
| schema:spouse | only Person |
| schema:children | only Person |
| hasIncome | only MonetaryValue |
| schema:address | some schema:PostalAddress |
| hasSkill | only Skill |
| hasQualification | only Qualification |
| Sex | equivalentClass | {person:male, person:female} |

**Reused Ontologies:**

* schema.org[[11]](#footnote-11) (A vocabulary as opposed to an ontology)
* Change ontology
* Units of measure ontology
* Time ontology

**Future work:**

* Attributes such as isLicensedDriver are currently captured as (Boolean) data properties. Future extensions may capture these attributes as object properties, should a more detailed representation be required (e.g. the introduction of a DriversLicense class, with attributes such as its category, expiration date, province of issue, etc). This possibility for future extension applies to many of the defined data properties in the icity ontologies in general.

## Household Ontology

*http://ontology.eil.utoronto.ca/icity/Household.owl*

**Namespace: household**

In order to define a Household, we require the following classes and properties:

* Family: The notion of Family simply makes the commitment that it is a group of people who are connected via the has-spouse or has-child properties. From these, we can derive grandparents, aunts, uncles, etcetera.  
  One question to consider is to what degree the general/extended Family concept makes sense or is useful. After a few generations the concept of a family will become quite large and confusing, with Persons belonging to many different Families. It may be more useful to consider a relatedTo property between Persons, or only defining restricted subclasses of Family; for example, different types of Family (e.g. Immediate, Extended) may be defined.
* Household: A Household **occupies** a particular Dwelling, according to some **tenure** type. It is defined by this location, so that if the members move (even collectively), the new residence constitutes a new Household.  
  Note that a Household, and likely many other classes may have different definitions in different contexts/applications. To address this we may be required to introduce specializations of the class (e.g. ILUTE\_Household, TTS\_Household) in future extensions.
* Dwelling Unit: A Dwelling Unit is **occupied** by a Household.   
  A Dwelling Unit has a **market** **value**.  
  A Dwelling Unit has some Location.



|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| FamilyPD | subclassOf | change:TimeVaryingConcept |
| equivalentClass | change:hasManifestation some Family and change:hasManifestation only Family |
| change:existsAt | exactly 1 time:Interval |
| Family | subclassOf | change:Manifestation |
| equivalentClass | change:manifestationOf some FamilyPD and change:manifestationOf only FamilyPD |
| change:existsAt | exactly 1 time:TemporalEntity |
| hasFamilyMember | min 2 person:Person |
| HouseholdPD | subclassOf | change:timeVaryingConcept |
| equivalentClass | change:hasManifestation some Household and change:hasManifestation only Household |
| change:existsAt | exactly 1 time:Interval |
| occupies | exactly 1 DwellingUnit |
| Household | subclassOf | change:Manifestation |
| subClassOf | gci:Household |
| equivalentClass | change:manifestationOf some HouseholdPD and change:manifestationOf only HouseholdPD |
| change:existsAt | exactly 1 time:TemporalEntity |
| hasHouseholdMember | only person:Person and some person:Person |
| DwellingUnitPD | subclassOf | change:TimeVaryingConcept |
| subclassOf | building:BuildingUnitPD |
| equivalentClass | change:hasManifestation some DwellingUnit and change:hasManifestation only DwellingUnit |
| change:existsAt | exactly 1 time:Interval |
|  |  |
| schema:address | only schema:PostalAddress |
| spatial\_loc:hasLocation | only spatial\_loc:SpatialFeature |
| DwellingUnit | subclassOf | change:Manifestation |
| subclassOf | building:Building and building:BuildingUnit |
| equivalentClass | change:manifestationOf some DwellingUnitPD and change:manifestationOf only DwellingUnitPD |
| change:existsAt | exactly 1 time:TemporalEntity |
| occupiedBy | exactly 1 Household |
| hasValue | only monetary:MonetaryValue |
| tenureType | only Tenure |

|  |  |  |
| --- | --- | --- |
| Property | Characteristic | Value (if applicable) |
| occupiedBy | inverseOf | Occupies |
| hasFamilyMember | subPropertyOf | mer:hasComponent |
| hasHouseholdMember | subPropertyOf | mer:hasComponent |

**Future Work:**

* Extend the definitions of the classes beyond OWL to capture the different notions of family membership and the types (subclasses) of Family that result.
  + hasParent subpropertyOf isRelated
  + hasChild subpropertyOf isRelated
  + hasParent o hasChild subpropertyOf isRelated
  + hasChild o hasParent subPropertyOf isRelated
  + hasParent o (hasParent)- subPropertyOf isRelated
  + …

**Reused Ontologies:**

* schema.org
* gci: GCI-Shelter Ontology[[12]](#footnote-12)
* mer:Mereology Ontology

## Organization Ontology

*http://ontology.eil.utoronto.ca/icity/Organization.owl*

**Namespace: org**

* Organization: A company or other sort of group of individuals in the urban system with some goal(s).  
  An Organization may **own** Property, including different types of Buildings.  
  An Organization may have an address.  
  An Organization has at least 2 members.  
  An Organization has some Goal(s); this represents some state or complex states, and allows for the representation of various groups' responsibilities.  
  An Organization may be divided into Divisions.
* Organization Agent: Members of an organization.  
  Organization Agents have goals, authority, and may be members of some team.  
  An Organization Agent plays a Role within the Organization.
* Role: A Role has a single (possibly complex) Goal.  
  A Role has some authority, requires some skill, and may also have some associated processes.
* Firm: A Firm is a type of organization.  
  A Firm has an address and an industry type, and some Employees.  
  A Firm may have a Business Establishment(s).
* Business Establishment: A Business establishment is a physical location where a Firm conducts business.  
  A Business Establishment has a Location and may have an address.
* Employee: A Firm **has** some **Employees**, whom it **employs for** some Occupation.  
  An Employee is a type of Organization Agent.  
  An Employee may be employed at a particular Business Establishment.  
  An Employee may be responsible for one or more Roles within the Organization.  
  An Employee is **employed by** some Organization, unless the Person is self-employed.   
  An Employee **has a Wage/Salary** and **may work at** some **Location** (this may be the location of the Firm, an alternate Location, or a Location that is subject to change).   
  An employee has some employment status. An employment status may be categorized as one of: full-time regular, part-time regular, full-time-work-at-home, part-time-work-at-home
* Student: A Student is a kind of Organization Agent (and Person) who is enrolled in some EducationalInstitution
* Occupation: An occupation describes the type of work performed by some employee. Different classes of occupations may be defined, such as: General Office / Clerical, Manufacturing / Construction / Trades, Professional / Management / Technical, Retail Sales and Service

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| OrganizationPD | subclassOf | change:TimeVaryingConcept |
| equivalentClass | change:hasManifestation some Organization and change:hasManifestation only Organization |
| change:existsAt | exactly 1 time:Interval |
| Organization | subclassOf | change:Manifestation |
| subclassOf | tove:Organization |
| equivalentClass | change:manifestationOf some OrganizationPD and change:manifestationOf only OrganizationPD |
| change:existsAt | exactly 1 time:TemporalEntity |
| schema:address | only schema:PostalAddress |
| tove:has\_goal | only tove:Goal |
| tove:consists\_of | only tove:Division |
| spatialloc:assiociatedLocation | only geosparql:Feature |
| tove:Role | tove:has\_goal | only tove:Goal |
| tove:has\_process | only (tove:Process or activity:Activity) |
| tove:has\_authority | only tove:Authority |
| tove:requires\_skill | only tove:Skill |
| tove:has\_resource | only resource:ResourceType |
| tove:Goal | subClassOf | StateType |
| FirmPD | subclassOf | tove:Organization |
| hasFirmId | only FirmId |
| equivalentClass | change:hasManifestation some Firm and change:hasManifestation only Firm |
| change:existsAt | exactly 1 time:Interval |
| Firm | subclassOf | tove:Organization |
| equivalentClass | change:manifestationOf some FirmPD and change:manifestationOf only FirmPD |
| change:existsAt | exactly 1 time:TemporalEntity |
| schema:address | exactly 1 schema:PostalAddress |
| hasIndustryType | only IndustryType |
| hasEstablishment | only BusinessEstablishment |
| BusinessEstablishmentPD | subclassOf | change:TimeVaryingConcept |
| change:existsAt | exactly 1 time:Interval |
| hasBusinessId | only BusinessId |
| equivalentClass | change:hasManifestation some BusinessEstablishment and change:hasManifestation only BusinessEstablishment |
| BusinessEstablishment | subclassOf | change:Manifestation |
| equivalentClass | change:manifestationOf some BusinessEstablishmentPD and change:manifestationOf only BusinessEstablishmentPD |
| change:existsAt | exactly 1 time:TemporalEntity |
| spatial\_loc:hasLocation | exactly 1 spatial\_loc:SpatialFeature |
| schema:address | only schema:PostalAddress |
| tove:OrganizationAgent | tove:member\_of | only tove:Division |
| tove:plays | only tove:Role |
| tove:has\_goal | only tove:Goal |
| tove:has\_authority | only tove:Authority |
| Employee | subclassOf | tove:OrganizationAgent |
| employedAs | some Occupation |
| hasPay | some Wage or Salary |
| worksAt | some spatial\_loc:SpatialFeature |
| hasEmploymentStatus | only EmploymentStatus |
| FullTimeEmployee | subClassOf | Employee |
| FullTimeHomeEmployee | subClassOf | FullTimeEmployee |
| FullTimeRegEmployee | (subClassOf | FullTimeEmployee) and (not FullTimeHomeEmployee) |
| PartTimeEmployee | subClassOf | Employee |
| PartTimeHomeEmployee | subClassOf | PartTimeEmployee |
| PartTimeTimeRegEmployee | (subClassOf | PartTimeEmployee) and (not PartTimeHomeEmployee) |
| Wage | hourlyPay | exactly 1 monetary:MonetaryValue |
| overtimePay | only monetary:MonetaryValue |
| Salary | hasAnnualPay | exactly 1 monetary:MonetaryValue |
| tove:Activity | equivalentClass | activity:Activity |
| tove:Resource | equivalentClass | resource:Resource |
| EmploymentStatus | equivalentClass | {fulltime\_regular, parttime\_regular, fulltime\_home, parttime\_home} |
| GeneralOffice | subClassOf | Occupation |
| Trades | subClassOf | Occupation |
| Professional | subClassOf | Occupation |
| Sales | subClassOf | Occupation |
| EducationalInstitution | subClassOf | Organization |
| Student | subClassOf | OrganizationAgent |
| enrolledIn | min 1 EducationalInstitution |
| FullTimeStudent | subClassOf | Student |
| PartTimeStudent | subClassOf | Student |

* **hasOrgMember subPropertyOf tove:hasMember**
* **org:Organization hasOrgMember min 2 tove:OrganizationAgent**

**Reused Ontologies:**

* tove: The TOVE Organization ontology[[13]](#footnote-13), as originally presented by (Fox, Barbuceanu, Gruninger, & Lin, 1998) with modifications to account for the difference in our representation of states, where a Goal is a subclass of StateType, and where Activities are enabled/caused by state types.  
  This modification also results in the removal of the StateEmpowerment class. Note that it is possible to introduce a similar concept if required, however this would likely take the form of a property that relates an organization agent to some state-types (where the states they are empowered to take an object to, and the object itself, are described by the state type).
* icity-foundation: iCity-Foundation Ontology
* schema.org (vocabulary)

**Future Work:**

* Define part-time / full-time employees and students in more detail (e.g. with respect to their work locations).
* Define part-time /full-time students according to some enrollment criteria

## Building Ontology

*http://ontology.eil.utoronto.ca/icity/Building.owl*

**Namespace: building**

* Building: A Building is a structure with some location in the urban system. The location of the Building in space may change due to construction, but the Parcel/Lot of land it is located on cannot.  
  There are different types (**subclasses**) of buildings, such as House, Apartment Building, Office Building, and so on.  
  A Building or BuildingUnit may contain some Building Facility(s), e.g. kitchen, bath, or air conditioning. Note that this is distinct from the notion of including amenities that are not a physical part of the Building (Unit), but which may be part of the Tenure.  
  A Building has a market **value**.  
  A Building **has** some **Location**.  
  A Building contains one or many units.
* BuildingFacility: A Building Facility refers to services/features that are included in the Building/Building unit by nature of its physical design (e.g. HVAC, kitchen, bathroom, etc)
* BuildingUnit: A BuildingUnit has a size (square footage, number of rooms)  
  A Building or BuildingUnit may contain some Facility(s), e.g. kitchen, bath, or air conditioning. Note that this is distinct from the notion of including amenities that are not a physical part of the Building (Unit), but which may be part of the Tenure.  
  A BuildingUnit has an address.  
  A BuildingUnit has a value, and may have some rental fee.



|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| BuildingPD | subClassOf | change:TimeVaryingConcept |
| equivalentClass | change:hasManifestation some Building and change:hasManifestation only Building |
| change:existsAt | exactly 1 Interval |
| Building | equivalentClass | change:manifestationOf some BuildingPD and change:manifestationOf only BuildingPD |
| subClassOf | change:Manifestation |
| change:existsAt | exactly 1 TemporalEntity |
| spatial\_loc:hasLocation | exactly 1 spatial\_loc:SpatialFeature |
| monetary:hasValue | only monetary:MonetaryValue |
| hasBuildingFacility | only BuildingFacility |
| hasBuildingUnit | only BuildingUnit |
| House | subclassOf | Building |
| ApartmentBuilding | subclassOf | Building |
| OfficeBuilding | subclassOf | Building |
| IndustrialBuilding | subclassOf | Building |
| BuildingUnitPD | subclassOf | change:TimeVaryingConcept |
| change:existsAt | exactly 1 Interval |
| equivalentClass | change:hasManifestation some BuildingUnit and change:hasManifestation only BuildingUnit |
| ~~mereology:containedIn~~  unitInBuilding | exactly 1 Building |
| schema:address | exactly 1 schema:PostalAddress |
| BuildingUnit | subclassOf | change:Manifestation |
| equivalentClass | change:manifestationOf some BuildingUnitPD and change:manifestationOf only BuildingUnitPD |
| change:existsAt | exactly 1 TemporalEntity |
| monetary:hasValue | only monetary:MonetaryValue |
| hasRent | only monetary:MonetaryValue |
| hasUnitSize | only om:area |
| hasRooms | only xsd:int |
| ~~hasFacility~~ hasBuildingFacility | only Facility |

|  |  |  |
| --- | --- | --- |
| Property | Characteristic | Value (if applicable) |
| hasBuildingFacility | subPropertyOf | mer:hasComponent |
| hasBuildingUnit | inverseOf | unitInBuilding |
| subPropertyOf | mer:hasComponent |
| subPropertyOf | mer:contains |
| unitInBuilding | inverseOf | hasBuildingUnit |
| subPropertyOf | mer:componentOf |
| subPropertyOf | mer:containedIn |

**Reused Ontologies:**

* Change
* Units of measure
* Mereology
* Spatial location

**Future work:**

* Consider adding an BuildingAmenity class to capture common spaces or features may be included / excluded for occupants by virtue of some rental agreement

## Vehicle Ontology

*http://ontology.eil.utoronto.ca/icity/Vehicle.owl*

**Namespace: icity-vehicle**

* Vehicle: A Vehicle provides a means of transportation within the urban system.  
  A Vehicle is **associated with some Mode** of transportation.  
  A Vehicle has a Vintage.  
  A Vehicle has a Manufacturer (make).  
  There are different types (**subclasses**) of vehicles: Motorcycle, Sedan, Truck, Bus, Commercial Cargo Vehicle, … These types may be identified and defined in different, complementary ways. The VehicleType class allows for the specifications of various types of vehicles, which may or may not also be captured as subclasses of the Vehicle class. Should a vehicle type also be a subclass, then the subclass should be defined such that it is equivalent to the class of all individuals that have the vehicle type as a property *hasVehicleType value <vehicle type>.*  
  A Vehicle **has a capacity** of passengers  
  A Vehicle **has a capacity** of cargo  
  A Vehicle **has a Speed** at some point in time  
  A Vehicle **has a location** at some point in time.

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| VehiclePD | equivalentClass | change:hasManifestation some Vehicle and change:hasManifestation only Vehicle |
| subclassOf | change:TimeVaryingConcept |
| change:existsAt | exactly 1 time:Interval |
| hasVehicleType | only VehicleType |
| schema:productionDate | only time:DateTimeDescription |
| schema:brand | only schema:Brand |
| schema:vehicleSeatingCapacity | exactly 1 xsd:int |
| schema:cargoVolume | only om:volume |
| hasCargoCapacityLoad | only om:Quantity |
| schema:driveWheelConfiguration | schema:DriveWheelConfigurationValue |
| schema:fuelConsumption | schema:QuantitativeValue |
| schema:fuelEfficiency | schema:QuantitativeValue |
| schema:fuelType | schema:QualitativeValue |
| schema:mileageFromOdometer | schema:QuantitativeValue |
| schema:numberOfDoors | only xsd:int |
| schema:numberOfAxels | only xsd:int |
| Vehicle | equivalentClass | change:manifestationOf some VehiclePD and change:manifestationOf only VehiclePD |
| subclassOf | change:Manifestation |
| change:existsAt | exactly 1 time:TemporalEntity |
| schema:purchaseDate | only time:DateTimeDescription |
| hasSpeed | only om:speed |
| spatial\_loc:hasLocation | only spatial\_loc:SpatialFeature |
| accommodatesWheelchair | max 1 xsd:Boolean |
| accommodatesBicycle | max 1 xsd:Boolean |
| schema:QualitativeValue | subClassOf | om:quantity |

**Ontologies Reused:**

* Schema.org (vocabulary)
* iCity-Foundation

## Transportation System Ontology

*http://ontology.eil.utoronto.ca/icity/TransportationSystem.owl*

**Namespace:transport**

While most existing work attempts to describe the network based on its physical constructs, we model the network flow and the physical infrastructure separately. The motivation for this is that the constraints on transportation flow are something that is *applied to* the physical infrastructure. These constraints are distinct from the physical characteristics and so should be defined separately. Although some constraints may be related, such as flow constraints imposed by the size of the lane that an arc accesses, this is a specific relationship that should be captured rather than conflating the concepts. For example, there is nothing to stop a vehicle from going the wrong way on a road, except for the flow 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 (a directed graph), and the Transportation Complex (a physical feature where transportation occurs).

We relate the Network and the Infrastructure by relating an Arc to a Transportation Complex (or other Road Segment) with the "accesses" property. In this way, we may define an Arc accessing various Transportation Complexes at different Levels of Detail (LOD).

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. A Node may have a control (e.g. a signal) with a physical presence somewhere else (traffic lights apply to one side of the intersection, but are actually located on the other side of the intersection); by separating the physical infrastructure and the network flow we are able to accurately represent this.

The OTN (Ontology of Transportation Networks[[14]](#footnote-14)) ontology, as presented by (Lorenz, Ohlbach, & Yang, 2005), also defines terms such as nodes, arcs, and road/rail elements. The lack of maintenance and activity on the OTN poses a potential issue, and the lack of modularity in its structure makes it difficult to use. Therefore, although its scope is similar, we have elected not to reuse it in the design of this ontology.

* Network: A collection of Nodes and Arcs that enables transportation. A Network may have some cost associated to its access.
* Link: A directed connection in the Network that enables transportation via some Mode(s) from one Node to another.   
  A link contains one or more Arcs that represent individual flows of traffic (e.g. traffic lanes, bicycle lanes).  
  A link begins and ends at a source and sink Node.  
  A link has some (straight-line) length description, in km.  
  A link is associated with, or considered to be *in*, a municipality and a planning district.   
  A link supports one or more Mode(s) of access.
* Arc: A directed connection in the Network that enables transportation via a particular Mode(s) from one Node to another.   
  An Arc begins and ends at the source and sink of the Link it is contained in.  
  An Arc has access to some Spatial Thing (such as a road), which may change over time.  
  An Arc may impose access restrictions (for example, based on the size of vehicle), which are subject to change.  
  An Arc may have some cost associated to its travel.  
  An Arc supports one or more Modes of access.  
  An Arc may have some posted and/or free flow speed. It may also be described with a volume delay function (VDF).
* Node**:** A point in the Network at which Arcs are connected. A node as a unique identifier; for example, as defined in the EMME NCS11.  
  A Node may contain different types of controls: Network Transfer, Signal Control, and Flow Control.  
  A Node may be associated with specific location information (e.g. coordinates). Note that this may be subject to change. The physical location of a node (generally larger than a single point) may be inferred based on the locations of the transportation complexes which it connects.  
  A Node accesses some TransportationComplex, such as an Intersection. In the future, it may be useful to define other specific types of TransportationComplexes that are accessed by nodes, (e.g. bus stops).
* Network Transfer: Enables transfer between networks at a given Node.
* Signal Control: Controls the flow of transportation between some of the incoming and outgoing arcs that the Node connects. Signal Controls have specialized attributes such as the number of phases, phase length, signal timing, type of signal. Note that the phases and/or the phase length may vary as a function of time of day or other triggers (e.g. ground sensors, traffic sensors).
* Flow Control: Controls the flow of traffic at a given Node.   
  A Flow Control may be operative/inoperative at different times. For example, "no left turns from 4-6pm".  
  A Flow Control may be a generalization of Signal Control.
* Mode: A mode of transportation is a **means of** performing travel within the urban system.  
  There are various types (instances) of Mode: Foot, Bike, PersonalVehicle, PublicTransit, Cab, CommercialVehicle, Plane, Boat, Train.
* LoopDetector: A Loop Detector is a kind of Sensor that detects vehicle presence at some point on a road segment. A Loop Detector is owned by some Organization; it has some location, and is associated with (has a feature of interest) the particular part of the transportation network (i.e. a transport:Arc) that it is located on.   
  A Loop Detector makes observations about the vehicle presence on the road segment that is its feature of interest.  
  The vehicle presence is a proxy for the occupancy of the road segment and the average vehicle speed on the road segment.
* TTI
* MeanTTI

The physical Infrastructure of the transportation system is defined, as required, at different levels of detail (LOD). Specific types of Transportation Complex (a term we adopt from the CityGML schema) may be defined according to the Arcs that access them. We define the following types of Transportation Complex.

* Road
* Rail
* Waterway
* Airway
* Bike Trail
* Footpath
* Parking

Each Transportation Complex may be further defined as follows:

* **Road**: An aggregation of Road Segments with the same name.
* **RoadSegmentPD**: accessed only by Links that are not accessible by water or air modes.  
  Different RoadSegments Perdurants will be accessed by Arcs that are accessible by various other Modes, not necessarily *everything* else. A Road Segment Perdurant is comprised of Road Segments that exist over time.
* **RoadSegment**: A RoadSegment has variant attributes.  
  A RoadSegment has an owner, access restrictions, and is accessed by some Arc(s) -- all of which may change over time.  
  A RoadSegment has some location, which is co-located with (contains the locations of) the Arcs and Nodes it contains.
* **Rail**: An aggregation of Rail Segments with the same name.
* **RailSegmentPD**: Accessed only by Arcs that are accessible by rail modes.  
  A RailSegment Perdurant has an invariant location, which is co-located with (contains the locations of) the Arcs and Nodes it contains. A Rail Segment Perdurant is comprised of Rail Segments that exist over time.
* **RailSegment**: A RailSegment has an owner, access restrictions, and is accessed by some Link(s).
* Note that the location of a RoadSegment is variable (e.g. road widening or other activities do not change the identity of the road element), whereas a RailSegment's is not.
* **IntersectionPD:** Accessed only by NodePDs. An Intersection Perdurant captures the physical entity of an intersection, which is co-located with various other transportation complexes (e.g. roads, paths) that pass through it. An Intersection Perdurant is comprised of Intersections that exist over time.
* **Intersection:** An Intersection exists at some time. It has some location. It may have some owner and is accessed by some Node. In the future, it may be useful to extend this class and relate it to certain aspects of the physical infrastructure such as signs, signals, etc.

Classes may be defined for footpaths, bicycle lanes/trails, and so on. Should it be useful, this representation could be extended to define individual traffic lanes, (e.g. the transportation complex that is accessed by a single arc).



Figure 16: Structure of the Transportation Network (some omissions).

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| NetworkPD | subclassOf | change:TimeVaryingConcept |
| equivalentClass | change:hasManifestation some Network and change:hasManifestation only Network |
| change:existsAt | exactly 1 time:Interval |
| Network | subclassOf | change:Manifestation |
| equivalentClass | change:manifestationOf some NetworkPD and change:manifestationOf only NetworkPD |
| change:existsAt | exactly 1 time:TemporalEntity |
| hasNetworkComponent | only Arc or Node |
| NodePD | subclassOf | change:TimeVaryingConcept |
| equivalentClass | change:hasManifestation some Node and change:hasManifestation only Node |
| change:existsAt | exactly 1 time:Interval |
| hasNodeID | max 1 NodeId |
| Node | subclassOf | change:Manifestation |
| equivalentClass | change:manifestationOf some NodePD and change:manifestationOf only NodePD |
| change:existsAt | exactly 1 TemporalEntity |
| inverse (hasNetworkComponent) | only Network |
| connectedTo | min 1 Arc |
| hasControl | only (NetworkTransfer or SignalControl or FlowControl) |
| associatedLocation | only spatial\_loc:Feature |
| LinkPD | subclassOf | change:TimeVaryingConcept |
| equivalentClass | change:hasManifestation some Link and change:hasManifestation only Link |
| change:existsAt | exactly 1 time:Interval |
|  |  |
| startNode | exactly 1 NodePD |
| endNode | exactly 1 NodePD |
| accessesComplex | only TransportationComplexPD |
| Link | subclassOf | change:Manifestation |
| equivalentClass | change:manifestationOf some LinkPD and change:manifestationOf only LinkPD |
| change:existsAt | exactly 1 time:TemporalEntity |
| containsArc | min 1 ArcPD |
| inverse (hasNetworkComponent) | only Network (variant or invariant?) |
| associatedLinkLength | exactly 1 om:length |
| supportsMode | min 1 Mode |
| hasNumLanes | exactly 1 xsd:integer |
| hasVDF | max 1 om: Quantity |
| hasLinkCapacity | max 1 (om:Quantity and om:'has value' only (om:'has unit' only (om:'has numerator' only om:CardinalityUnitPerTime) and (om:'has denominator' only (om:'Cardinality Unit' and inverse(om:'has unit') only (inverse(om:'has value') only (gci:cardinality\_of only (gci:defined\_by only Arc))))))) |
| hasFreeFlowSpeed | max 1 om:speed |
| hasPostedSpeed | max 1 om:speed |
| hasToll | only MonetaryValue |
| inMunicipality | exactly 1 Municipality |
| inPlanningDistrict | exactly 1 PlanningDistrict |
| ArcPD | subclassOf | change:TimeVaryingConcept |
| equivalentClass | change:hasManifestation some Arc and change:hasManifestation only Arc |
| startNode | exactly 1 NodePD |
| endNode | exactly 1 NodePD |
| change:existsAt | exactly 1 time:Interval |
| accessesComplex | only TransportationComplexPD |
| containedInLink | exactly 1 LinkPD |
| Arc | subclassOf | change:Manifestation |
| equivalentClass | change:manifestationOf some ArcPD and change:manifestationOf only ArcPD |
| change:existsAt | exactly 1 time:TemporalEntity |
| accessesComplex | only TransportationComplex |
| inverse (hasNetworkComponent) | only Network |
| hasControl | only AccessRestriction |
| supportsMode | min 1 Mode |
| hasLaneCapacity | exactly 1 om:CapacityRate |
| hasVDF | max 1 om:quantity |
| hasFreeFlowSpeed | max 1 om:speed |
| hasPostedSpeed | max 1 om:speed |
| hasToll | only MonetaryValue |
| inMunicipality | only Municipality |
| inPlanningDistrict | exactly 1 PlanningDistrict |
| NetworkTransfer | controlFor | only Node |
| connectsNetworks | min 2 Network |
| FlowControl | controlFor | only Node |
| hasInflow | min 1 Arc |
| hasOutflow | min 1 Arc |
| SignalControlPD | subClassOf | change:TimeVaryingConcept |
| equivalentClass | change:hasManifestation some SignalControl and change:hasManifestation only SignalControl |
| change:existsAt | exactly 1 time:Interval |
| controlFor | only Node |
| hasInflow | min 1 Arc |
| hasOutflow | min 1 Arc |
| SignalControl | subClassOf | change:Manifestation |
| equivalentClass | change:manifestationOf some SignalControlPD and change:manifestationOf only SignalControlPD |
| change:existsAt | exactly 1 time:TemporalEntity |
| hasPhase | only SignalPhase |
| SignalPhase | signalLength | only time:DurationDescription |
| TransportationComplexPD | subClassOf | change:TimeVaryingConcept |
|  | equivalentClass | change:hasManifestation some TransportationComplex and change:hasManifestation only TransportationComplex |
| TransportationComplex | subclassOf | change:Manifestation |
| equivalentClass | change:manifestationOf some TransportationComplexPD and change:manifestationOf only TransportationComplexPD |
| spatial\_loc:hasLocation | only spatial\_loc:Feature |
| otn:Road | hasRoadId | only RoadId |
| aggregationOf | only RoadSegment |
| RoadSegmentPD | subclassOf | TransportationComplexPD |
| equivalentClass | change:hasManifestation some RoadSegment and change:hasManifestation only RoadSegment |
| hasRoadSegmentId | only RoadSegmentId |
| change:existsAt | exactly 1 time:Interval |
| RoadSegment | equivalentClass | otn:RoadElement |
| subClassOf | TransportationComplex |
| equivalentClass | change:manifestationOf some RoadSegmentPD and change:manifestationOf only RoadSegmentPD |
| change:existsAt | exactly 1 time:TemporalEntity |
| spatial\_loc:hasLocation | only spatial\_loc:Feature |
|  | inMunicipality | only Municipality |
|  |  |  |
| Mode | equivalentClass[[15]](#footnote-15) | {C,E,F,H,I,J,B,G,L,M,P,Q,R,S,A,K,T,U,V,W,Y} |
| Municipality |  |  |
| PlanningDistrict |  |  |
| LoopDetector | sosa:detects | {vehicle\_presence} |
| sosa:observes | {road\_occupancy} |
| sosa:observes | {vehicle\_volume} |
| sosa:observes | {mean\_travel\_speed} |
| sosa:madeObservation | only (sosa:Observation and sosa:hasFeatureOfInterest only transport:Arc and sosa:wasOriginatedBy {vehicle\_presence} and sosa:hasResult RoadOccupancy or VehicleVolume or MeanTravelSpeed) |
| {vehicle\_presence} | a | ssn:Stimulus |
| {road\_occupancy} | a | ssn:ObservableProperty |
| {vehicle\_volume} | a | ssn:ObservableProperty |
| {mean\_travel\_speed} | a | ssn:ObservableProperty |
| VehicleVolume | subClassOf | om-2:Quantity |
| om-2:hasValue | only (om-2:hasUnit only CardinalityUnitPerTime) |
| gci:cardinalityOf | only LocVehiclePopulation |
| LocVehiclePopulation\*  \*precise definition only possible for a particular location | gci:definedBy | only (Vehicle and hasLocation some Feature) |
| RoadOccupancy | subClassOf | om-2:Quantity |
| om-2:hasValue | only (om-2:hasUnit only RoadOccupancyUnit) |
| RoadOccupancyUnit | subClassOf | om-2:UnitDivision |
| om-2:hasNumerator | only om-2:TimeUnit |
| om-2:hasDenominator | only om-2:TimeUnit |
| MeanTravelSpeed | subClassOf | om-2:Speed |
| om-2:hasAggregateFunction | value {om-2:average} |
| LaneCapacity\_unit | subClassOf | om-2:Unit |
| LinkCapacity\_unit | subClassOf | om-2:Unit |
| {vehicles\_per\_hour} | a | LaneCapacity\_unit |
| {vehicles\_per\_hour\_per\_lane} | a | LinkCapacity\_unit |

1. Note that the classes of observable properties are primarily introduced for consistency with the SSN representation as a means of capturing the semantics of a class of Sensors (in this case, Loop Detectors). Any instance of, e.g. RoadOccupancy simply corresponds to a RoadSegment occupied by some thing, or occupied by nothing:  
   RoadOccupancy(x) ⬄ isPropertyOf(x,y) & RoadSegment(y) & [ exists (t) occupiedBy(y,t) | -exists(t) occupiedBy(y,t)]  
   As a consequence of the 4D representation, an instance of the observable property RoadOccupancy refers to a property of a road segment at some time, t.
2. Additional semantics of sensors and observations: temporal restrictions, connection to object properties
3. A RoadSegment’s vehicle count can be calculated based on the KB, but can we formalize the relationship between the count and the KB? i.e. number of observations in a given interval?

|  |  |  |
| --- | --- | --- |
| IntersectionPD | subclassOf | change:TimeVaryingConcept |
| subclassOf | TransportationComplexPD |
| equivalentClass | change:hasManifestation some Intersection and change:hasManifestation only Intersection |
| inverse(accessesComplex) | only NodePD |
| change:existsAt | exactly 1 time:Interval |
| Intersection | equivalentClass | otn:RoadElement |
| subclassOf | change:Manifestation |
| subClassOf | TransportationComplex |
| equivalentClass | change:manifestationOf some RoadSegmentPD and change:manifestationOf only RoadSegmentPD |
| change:existsAt | exactly 1 time:TemporalEntity |
| spatial\_loc:hasLocation | only geosparql:Feature |
| inverse(accessesComplex) | only Node |

**Ontologies Reused:**

* Change
* SpatialLoc
* SSN: Semantic Sensor Network ontology to capture sensors and their observations. These observations are processed or used directly as attributes of the network.

**Notes:**

* We observe that the properties *inMunicipality* and *inPlanningDistrict* may apply to other areas of the domain (e.g. land use, building ontologies), in which case they will be better defined at a lower (more foundational) level within the ontology. However, as they are currently only required for the Transportation System sub-ontology, it is currently not clear where and how this should be done. For now, we define these properties within the Transportation Network System ontology and leave the final organization for a future iteration if and when requirements for their widespread use are identified.

**Future Work:**

* Define lane and link capacity units in greater detail (e.g. with numerators and denominators).
* There is a relationship between the modes of access of a link and those of the arcs it contains that should be captured in a more detailed representation.
* The Municipality class should be defined in greater detail

### Travel Costs

*http://ontology.eil.utoronto.ca/icity/TravelCost.owl*

**Namespace: icity-travelcost**

An extension of the transportation network (and other generic ontologies) is required in order to represent the different costs associated with accessing and travelling on the networks. These may take the form of direct costs such as tolls and fares, or possible indirect costs such as vehicle wear and tear, gas, etc. In addition, there may be non-monetary costs associated with travel such as pollution and travel time. Costs are associated with Network access, but also with individual Arcs. They may also be dependent on situational factors such as time of day, or age of traveler. Travel Costs define the costs associated with accessing the transportation system; a travel cost is a property of an arc or its network. We define a separate extension of Trip Costs to capture other, indirect costs that may vary between individual trips; a trip cost is a property of some instance of travelling.

* Travel Cost: There are different types of Travel Costs which are derived from different factors, and may be defined in different ways. Travel Costs apply to Arcs and / or Networks.
* Distance Fee is a type of Travel Cost  
  Distance Fee has an associated Cost  
  It applies for a certain distance (between nodes, or per km)  
  It applies to some Arc  
  It may have an associated time-of-day applicability  
  It may be associated to specific modes of transport
* Access Fee is a type of Travel Cost  
  Access Fee has an associated Cost  
  It may have an associated time-of-day applicability  
  It may be associated to specific modes  
  It applies to some Network

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| TravelCost | travelCostOf | only (transportation:Arc or transportation:Network) |
| applicableFor | only time:TimePeriod or time:CalendarPeriod |
| applicableTo | only transportation:Mode |
| hasMonetaryCost | only monetary:MonetaryValue |
| transportation:Arc | hasTravelCost | only TravelCost |
| transportation:Network | hasTravelCost | only TravelCost |
| DistanceFee | subclassOf | TravelCost |
| forDistance | only om:length |
| travelCostOf | only transportation:Arc |
| AccessFee | subClassOf | TravelCost |
| travelCostOf | only transportation:Network |

|  |  |  |
| --- | --- | --- |
| Property | Characteristic | Value (if applicable) |
| travelCostOf | inverseOf | hasTravelCost |

**Ontologies Reused:**

* iCity-Transportation Network

## Parking Ontology

*http://ontology.eil.utoronto.ca/icity/Parking.owl*

**Namespace: parking**

* Parking Area: Parking Area refers to some area that enables parking of Vehicles.  
  A Parking Area may contain **sub-Parking Areas**, the area of which may change.  
  A Parking Area has some Parking **Policy**  
  A Parking Area may provide **car changing** stations.A Parking Area has some **Location**.  
  A Parking Area has some vacancy (or occupancy) at some point in time.  
  A parking area may be owned by some Person or Organization, and it may be allocated for some Building, Location, Person, or Organization. Note that ownership and allocation of a Parking Area are distinct: an organization may own a parking area, but it may be allocated (e.g. rented) to some other organization or individual(s).  
  A Parking Area may have some hours of operation.  
  A Parking Area may have some limit on the dimensions of allowed vehicles (height/width/length)  
  *associated location information (e.g. nearby crossroads, landmark, etc)*  
  Different types (subclasses) of Parking Area may be defined as required, such as Street Parking Area, Lot Parking Area, Garage Parking Area, Illegal Parking Area, Loading/Unloading Zone Parking Area,…
* Parking Space: A Parking Space is a Parking Area with the capacity for a single vehicle. (hasCapacity 1, hasVacancy 0 or 1). Specializations of parking space may be defined based on accommodated vehicle type (e.g. small vehicles, commercial vehicles, electric vehicles,…).  
  has Reservations?  
  has Schedules?  
  A Parking Space may or may not be occupied by some vehicle at a particular point in time. If a space is occupied, its availability may be determined (or approximated) based on the scheduled/purchased time by its current occupant.
* A Parking Facility is a parking area that is not contained by any other parking area. A Parking Facility may be owned by some organization and have some hours of operation; it may have a name, contact phone number, address, and possibly an associated website.
* Accessible Parking Space: A type of parking space reserved for users with disabilities
* EV Space: A type of parking space that provides access to some EV Charger(s)
* Parking Policy: A Parking Policy dictates under what terms some Parking Area is accessible for parking.  
  A Parking Policy may have a **Rate**.  
  A Parking Policy may have a **max duration**.  
  A Parking Policy may have **allowable periods** *(these periods must be during the hours of operation of the parking area)*.  
  A Parking Policy may apply only to a particular class of users.  
  Different sorts of parking policies (subclasses) may be defined: e.g. free parking, policies for EVs, persons with accessibility needs.
* Rate: A Rate has a **monetary value** and an **associated duration**.  
  A Rate has a **ParkingPaymentMethod** (e.g. mobile, license plate entry, cashier, meter).  
  A Rate may have some minimum charge, specified as either a monetary value or duration (e.g. regardless of the time parked, the customer will be charged at least $5, or the rate will be applied for at least 30 min). A maximum cost may also be specified; for example, the rate may be $5 per hour, with a maximum of $20 to park for the remainder of the policy’s hours of operation. It is not always the case that the maximum cost coincides with the maximum time-based rate of the hours parked.
* EV charger: A charger for electric vehicles is an amenity which may be provided by some parking spaces.  
  An EV charger has some model and is capable of charging certain classes of vehicles.  
  An EV charger may be available or unavailable at a given time. This availability may be predetermined based on the scheduled duration of a vehicle’s occupancy, and the time left to charge the vehicle.

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| ParkingAreaPD | subclassOf | change:TimeVaryingConcept |
| equivalentClass | change:hasManifestation some ParkingArea and change:hasManifestation only ParkingArea |
| change:existsAt | exactly 1 time:Interval |
| spatial\_loc:hasLocation | exactly 1 spatial\_loc:SpatialFeature |
| spatial\_loc:hasAssociatedLocation | only spatial\_loc:SpatialFeature |
| parkingPartOfBuilding | only Building |
| maxAdmittableHeight | exactly 1 om:length |
| maxAdmittableWidth | exactly 1 om:length |
| maxAdmittableLength | exactly 1 om:length |
| has Address | only icontact:Address |
| ParkingArea | subclassOf | change:Manifestation |
| equivalentClass | change:manifestationOf some ParkingAreaPD and change:manifestationOf only ParkingAreaPD |
| change:existsAt | exactly 1 time:TemporalEntity |
| hasSubParkingArea | only ParkingArea |
| hasVehicleCapacity | only (CapacitySize and gci:cardinality\_of only (gci:defined\_by only Vehicle)) |
| hasParkingPolicy | only ParkingPolicy |
| hasChargingStations | exactly 1 xsd:integer |
| resource:ownedBy | some Person or Organization |
| occupiedBy | only Vehicle |
| isOpen | exactly 1 xsd:boolean |
| hasParkingService | only ParkingService |
| parkingAllocatedTo | only (Person or Building or Organization or Feature) |
| ParkingFacilityPD | subclassOf | park:ParkingAreaPD |
| equivalentClass | change:hasManifestation some ParkingLot and change:hasManifestation only ParkingLot |
| ParkingFacility | subClassOf | ParkingArea |
| subParkingAreaOf | exactly 0 ParkingArea |
| foaf:name | only xsd:string |
| icontact:hasWebsite | only xsd:string |
| icontact:hasAddress | only contact:Address |
| icontact:hasOperatingHours | only rec:HoursOfOperation |
| icontact:hasTelephone | only icontact:PhoneNumber |
| ParkingSpace | subclassOf | ParkingArea |
| hasVehicleCapacity | some (om:hasValue some ( om:has\_numerical\_value value 1)) |
| AccessibleSpace | subclassOf | ParkingSpace |
| hasParkingPolicy | only AccessibilityParkingPolicy (to define) |
| EVSpace | subclassOf | ParkingSpace |
| hasParkingPolicy | only EVParkingPolicty (to define) |
| ParkingService | \*may be defined in greater detail in the future |  |
| Valet | subclassOf | ParkingService |
| Carwash | subclassOf | ParkingService |
| ParkingPolicy | hasParkingRate | only ParkingRate |
| maxDuration | only time:DurationDescription |
| appliesDuring | only contact:HoursOfOperation |
| appliesTo | only person:Person |
| appliesFor | only vehicle:VehicleType |
| hasGracePeriod | max 1 time:DurationDescription |
| excludesPublicHoliday | exactly 1 xsd:boolean |
| ParkingRate | hasMonetaryCost | only om:MonetaryValue |
| forDuration | only time:DurationDescription |
| hasPayment | only ParkingPaymentMethod |
| appliesTo | only person:Person |
| minParkingCharge | only (om:MonetaryValue or time:DurationDescription) |
| maxParkingCost | only om:MonetaryValue |
| FreeParkingPolicy | hasParkingRate | only (ParkingRate and hasMonetaryCost only (om:MonetaryValue and om:numerical\_value [21])) |

|  |  |  |
| --- | --- | --- |
| Property | Characteristic | Value (if applicable) |
| hasSubParkingArea | subPropertyOf | mer:hasProperPart |
| domain | ParkingArea |
| range | ParkingArea |
| inverse | subParkingAreaOf |
| subParkingAreaOf | subPropertyOf | mer:properPartOf |
| domain | ParkingArea |
| range | ParkingArea |
| inverse of | hasSubParkingArea |

**Ontologies Reused:**

* Mereology
* Change
* Time
* OM
* Person
* Vehicle
* Contact

**Future work:**

Constraints may be defined to relate the hours of operation with the parking lot’s associated parking policies and their hours of operation: a parking lot should have policies defined during all of its hours of operation.

If required, parking services may be defined in greater detail.

## Public Transit Ontology

[*http://ontology.eil.utoronto.ca/icity/PublicTransit.owl*](https://w3id.org/icity/PublicTransit.owl)

**Namespace: transit**

* TransitSystem: A TransitSystem is a **collection of Routes**.  
  A TransitSystem may be **accessed by** some Fare or Transit Pass.
* Route: A Route consists of a series of Route Links and may be divided into Route Sections.  
  A Route has some directionality (captured by the route links).
* Route Section: A Route Section is part of some Route and consists of Route Links.  
  A Route Section begins and ends at a Stop Point.
* Route Link: A Route Link is part of some Route. It is a primitive element of a route, operating on single Arc or Link within the transportation system.
* Stop Point: A Stop Point marks the **start or end of** a Route Link (e.g. a subway stop or bus stop).  
  A Stop Point is a subclass of a Node, as defined in the Transportation System ontology.  
  Like a Node, a Stop Point **has an associated Location**.  
  A Person may enter or exit the transit vehicle at a Stop Point.

(to do: Station subclass of StopPoint)

* Station: A Station is a specialized type of Stop Point that contains multiple Stop Points.   
  A Station may have an actual and associated location; it may provide various amenities (e.g. businesses or restrooms)
* Transit Incidents, broadly, are events of interest that occur on a particular transit trip. Typically, they are problematic, unplanned issues resulting in some delay.  
  A TransitIncident is a subclass of Activity.  
  It is associated with some station or stop point.  
  An incident may be described (and so classified) by a predefined code: hasCode only xsd:String.  
  An incident will have some resulting caused gap (i.e. the time from the incident until the next train arrives at the station).
* TransitTrip is a subclass of Trip.   
  Transit Trips have specific restrictions and specialized properties. A Transit Trip occurs on some predefined route. A Transit Trip may also describe a trip on some smaller part of a Route, i.e. a Route Link. In exceptional cases, is possible that a TransitTrip may occur off-route (e.g. detours). The start and destination of a Transit Trip must be a Stop Point, and all Transit Trips must be performed with a Transit Vehicle.
* ScheduledTransitTrip is a type of RecurringEvent that only has TransitTrips as occurrences. A ScheduledTransitTrip is scheduled on some Route, RouteLink, or RouteSection, however it is not necessarily the case that the trip is accessible to travelers at the beginning stop point. It is possible that the scheduled trip will not pick up any passengers, or that passengers must pre-arrange in order to be picked up by the scheduled trip. A Scheduled Transit Trip may have a pick-up type and/or drop-off type as defined by some Trip Access Arrangement Type: as scheduled, not available, arranged with agency, or arranged with driver.  
  ScheduledTransitTrips may be used to specify route and stop timetables. Like a TransitTrip, a ScheduledTransitTrip may be described as inbound or outbound with the isOutbound data property. Scheduled trips may be defined to require only the assignment of vehicles that accommodate a wheelchair rider(s); this property may be captured with the isWheelchairAccessible data property.  
  The start and end times of scheduled (recurring) transit trips may be used to specify route and stop timetables.
* TransitVehicle is a subclass of Vehicle.   
  A TransitVehicle has a transit vehicle id. This refers to the identifier assigned by the transit authority, as opposed to a serial number.  
  Transit Vehicles are owned and operated by some transit authority. There are specialized types of transit vehicles (e.g. different types of streetcars), and a restricted set of modes. Transit Vehicles typically only operate on pre-defined routes, however there are exceptions (e.g. detours, travel for maintenance, etc).
* AccessMethod: An Access Method is the means of **access to** a Line  
  An AccessMethod **has a Monetary Value**.  
  An AccessMethod may be **valid for** a specific distance or time.
* RouteTimetable: A Timetable represents schedule information fora particular Route, or Route Link.  
  A RouteTimetable has an **expected travel time (Duration)** for the Route, or Route Link.
* A StopTimetable has an **expected arrival time (Time Instant)** for some Stop Point.
* VehicleBlock: A Vehicle Block represents a grouping of transit trips to be allocated to a particular vehicle. A transit trip is part of a single block and each block may contain multiple transit trips, therefore the allocatedFor property relating vehicle blocks and transit trips is inverse functional. Each block may be allocated multiple vehicles, but only one vehicle at a given point in time therefore the allocatedTo property which relates vehicle blocks to vehicles is functional.
* Two complementary properties (one object and one data property) have been added to capture information regarding transit passes. The data property provides a simply Boolean value to capture whether a person (at some time) has a transit pass; whereas the object property provides the ability to associate a particular transit pass (with some properties regarding, for example, its access, cost, and balance).

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| TransitSystemPD | subclassOf | change:TimeVaryingConcept |
| equivalentClass | change:hasManifestation some TransitSystem and change:hasManifestation only TransitSystem |
| change:existsAt | exactly 1 time:Interval |
| operatedBy | org:OrganizationPD |
| TransitSystem | subclassOf | change:Manifestation |
| equivalentClass | change:manifestationOf some TransitSystemPD and change:manifestationOf only TransitSystemPD |
| change:existsAt | exactly 1 time:TemporalEntity |
| hasRoutes | only Route |
| accessBy | only AccessMethod |
| AccessMethod | hasMonetaryCost | only monetary:MonetaryValue |
| validFor | only (time:DurationDescription or om:length) |
| Fare | subclassOf | AccessMethod |
| TransitPass | subclassOf | AccessMethod |
| RoutePD | ~~hasRouteId~~ | ~~exactly 1 RouteId~~ |
| subClassOf | change:TimeVaryingConcept |
| equivalentClass | change:hasManifestation some Route and change:hasManifestation only Route |
| change:existsAt | only time:Interval |
| hasGTFSRouteType | exactly 1 {0,1,2,3,4,5,6,7} |
| Route | subclassOf | change:Manifestation |
| equivalentClass | change:manifestationOf some RoutePD and change:manifestationOf only RoutePD |
| change:existsAt | only time:TemporalEntity |
| routeShortName | max 1 xsd:string |
| foaf:name | max 1 xsd:string |
| hasSection | only RouteSection |
| operatesOn | only ArcPD |
| hasDisplayColor | max 1 xsd:string |
| hasRouteTextColor | max 1 xsd:string |
| icontact:hasOperatingHours | some rec:HoursOfOperation |
| RouteSection | mereology:contains | only RouteLink |
| beginsAtStop | exactly 1 StopPoint |
| endsAtStop | exactly 1 StopPoint |
| operatesOn | only ArcPD |
| RouteLink | operatesOn | exactly 1 ArcPD |
| StopPoint | subclassOf | transport:Node |
| spatial\_loc:hasLocation | exactly 1 spatial\_loc:Feature |
| transit:hasStopCode | exactly 1 xsd:string |
| foaf:name | min 1 xsd: string |
| transit:wheelchairBoarding | exactly 1 xsd:boolean |
| AccessibleStopPoint | equivalentClass | StopPoint and transit:wheelchairAccessible value true |
| Station | subclassOf | StopPoint |
| mereology:contains | min 1 StopPoint |
| spatial\_loc:associatedLocation | some spatial\_loc:Feature |
| TransitIncident | subclassOf | activity:Activity |
| associatedWithStop | only StopPoint |
| hasIncidentCode | min 1 xsd:string |
| causedGap | only time:Interval |
| associatedWithTrip | only TransitTrip |
| TransitTrip | subclassOf | trip:Trip |
| transit:occursOn | only transit:Route or transit:RouteSection or transit:RouteLink or transport:TransportationComplex |
| transit:viaVehicle | exactly 1 transit:TransitVehicle |
| transit:isOutbound | only xsd:boolean |
| ScheduledTransitTrip | subclassOf | rec:RecurringEvent |
| rec:hasOccurrence | only transit:TransitTrip |
| transit:scheduledOn | only transit:Route or transit:RouteSection or transit:RouteLink |
| transit:isOutbound | only xsd:boolean |
| transit:isWheelchairAccessible | only xsd:boolean |
| hasPickupType | max 1 TripAccessArrangement |
| hasDropoffType | max 1 TripAccessArrangement |
| TripAccessArrangement | equivalentClass | {AccessAsScheduled, AccessNotAvailable, AccessArrangedViaAgency, AccessArrangedViaDriver} |
| TransitVehicle | subclassOf | vehicle:Vehicle |
| hasTransitVehicleId | exactly 1 xsd:string |
| VehicleBlock | assignedTo | only transit:TransitVehicle |
| assignedFor | min 1 ScheduledTransitTrip |
| person:Person | transitPass | only TransitPass |
| hasTransitPass | only xsd:boolean |

**Ontologies Reused:**

* Activity
* Change
* Spatial Location
* TransportationSystem
* Trip
* Organization

**Future work:**

Though not applicable for the TTC, future work should consider a representation of zone or similar information that may be used in some systems to calculate fare cost.

There is some potential to incorporate detailed constraints on the types of routes (bus, rail, etc) and the arcs in the network that the routes access, according to the mode supported by the arcs.

Constraints may also be enforced on the times of trips as compared to the hours of operation for a particular route (i.e. a trip should occur within the defined hours of operation).

With additional information, the stops associated with a particular trip may be validated against its direction id to confirm that the sequence is capturing either an inbound or outbound path.

Constraints may be added to enforce the types of vehicles that perform a particular transit trip, based upon the specifications of the scheduled trip of which the transit trip is an occurrence. For example, if the scheduled trip is wheelchair accessible, then any vehicle that performs the transit trips (or is assigned a block containing the scheduled trip) should accommodate a wheelchair. On the other hand, it may be the case that vehicle assignments sometimes conflict with the scheduled trip type and so such constraints may not be accurate/desirable.

We may also be able to infer whether a stop offers wheelchair boarding based on the associated routes and trips.

Rules may be added to express the relationship between the Arc that a Route Link operates on and the set of Arcs that a Route Section or Route operate on (i.e. the sum of all Arcs operated on by all Route Links contained in the Route Section/Route).

In extensions beyond OWL, it may be useful to formalize the relationship between transitPass and hasTransitPass properties.

## Land Use Ontology

*http://ontology.eil.utoronto.ca/icity/LandUse*

**Namespace: landuse**

* Parcel: A Parcel is a way of defining some area in an urban system.  
  A Parcel **has a Location**; at a given point in time, a Parcel is a spatial Feature.  
  A Parcel may be classified as **having some type of Land Use**.  
  There may be other types (**subclasses**) of Parcel, defined in more precise or different ways, such as a Zone.  
  A Parcel may have some associated Area. This is currently a variant property and we have yet to determine whether this is equivalent to the area of the Geometry of the Parcel’s location (e.g. there may be various values with different accuracy from different sources).  
  A Parcel may have some population that is subject to change over time.  
  A Parcel may have a number of employed residents that is subject to change over time.
* LandUseClassification: Land Use Classifications provide a means of describing the land cover/use in a standard way. Various classification systems are used to identify types of land use. Currently, we include LBCS, CLUMP, and AAFC.
* The LBCS recognizes different dimensions of Land Use: Activity, Function, Structure, Site, and Ownership Classifications. Each dimension is further defined by a taxonomy of specialized classifications. For each dimension, we introduce an equivalent class name for disambiguation, e.g. to distinguish between the Activity dimension of land use (we refer to this as ActivityClassification) and the notion of an Activity in icity.
  + Activity Classification: An Activity Classification identifies the **activity use** of some Land Parcel.
    - Residential Activities
    - Shopping Activities
    - Industrial Activities
    - ...
  + Function Classification: A Function Classification identifies the **economic function of** some Land Parcel,
  + Structure Classification: A Structure Classification identifies the **type of structure(s) on** some Land Parcel.
  + Site Classification: A Site Classification identifies the **state of the site development on** some Land Parcel (e.g. is it developed or not?)
  + Ownership Classification: An Ownership Classification identifies any **constraints on the use of the land and its ownership for** some Land Parcel.
* CLUMPClassification: Canada Land Use Monitoring Program Classification is a type (subclass) of Land Use classification. CLUMP identifies 15 different types of land use, each with an associated code used in datasets. We have made the design decision that the code need not be unique to a particular land use classification, as a classification from one system may correspond to multiple classifications in CLUMP. CLUMP introduces the following land use classifications:
  + B - Urban built-up area
  + E - Mines, quarries, sand and gravel pits
  + O - Outdoor recreation
  + H - Horticulture
  + G - Orchards and vineyards
  + A - Cropland
  + P - Improved pasture and forage crops
  + K - Unimproved pasture and range land
  + T - Productive woodland
  + U - Non-productive woodland
  + M - Swamp, marsh or bog
  + S - Unproductive land - sand
  + L - Unproductive land - rock
  + 8 - Unmapped areas (technically not a CLUMP classification but it is used in the land use data)
  + Z - Water areas (technically not a CLUMP classification but it is used in the land use data)
* AAFCClassification: Agriculture and Agri-Foods Canada Classification is a type (subclass of) land use classification. The codes are based on the IPCC (International Panel on Climate Change) protocol. We have made the design decision that the code need not be unique to a particular land use classification, as a classification from one system may correspond to multiple classifications in AAFC. AAFC uses the following land use classifications:
  + Unclassified
  + Settlement
  + Roads
  + Water
  + Forest
  + Forest Wetland
  + Trees
  + Treed Wetland
  + Cropland
  + Grassland Managed
  + Grassland Unmanaged
  + Wetland
  + Wetland Shrub
  + Wetland Herb
  + Other land
* TrafficZone: traffic zone is a kind of (subclass of) Parcel. It may be identified with a predefined set of identifiers, corresponding to its centroid node ID.

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| ParcelPD | subclassOf | change:TimeVaryingConcept |
| equivalentClass | change:hasManifestation some Parcel and change:hasManifestation only Parcel |
| change:existsAt | exactly 1 time:Interval |
| ~~spatial\_loc:hasLocation~~ | ~~exactly 1 spatial\_loc;SpatialFeature~~ |
| lbcs:Parcel | subClassOf | spatial\_loc:Feature |
| subclassOf | change:Manifestation |
| equivalentClass | change:manifestationOf some ParcelPD and change:manifestationOf only ParcelPD |
| change:existsAt | exactly 1 time:TemporalEntity |
| hasLandUse | min 1 LandUseClassification |
| associatedArea | only om:area |
| hasPopulation | only Population |
| ResidentPopulation | subclassOf | govstat:Population |
| EmployedPopulation | subclassOf | ResidentPopulation |
| LBCSClassification | subclassOf | LandUseClassification |
| ActivityClassification | subclassOf | LBCSClassification |
| equivalentClass | lbcs:Activity |
| FunctionClassification | subclassOf | LBCSClassification |
| equivalentClass | lbcs:Function |
| StructureClassification | subclassOf | LBCSClassification |
| equivalentClass | lbcs:Structure |
| SiteClassification | subclassOf | LBCSClassification |
| equivalentClass | lbcs:Site |
| OwnershipClassification | subclassOf | LBCSClassification |
| equivalentClass | lbcs:Ownership |
| CLUMPClassification | subclassOf | LandUseClassification |
| equivalentTo | hasCLUMPCode min 1 xsd:string |
| AAFCClassification | subclassOf | LandUseClassification |
| equivalentTo | hasAAFCCode min 1 xsd:string |
| Unclassified | subclassOf | AAFCClassification |
| equivalentTo | hasAAFCCode value "11" |
| Settlement | subclassOf | AAFCClassification |
| equivalentTo | hasAAFCCode value "21" |
| Roads | subclassOf | AAFCClassification |
| equivalentTo | hasAAFCCode value "25" |
| Water | subclassOf | AAFCClassification |
| equivalentTo | hasAAFCCode value "31" |
| Forest | subclassOf | AAFCClassification |
| equivalentTo | hasAAFCCode value "41" |
| ForestWetland | subclassOf | AAFCClassification |
| equivalentTo | hasAAFCCode value "42" |
| Trees | subclassOf | AAFCClassification |
| equivalentTo | hasAAFCCode value "45" |
| TreedWetland | subclassOf | AAFCClassification |
| equivalentTo | hasAAFCCode value "46" |
| AAFCCropland | subclassOf | AAFCClassification |
| equivalentTo | hasAAFCCode value "51" |
| GrasslandManaged | subclassOf | AAFCClassification |
| equivalentTo | hasAAFCCode value "61" |
| GrasslandUnmanaged | subclassOf | AAFCClassification |
| equivalentTo | hasAAFCCode value "62" |
| Wetland | subclassOf | AAFCClassification |
| equivalentTo | hasAAFCCode value "71" |
| WetlandShrub | subclassOf | AAFCClassification |
| equivalentTo | hasAAFCCode value "73" |
| WetlandHerb | subclassOf | AAFCClassification |
| equivalentTo | hasAAFCCode value "74" |
| OtherLand | subclassOf | AAFCClassification |
| equivalentTo | hasAAFCCode value "91" |
| UrbanBuiltUp | subclassOf | CLUMPClassification |
| equivalentTo | hasCLUMPCode value "B" |
| MinesQuarriesSandGravelPits | subclassOf | CLUMPClassification |
| equivalentTo | hasCLUMPCode value "E" |
| CLUMPCropland | subclassOf | CLUMPClassification |
| equivalentTo | hasCLUMPCode value "A" |
| CLUMPWater | subclassOf | CLUMPClassification |
| equivalentTo | hasCLUMPCode value "Z" |
| Horticulture | subclassOf | CLUMPClassification |
| equivalentTo | hasCLUMPCode value "H" |
| ImprovedPasture | subclassOf | CLUMPClassification |
| equivalentTo | hasCLUMPCode value "P" |
| NonProductiveWoodland | subclassOf | CLUMPClassification |
| equivalentTo | hasCLUMPCode value "U" |
| OrchardsVineyards | subclassOf | CLUMPClassification |
| equivalentTo | hasCLUMPCode value "G" |
| OutdoorRecreation | subclassOf | CLUMPClassification |
| equivalentTo | hasCLUMPCode value "O" |
| ProductiveWoodland | subclassOf | CLUMPClassification |
| equivalentTo | hasCLUMPCode value "T" |
| SwampMarshBog | subclassOf | CLUMPClassification |
| equivalentTo | hasCLUMPCode value "M" |
| UnimprovedPasture | subclassOf | CLUMPClassification |
| equivalentTo | hasCLUMPCode value "K" |
| Unmapped | subclassOf | CLUMPClassification |
| equivalentTo | hasCLUMPCode value "8" |
| UnproductiveRock | subclassOf | CLUMPClassification |
| equivalentTo | hasCLUMPCode value "L" |
| UnproductiveSand | subclassOf | CLUMPClassification |
|  | equivalentTo | hasCLUMPCode value "S" |

**Reused Ontologies:**

* lbcs: Land Based Classification Standards (LBCS) Ontology[[16]](#footnote-16) presented by (Montenegro, Gomes, Urbano, & Duarte, 2011).
* iCity-Foundation

**Future Work:**

* In future versions of the ontology, it may be desirable to include an optional relationship for Parcel that identifies its associated organization (e.g. municipal / federal government, transit agency, etc.)
* Future work may extend the population representation to capture various sorts of populations (employed, students, etc)

## Trip Ontology

*http://ontology.eil.utoronto.ca/icity/Trip.owl*

**Namespace: trip**

* Trip: A Trip 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 specialization of the **has participant** property: **hasDriver** and/or **hasPassenger**.  
  A Trip **starts at** some **Location** and **ends at** some **Location**.  
  A Trip **occurs during** some Interval.  
  A Trip **occurs in** some Network(s).  
  A Trip **occurs via** some Arc(s).  
  A Trip **occurs on** some Transportation Complex. (e.g. a road or a rail)  
  A Trip contains some Trip Segments.  
  A Trip may incur some cost (monetary or otherwise).
* A Trip Segment describes part of a trip. It may be used, for example, to identify different parts of the Trip by Mode.  
  The restrictions on the Mode and possibly Vehicle used will become more complicated as we begin to incorporate restrictions based on a Persons access to a vehicle (age, household).  
  A Trip Segment is a specialization of a Trip that is subactivity of some Trip.  
  A Trip Segment **occurs during** some Interval.  
  A Trip Segment **occurs in** some Network(s).  
  A Trip Segment occurs via some Arc(s).  
  A Trip occurs on some Transportation Complex.  
  A Trip Segment may incur some cost (monetary or otherwise).
* Tour: A sequence of Trips made by one Person.  
  A Tour **starts and ends at** the same Location.

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| Trip | subclassOf | activity:Activity |
| startLoc | only spatial\_loc:SpatialFeature |
| endLoc | only spatial\_loc:SpatialFeature |
| ~~during~~ | ~~exactly 1 time:Interval~~ |
| accessesNetwork | min 1 transportation:Network |
| accessesArc | min 1 transportation:Arc |
| occursOn | min 1 transportation:TransportationComplex |
| viaMode | min 1 transportation:Mode |
| viaVehicle | only Vehicle |
| hasDriver | only change:Manifestation |
| hasPassenger | only change:Manifestation |
| TripSegment | subclassOf | Trip |
| inverse (hasSubactivity) | min 1 Trip |
| viaMode | ~~min~~ exactly 1 vehicle:Mode |
| viaVehicle | only vehicle:Vehicle |
| Tour | subClassOf | Trip |
| startLoc | startLoc only (inverse (endLoc) Self) |

**Reused Ontologies:**

* iCity-TransportationSystem
* iCity-Vehicle

### Trip Costs

*http://ontology.eil.utoronto.ca/icity/TripCost.owl*

**Namespace: tripcost**

Different costs are associated with the performance of Trips. These may take the form of direct costs such as those presented in the Travel Cost Ontology, but there may 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; a trip cost is a property of some instance of travelling.

* A Duration Cost is a Trip Cost.  
  A duration cost has an associated cost in terms of duration; e.g. the length of time to perform the trip or trip segment  
  A duration cost may have an associated monetary cost (valuation); e.g. the monetary cost applied to the length of time taken to perform the trip or trip cost.
* A Distance is a Trip Cost  
  A distance has an associated cost in terms of the distance travelled.  
  It may also have an associated monetary cost (valuation)
* An Environmental Cost is a Trip Cost
* A Vehicle Cost is a Trip Cost

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| TripCost | hasMonetaryCost | only om:MonetaryValue |
| tripCostOf | only (trip:Tour or trip:Trip or trip:TripSegment) |
| DurationCost | subclassOf | TripCost |
| hasDurationCost | only time:DurationDescription |
| DistanceCost | subclassOf | TripCost |
| hasDistanceCost | only om:length or om:MonetaryValue |
| EnvironmentalCost | subclassOf | TripCost |
| hasEnvironmentalCost | only CarbonEmissions |
| VehicleCost | subclassOf | TripCost |

**Reused Ontologies:**

* iCity-Trip

## Urban System Ontology

*http://ontology.eil.utoronto.ca/icity/UrbanSystem.owl*

**Namespace: urbansys**

Earlier in this report, we recognized that the urban system covers many different concepts, thus motivating the design of the preceding, so-called generic ontologies. However, it must be recognized that in isolation, these concepts do not effectively capture the urban system. The urban system not only includes these concepts, but relationships between them. The Urban System Ontology extends all of the previously defined ontologies in order to capture the relationships between them, in the context of the urban system.

* A Person may be a **member of** a Family and/or a Household.  
  A Person may work for another Person, or some Organization, or be enrolled at some Educational Institution.  
  A Person may **have access to** some **Vehicle**.  
  A Person may **have access to** some **Bicycle**.  
  A Person has a **Schedule** for a given point (period) in time.
* A Schedule is a plan for some Activity to occur at/over some point in time.
* A Family **has members** who are Persons, and who are related via the has-spouse or has-child properties.
* A Household has one or more Persons as **members**. We do not make any commitment regarding the identity of the Persons, and in fact a Person may belong to more than one Household.
* A Dwelling Unit is **located in some Building** (e.g. House, Apartment,...)
* An Organization must have at least 2 Person(s) as members(s).
* A Firm or a Business Establishment may have a Person as an employee
* An Employee is a type of Person(s).
* Occupation: An Occupation **is performed by** some Person.  
  An Occupation has a type (e.g. sales, skilled trades)
* A Building may be located on some Parcel of land (this is an invariant property of any building).  
  A Building **has an owner**, which may be a Persons or some Organization.  
  A Building **has occupants**, which may or may not be the same Persons or Firm who own it.  
  A Building may **provide** some **Parking**.
* A Building Unit may be **occupied by** some Persons or Organization.  
  A Building Unit may be **provide some Parking**.
* A Vehicle may be **occupied by** at least one Person, and some cargo.  
  A Vehicle is **owned by** some Person(s) or Firm.  
  A Vehicle has some associated **Mode**.
* Occupant: An occupant is a Person who is occupying a Vehicle during transit.  
  An Occupant may be a Driver or a Passenger
* Cargo: A Cargo is some Thing that is not a Person and is occupying a Vehicle during transit.
* An *entire* Arc is accessible by a single set of Mode(s).
* A Road Segment is accessed by some Arc(s) with modes that are not water, air, or rail.
* A Parking Area has some **owner**.  
  A Parking Area may be **occupied by** some Vehicle (however, it might also be occupied by some debris or activities such as construction).
* A Parking Policy may **apply to** a specific group of Persons or Organizations.  
  A Parking Policy may have a **vehicle type restriction.**
* A TransitSystem may be **owned by** some Organization.
* A Route is **executed by** various Vehicles at different points in time.
* A Trip is **made by** a Person to **facilitate participation in some Activity**.

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| person:Person | memberOf | min 1 household:Family |
| memberOf | min 0 household:Household |
| schema:worksFor | some (person:Person or org:Organization) |
| hasAccess | some (vehicle:Vehicle or Bicycle) |
| hasSchedule | some Schedule |
| Schedule | hasActivity | only activity:Activity |
| scheduledFor | exactly 1 time:Interval |
| household:Family | hasMember | only person:Person |
| household:Household | hasMember | min 1 (household:Family or person:Person) |
| household:DwellingUnitPD | locatedIn | some building:Building |
| org:Organization | org:hasOrgMember | min 2 person:Person |
| org:Firm | hasEmployee | only person:Person |
| org:BusinessEstablishment | hasEmployee | only person:Person |
| org:Employee | equivalentClass | person:Person and employedBy some ( tove:Organization or person:Person) |
| Occupation | performedBy | some person:Person |
| hasOccupationType | only OccupationType |
| building:BuildingPD | locatedOn | only landuse:Parcel |
| building:Building | hasOwner | min 1 (person:Person or org:Organization) |
| hasOccupant | some person:Person or org:Organization or org:BusinessEstablishment |
| hasParking | only parking:ParkingArea |
| vehicle:Vehicle | occupiedBy | only (Occupant or Cargo) |
| hasOwner | only (person:Person or org:Organization) |
| hasMode | only transportation:Mode |
| Occupant | equivalentClass | person:Person and occupies some vehicle:Vehicle |
| Cargo | equivalentClass | not(person:Person) and occupies some vehicle:Vehicle |
| transit:TransitSystem | hasOwner | only org:Organization |
| transit:Route | executedBy | only vehicle:Vehicle |
| trip:Trip | subClassOf | activity:Activity |
| performedBy | some person:Person |
| associatedWith | only activity:Activity |

**Future work:**

* May be useful to add a generalized ‘hasPass’ relationship to capture various possible passes a person may have (transit and otherwise)
* Many extensions of this ontology are possible. Additional axioms and properties may be added in future work as new use cases are identified.

# Extra-logical Design Practices

Here, we summarize and explain the design practices that were adopted in the creation of the ontologies. These practices do not pertain to the semantic definitions, but rather are adopted to address pragmatic concerns regarding the organization and maintenance of the ontologies.

* Organizational terms for reuse (full import) of ontologies: e.g. owl-time. In order to create the required groupings under organizational subclasses, it is easiest to merge the imported ontology into the iCity container (e.g. icity/Time/). This allows for the addition of organizational subclass assertions (e.g. TemporalEntity subclassOf TimeOntologyThing) and also ensures that the appropriate version is captured/reused as a snapshot. This prevents any issues should versioning IRIs not be used by the ontology’s author.
* IRI reference instead of import for large vocabularies (e.g. schema.org)

# Evaluation

Throughout development, the iCity ontologies were presented to the iCity-ORF researchers and other stakeholders for review and feedback. These activities served as a kind of informal evaluation that helped to inform, improve, and validate the design of the ontology. In addition, the ontology has been formally evaluated against the requirements described in Section 5. In this section, we review the results of the ontology evaluation for consistency, competency, and application.

1. Evaluation: the task of evaluation is an important step that was addressed in several dimensions in this project:
   1. *Consistency*: Using the ontologies shall be classified using an automated reasoner to demonstrate consistency of the definitions and absence of unsatisfiable classes.
   2. *Competency:* The ontologies shall be assessed against the Competency Questions specified in the Requirements stage.
   3. *Application:* The ontology shall be applied in a variety of case studies to serve as a concrete demonstration of its viability as a solution for several of the motivating scenarios. This will also illustrate the adequacy of the ontology to support mappings from relevant data sources (described previously).

## Consistency

A fundamental requirement for any ontology is consistency. If the axioms in the ontology are inconsistent, then the classes are unsatisfiable and any data that is mapped into the ontology will be inconsistent. This inhibits the application of the ontology for data verification. In addition, any sentence may be deduced from an inconsistent set of axioms, so this is also problematic for any reasoning applications. From a basic ontology design perspective, if the axioms are inconsistent then there is something wrong with the way the domain has been formalized; the ontology contains some set of statements that in some way contradict each other. Similarly, it is important to check for (and avoid) any unsatisfiable classes. In a consistent ontology it is still possible that select classes may not be satisfiable. In such cases it is impossible to instantiate the class with any data and maintain consistency. The ontology has been evaluated for both consistency and (absence of) unsatisfiable classes using the Pellet OWL reasoner. One unsatisfiable class was identified, however the class (time:January[[17]](#footnote-17)) is not reused in the extensions and is deprecated in the version of the W3C Time Ontology that is imported by the iCity ontologies.

## Competency

The Requirements stage of ontology development resulted in the identification of five motivating scenarios and ## associated competency questions. Competency questions provide guidance for ontology design, as well as a clear set of criteria against which the ontology may be evaluated. The evaluation focuses on determining whether the ontology is sufficient to formalize the identified competency questions. It is straightforward to demonstrate that the requirements are satisfied by formalizing each of the competency questions using the ontology. Since the ontology has been formalized in OWL 2, the usual mechanism of accessing the data it encodes with be with the SPARQL query language[[18]](#footnote-18). Therefore, the ontology has been evaluated with the use SPARQL to formalize each of the identified competency questions. Implicit in each formalism is a mapping between the natural language used in the requirement and the terms defined in the ontology. This mapping will be made explicit in the application of the ontology, which addresses the mapping models required to encode information in datasets as instances in the ontology.

In the following, we demonstrate the results of evaluation by formalizing each of the identified competency questions in SPARQL. The following namespaces will be used in addition to the namespaces defined in the previous section:

* rdf:
* rdfs:
* owl:

Many of the competency questions pertain to some given individual of interest (e.g. a particular household or traffic zone). We capture such cases with a placeholder denoted in curly brackets (e.g. {household-1}) to illustrate where the individual or individuals of interest would be substituted.

**On the role of GeoSPARQL Functions:** In practice, the spatial relationships between objects may not be encoded in the knowledge base. In such cases, GeoSPARQL functions may be employed in the query to compute these relationships using the coordinate data defined for the geo:Geometry objects. As the implementation of these functions is subject to some variation between triple stores, for the purposes of evaluation we design the queries under the assumption that the spatial relationships between geo:Feature objects are given. This allows us to maintain a consistent, triple store-independent formalization.

### CQs for Land Use and Transportation Simulation

CQ1-1: What trips originated/ended[[19]](#footnote-19) in a given zone?

SELECT ?trip WHERE {

?trip rdf:type trip:Trip.

?trip trip:startLoc ?sloc.

{zone} a landuse:TrafficZone;

loc:hasLocation ?zloc.

?zloc geo:contains ?sloc.

}

CQ1-2: What is the occupation breakdown of the travelers whose trips originated/ended in a given zone?

SELECT ?occupation (COUNT ?trip as ?trips) WHERE {

?trip rdf:type trip:Trip.

?trip trip:startLoc ?sloc.

{zone} a landuse:TrafficZone;

loc:hasLocation ?zloc.

?zloc geo:contains ?sloc.

?trip urban:tripPerformedBy ?p.

?o org:performedBy ?p.

?o org:hasOccupationType ?occupation.

} GROUP BY ?occupation

CQ1-3: What were the purposes of the trips that originated/ended in a given zone?

CQ1-4: In a particular time period, how many trips originated/ended in a given zone?

CQ1-5: What were the transportation mode(s) taken by trips that originated/ended in a given zone?

CQ1-6: Who are the members of a particular household?

CQ1-7: What trips were performed, by which members of a particular household?

CQ1-8: What were the purposes of the trips performed by members of a particular household?

CQ1-9: What is the age, sex, and occupation of the traveler who performed a particular trip?

CQ1-10: What land use classification is associated with a particular parcel?

### CQs for Transit Research

CQ2-1: What date and time has a subway incident occurred?

CQ2-2: What are the locations of buses from a particular station after the occurrence of a subway incident?

CQ2-3: Are any buses located more than a certain distance from their assigned route at a given point in time?

### CQs for Smart Parking Applications

CQ3-1 What is the address of the parking lot P?

CQ3-2 What is the capacity of parking lot P?

CQ3-3 Is it accessible by disabled people, and if so how many parking lots are for disabled vehicles?

CQ3-4 Is there a height limit for vehicles for a parking lot P?

CQ3-5 What are the geographic coordinates for parking lot P?

CQ3-6 What building is a particular parking lot located in?

CQ3-7 Is a particular parking lot open to the public at a given time?

CQ3-8 How much does it cost to park in a particular parking lot?

CQ3-9 What types of payment are accepted at a particular parking lot?

CQ3-10 How many parking spots are designated for electric vehicles in a particular parking lot?

CQ3-11 What types of electric vehicle chargers are available in a particular parking lot?

### CQs for ATIS via IT-SoS

CQ4-1: What TTI\_Max values have been observed at some date/time?

CQ4-2: What is the TTI\_Max value at some location?

CQ4-3: What is the TTI\_Max value at some location, at some date/time?

### CQs for ArcGIS Query Support

(to be finalized)

## Application

Complementary to the competency question evaluation is the question of whether or not the data required to answer the competency questions can be mapped into the ontology. This is addressed for a subset of the competency questions in the application dimension of evaluation.

Discuss use case choice

Data capture requirement for capture of relevant data to support the correct response to the competency questions, or in some cases – as discussed in Section 5 – simply for the purpose of storing collected data for future use.

Complementary to the formulation of the competency questions is the expectation that data that is encoded in the ontology will produce the expected results for each competency question.

Another facet of evaluation is the application of the ontology. It is important to demonstrate that how the ontology may be used to capture and produce the data of interest. , and produce the expected results for the competency questions.

Closely tied to this is the requirement of adequacy: the ontology must provide sufficient terminology to capture the relevant data.

Data mappings: describe at a High level

Reference Karma R2RML models (add to appendix)

# Applications

Beyond providing formalizing a vocabulary for an integrated, iCity knowledge base, the ontology may be employed more directly support applications for urban informatics. Three such examples have been explored: (1) ontology support for the IT-SoS framework, including the development of a semantic trip planner; (2) ontology support for survey design and results storage; and (3) ontology-based support for simulation result question-answering. In this section we focus on the IT-SoS application and describe the progress made thus far. More detail will be added as each application is explored further.

## iCity Ontology for ATIS in the IT-SoS Framework (to revise based on revisions to project 1.2)

The tremendous amount and diversity of data generated by ITS (Intelligent Transportation Systems) has become an important source for its services and applications. Travelling from one place to another often involves different information from different ITS services. Unfortunately, the multiplicity of ITS and their complexity has produced a body of heterogeneous data that cannot easily be integrated. Data from different sources must be analyzed, classified and re-organized into a homogenous format to make it universally applicable.

The objective of this work is to support the creation of tools capable of dynamic data discovery, information management, and interoperability between data sources and services. The architecture focuses on three areas: the storage of the data in a data lake, the semantic representation of the data, and the services layer. The architecture is designed to be scalable and enhance overall system performance using a semantic representation and integration. Many institutions and companies have developed ICT solutions to close the gap and manage data integration and representation by using well-known industrial protocols likes GTFS. Nevertheless, these solutions lack the formal semantics of ontologies, and there is no common standard across systems to manage and exchange data and information. The iCity Ontology plays a key role in the proposed architecture, enabling an integrated representation of domain knowledge and supporting semantic interoperability through different tools and across systems.

In the iCity project, this architecture was demonstrated with an example implementation applied to a use case for the development of an Advanced Traveler Information System (ATIS) application that incorporates data from loop detectors.

### Project 1.2: IT-SoS Architecture

The IT-SoS architecture proposed in iCity Project 1.2 is combined of the following major components, as illustrated in Figure 17.

* **Infrastructure**: multi-cloud strategy has been adopted to host the above layers (data, Servicers and Applications). The right selection of the appropriate cloud resources and hosting is based on the data and services requirements. The cloud infrastructure provides dynamic recourse allocation and better cost management.
* **Data Lake**: to provide a storage repository that host a vast amount of data (structured and unstructured).
* **Ontology Engine:** semantic representation for the data hosted locally, Data Lake, or extremally.
* **Services Layer:** to provide a platform to develop the services, i.g GIS services by using Esri platform. The services consume the data which is provided by Data Lake layer or through the integration with Ontology Engine.
* **Application Layer:** to use or combine one or more servicersand presented on specific application, i.e. Advanced Traveler information system (ATIS)



Figure : IT-SoS Architecture

The iCity Ontology Engine supports the IT-SoS by enabling access to semantically integrated data, is depicted in Figure 1. In order for the ontology engine function, the data sources must somehow be interpretable in the language of the ontology(s). This requires some form of semantic annotation or mapping of the data in its original form; ontology will be used to explicitly describe the semantics of each entry in the data sources. We propose the adoption of R2RML (RDB to RDF Mapping Language) to specify these mappings. R2RML is a W3C Recommendation that has been developed specifically for this purpose.

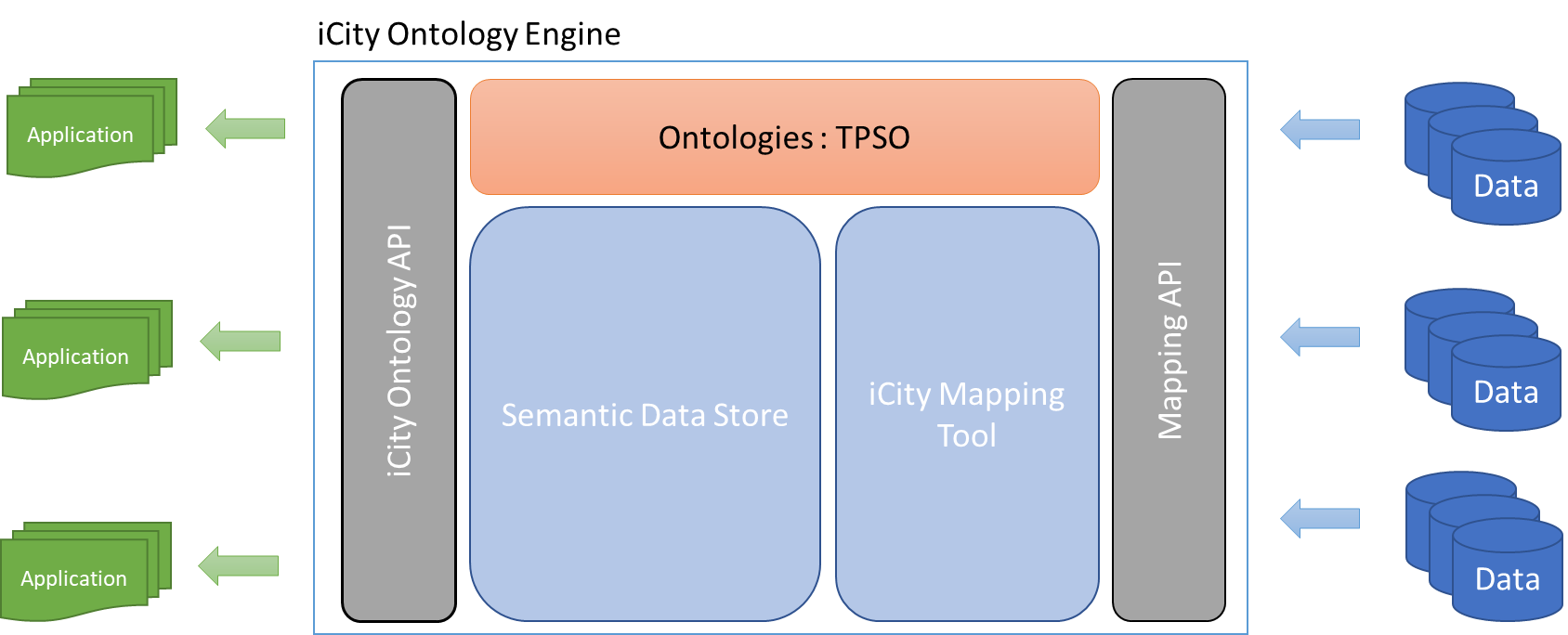


Figure 3: Architecture of the iCity Ontology Engine

Using the appropriate ontologies, these mappings will be defined for each type of data source. The ontologies may evolve and be extended over time, but changes will not necessarily be required to the mappings. On the other hand, changes to the data sources will require some modification to the R2RML mapping definitions however they will not necessarily require any changes to the ontologies. The inclusion of new data sources will require the definition of new R2RML mapping definitions, but will not impact any of the existing data sources or mappings.

The mappings and the data serve as input to a mapping tool which converts the data into information represented using the terminology of the ontology. This data is formatted according to Semantic Web Standards (i.e. it is serialized in RDF) such that it may then be loaded into a semantic graph data store.

The resulting data store houses all of the data. As a result of the mapping process, this data is now semantically annotated and integrated. In other words, the relationships between the various data stores are now explicit according to the concept definitions in the ontology. This data may be accessed via SPARQL queries: these are queries that are specified using the terminology defined by the ontology. In particular, the data store provides APIs that may be called by a variety of applications to access the data of interest via these queries.

An alternative architecture is possible in which the data is maintained solely in its original databases and is retrieved on-demand via Ontology-Based Data Access (OBDA) tools. This approach employs the same R2RML mappings, the main difference being that the data is not stored centrally, but assumed to be distributed in pre-existing relational databases. There are additional challenges related to this approach, thus it is a consideration for future work.

### ATIS Case Study

The application of the ontology engine architecture for the semantic enabling of sensor data was straightforward. Some minor cleaning of the datasets was required: primarily this involved some reformatting of data values in order to comply with standard datatypes (e.g. for date-time encodings). This cleaning was done using additional functionality provided by the mapping tool, but alternatively could have been accomplished with some preprocessing script.

The KARMA[[20]](#footnote-20) [22] tool was selected to support the transformation of the original sensor datasets into a semantic representation. This choice was motivated by several factors including: ease of use – the tool is straightforward to use and includes a GUI to support the R2RML specification process; range of acceptable data formats – the tool supports the transformation of not only data in relational databases, but also data in .csv and .json formats, among others; batch transformation – the tool easily enables the transformation of batches of files given the R2RML mappings and thus should easily scale to larger use cases. The Transportation Planning Suite of Ontologies (TPSO) [23] was used to define the concepts in the data. In particular, the Observations[[21]](#footnote-21) and Transportation System[[22]](#footnote-22) Ontologies play a key role. The TPSO was selected owing to the appropriateness of its domain. While there exist other ontologies in the transportation domain, they are not targeted to the task of transportation planning and so do not capture the wide range of concepts involved in the urban system. By using ontologies from the TPSO, we lay the foundation for future work where we might explore an expansion to include a variety of datasets (e.g. regarding agents in the system and the trips they take), such that the architecture may support a wide range of applications. More detail on the mappings applied to the loop detector datasets is provided in the following section.

The transformed data is stored in an implementation of the AllegroGraph semantic graph database that runs on an AWS machine (include specs?). There exist a number of other data stores that might have been used and would provide similar API functionality. AllegroGraph was chosen due to its popularity and its unique implementation of a quintuple representation that includes an identifier for each statement in the data store, as opposed to typical approaches which only provide identifiers at the dataset level. This functionality is required for future extensions to this work that address issues such as provenance and confidence in the facts in the data store.

Mapping the Data

The loop detector data was received in a simple, tabular format with the following column headings: WayID, Mean\_Value\_Max, Time, and Date. In fact, this data set was an excellent example of the challenges for semantic interoperability: communication with the persons responsible for generating the data set was required in order to understand the meaning of each of the attributes. This revealed the following, informal semantics for each attribute:

* WayID: this value is the identifier of the road segment over which the loop detector reading is aggregated.
* Mean\_Value\_Max: this value is the average Max TTI (Maximum Travel Time Index), aggregated over the wayID readings, at one-hour intervals.
* Time: this value indicates the time of day of the start of the one-hour interval, represented using an integer value that indicates hours past midnight. For example, “0” indicates 12:00 AM, “1” indicates “1:00 AM”, and so on.
* Date: this value represents the date during which the readings were taken, formatted as: year\_month\_day. For example, the value “017\_07\_01” indicates the date July 1, 2017.

Much of the information that is embedded in these values is not clear from the attribute labels alone. In order to enable interoperability, the semantics of these values must be made explicit. As described in [ref Architecture section] this is done with mappings expressed in R2RML, from the table into an ontology. Which ontology(s) is used in the mappings depends on the scope of the concepts represented in the data. Key concepts that we can recognize from the data are the notion of road segments, time, and measures – in particular the measure of a Maximum TTI (as defined in [Hasan to provide reference?]). As noted above, the TPSO was selected to provide the vocabulary for the R2RML mappings. Before the mappings could be defined, the data values were reformatted into standard datatypes: the Time and Date values were combined to be consistent with the xsd:dateTimeStamp datatype[[23]](#footnote-23). While this step is not strictly necessary for the architecture, it may be required in some cases in order to map the data values to specific data properties in the ontology.

In what follows, we describe the mappings that were defined for each attribute in order to support the data transformation. In some cases, some reformatting of the values into standard datatypes was also required.

The WayID value was defined as an individual member of the RoadSegment class, as defined in the Transportation System Ontology[[24]](#footnote-24) from the TPSO. The RoadSegment class represents part of a particular Road that makes up the physical infrastructure of the transportation system.

The Mean\_Value\_Max value was defined as the value of the numerical\_value property of a Measure that is the value of a MeanTTI\_Max Quantity. The concepts of a numerical\_value, a Measure, and a Quantity are defined in the Units of Measure Ontology[[25]](#footnote-25) from the TPSO, whereas the MeanTTI\_Max specialization of a Quantity is defined in the TransportationSystem Ontology. More specifically, the MeanTTI\_Max is captured as an aggregate of a TTI\_Max Quantity, that is the aggregate of a TTI\_Max value over a particular RoadSegment (the WayID), that is aggregated over a particular Interval in time. The concept of an interval is introduced in the Time Ontology[[26]](#footnote-26), and the Interval itself is captured using the transformed Time and Date values. The resulting value (an xsd:dateTimeStamp, as discussed above) provides a value for the start time of the Interval that the TTI\_Max is aggregated over, while a value one-hour later provides the end time for the Interval. This mapping is illustrated in Figure 1.



Figure : Mapping the data values into TPSO concepts. Data values are depicted in boldface blue and the ontology concepts are illustrated with the lines and rectangles.

## Analysis of TTC Data for Bus Bridging Study

## Exploration of Travel Model Data

Discuss use of ld-r tool

## iCity Ontology for Urban Simulation Results

Urban System Simulation Ontology

UrbanSystemSimulation.owl

Ontologies present the opportunity to concurrently address multiple challenges for urban modelling and simulation, such as:

1. the incomparability between models and results,
2. the need for bespoke query design, and
3. the opaqueness/complexity of models and results.

In this application, we focus on the use of the ontology to formalize the simulation results. Future work should extend this to focus on the models and the simulation runs.

The result of an urban system simulation is essentially an instance of some part(s) of the urban system and can be formalized by the urban system ontology. In addition, we need a way to distinguish such instances from real-world data. To accomplish this, we extend the Urban System Ontology with an ontology for simulations: the Urban System Simulation Ontology.

The following concepts are required for the Simulation extension:

* Simulation: A Simulation is an execution of some model system. It has some input and **output** data, defined by some instances of the UrbanSystemOntologyClass.   
  A Simulation has a **run date**.

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| Simulation | hasSimulationOutput | some UrbanSystemOntologyThing |
| hasRunDate | exactly 1 xsd:dateTime |

**Future work:** Additional aspects of the simulation (e.g. inputs, run dates, models used) are relevant, and should be defined in future work. They are discussed in Section 10.2.2.

# Integration with ArcGIS

In support of Esri Canada projects: CTI and NextGen-911. Inclusion of this section TBD.

# Workflows (in progress)

In this section we provide an overview of various workflows adopted for the iCity ontology, including:

1. Data Mapping
2. Data storage
3. Versioning
4. Documentation generation

## Data Mapping

* Discussion of alternatives

### Alternative approaches

In this guide we focus on the triplestore architecture, wherein the data sources are transformed into triples and uploaded to a triplestore(s). This triplestore may then be accessed via SPARQL queries (including applications using the Apache Jena framework). It should be noted that another possible architecture involves applying the semantic augmentation to access the data in a database, this is referred to as Ontology Based Data Access (OBDA).

This guide focuses on the use of the Karma Data Integration Tool[[27]](#footnote-27) for semantic augmentation and data transformation, however it should be noted that several similar tools exist, with varying capabilities and limitations. These tools are often referred to as R2RML processors or OBDA tools, examples are Mastro and Ontop, among others.

#### Factors to consider

* Data storage:
  + Which triplestore will you use?
  + May want to consider using the GUDR (Global Urban Data Repository)

### Basic data mapping/import workflow with Karma and Virtuoso:

1. Design mappings to capture the data using ontology. This step is performed offline and shall be done only once for a particular data source (i.e. all data of like format may be accessed/transformed with the same mapping). Karma provides a GUI to support this process. Note that some cleaning may be required in order to transform the data into an appropriate form.
   1. Open Karma, load dataset and relevant ontology files (in current Karma implementation, imports are not directly applied so uploading only the main ontology file may not capture all of the necessary terms).
   2. Data cleaning: transform the data as required (reformatting, separation of cell contents, etc).  
      This may require some use of Python. For example, in the TTS data we want to transform 3d coordinates to 2d coordinates, and format them according to the WKT format.  
      Simple reformat as WKT:

return "POLYGON(" + getValue("coordinates") + ")"

Reformat to remove 0-valued 3rd dimension from coordinates:

import re

line = getValue("coordinates")

line = re.sub(',',' ',line)

line = re.sub(' 0 ',',',line)

return line

The specification of IRIs is also a good step to take here. In some cases, this may require reformatting of some of the data. It will also likely require the introduction of some base namespace, e.g. “https://w3id.org/icity/TTC\_srt\_delays/...”

* 1. Specify ontology mappings in Karma.
  2. Export R2RML model (ttl or rdf) file. This model is a representation of the mapping of the data into the ontology.
  3. At this point, for a one-off transformation the transformed data may also be exported and saved for upload into the desired triplestore. However, if the mappings are to be generated and uploaded at a later date, only the R2RML model is required.

### Repeat Data Mappings

For multiple datasets with the same mapping, we can automate the above process once an initial mapping has been defined. This is possible using the batch mode in Karma[[28]](#footnote-28).

Example: let’s download a bunch of TTC incident files and try to map them with a single command, using the R2RML mapping that we defined for the first dataset.

Beginning with data files:

* SubwayDelay201706.csv
* SubwaySRTLogs201707.csv
* SubwaySRTLogs201708.csv

And a pre-defined mapping file

* SubwaySRT\_Mapping

There are 2 ways to do this: offline or online through the API. The API may eventually be useful should the mappings be incorporated into part of some larger process (e.g. a reaction to something: a file being uploaded or stream data being received). Note that a different process would need to be implemented for each file type in order to account for the different mapping files. For now, we’ll work with the offline implementation.

### Offline Batch Mapping

Batch mapping is useful for large quantities of files, or large file sizes. Note that for large mappings, the JVM memory may need to be increased when the commands are run.

**First-time setup:** To build the offline jar, go to the karma-offline subdirectory and execute the following:

cd karma-offline

mvn install -P shaded

java -cp karma-offline-0.0.1-SNAPSHOT-shaded.jar edu.isi.karma.rdf.OfflineRdfGenerator --sourcetype CSV --filepath "./files/SubwayDelay201706.csv" --modelfilepath "./files/SubwaySRT\_Mapping.ttl" --outputfile "./files/ttc-subway-delay-201706.n3" --sourcename "ttc"

#### A basic script to map a directory of files of the same type

Given:

* one or more files of the same type (i.e. with the same semantic mapping), in the directory “./karma-offline/target/files”.
* A predefined mapping file (SubwaySRT\_Mapping.ttl)

Execute from ./karma-offline/target directory:

for file in ./files/\*.csv; do java -cp karma-offline-0.0.1-SNAPSHOT-shaded.jar edu.isi.karma.rdf.OfflineRdfGenerator --sourcetype **CSV** --filepath "$file" --modelfilepath "./files/**SubwaySRT\_Mapping.ttl**" --outputfile "${file/%**csv**}ttl" --sourcename "**ttc**"; done

For large files, e.g.:

java -Xmx6000m -cp karma-offline-0.0.1-SNAPSHOT-shaded.jar edu.isi.karma.rdf.OfflineRdfGenerator --sourcetype CSV --filepath "files/trip\_stations.csv" --modelfilepath "files/trip\_stations\_model.ttl" --outputfile "files/trip\_stations.ttl" --sourcename "tasha\_microsim"

Result:

* A translated set of triples for each input file (<filename>.ttl)

#### Notes

* The Karma installation (one-click install) doesn’t come with karma-offline, you’ll need to install the full version from Github
* To run Karma (gui app) from the full installation:   
  >cd Web-Karma/karma-web  
  >mvn jetty:run  
  Karma should be accessible at: http://localhost:8080
* File paths are relative to the target directory that the command is executed from

## Data Storage

Alternatives:

* ODBC
* Triplestore
  + Alternatives: Virtuoso, AllegroGraph, …
  + Factors: cost, capabilities, …

### Upload to triplestore

Karma includes an option to configure upload to a triplestore (“publishing data”), therefore it’s possible that the mapping and upload process may be combined into a single step. However, it is not clear from the documentation whether this is possible in batch mode. It may be more appropriate to use the upload functionality provided by the chosen triplestore.

***Uploading large datasets server-side on Allegrograph:***

1. Transfer files to server where Allegrograph instance is running, e.g.

scp -r -i katsumi-key.pem <local location of files to upload> [ec2-user@ec2-35-183-119-164.ca-central-1.compute.amazonaws.com](mailto:ec2-user@ec2-35-183-119-164.ca-central-1.compute.amazonaws.com): <remote location of files to upload on aws>

1. Access server, e.g.

ssh -i katsumi-key.pem ec2-user@ec2-35-183-119-164.ca-central-1.compute.amazonaws.com

1. Run agtool to load file(s) onto specified graph:

agtool load http://test:xyzzy@ec2-35-183-119-164.ca-central-1.compute.amazonaws.com:10035/repositories/gtfs\_test ./gtfs\_to\_upload/\*.ttl

# Future Work

* Standardization: mapping to concepts in other areas of transportation & city services, consider alignment to foundational ontology
* Expand on transportation planning domain: Freight, Complete Streets
* Expand use cases: Simulation management, Survey management, Provenance
* Explore opportunities for inference
* Implementation with GUDR (data maintenance strategy implementation)
* Naming conventions for individuals (to be incorporated into mappings)

## Research

* Ontology versioning
* Ontology visualization (navigation of terms, understanding / querying data)
* Ontologies for simulation
* *Complex mappings and the need for (and definition of) shortcut properties*

Future iterations of the iCity Ontology will develop a deeper semantics for the concepts identified here, in addition to an expansion of scope. This will be dictated largely by use cases identified by the various project groups, which will not only determine additional requirements for representation, but potential applications for additional functionality that may be supported by the ontology.

…other sorts of CQs… It is expected that the ontologies will continue to evolve as more use cases are identified and other data becomes available.

## Extensions for iCity Applications

The first release of the iCity ontology is designed to capture the urban system. However, we anticipate additional concepts will be required for each iCity project to capture the nature of the data within a given application. Varying definitions of concepts within the urban system should be captured as part of the appropriate ontology (for example, multiple definitions of a Household should be represented by different definitions of Household in the Household ontology), on the other hand the iCity projects also introduce other concepts that are beyond the domain of the urban system, and more related to the applications themselves. For example, a simulation may produce output that captures information about an urban system, but we must also represent that this information is the result of a particular model being applied to some data to explain how it was generated and why it is of interest. We divide the iCity projects into 4 categories based on the nature of the applications: Data Collection, Simulation, Analysis, and Visualization. In the following subsections, we consider the classes and properties for each extension. The resulting structure for this future state of the iCity Ontology is illustrated inFigure 20.



Figure 18: iCity Ontology Structure

In identifying these concepts, a key question is: "What question(s) is the project/application trying to answer?"

Note that it is unclear whether or to what degree there may be some overlap between the requirements for Analysis and Simulation in that they both require some aspect of experiment management. This report concludes with some preliminary notes on the requirements for each category of application in the following sections.

### Data Collection

To completely capture collected data requires representation of its origin: what was the means of collection? When was it collected? How may the data be accessed? It requires the representation of concepts *about* the data collection itself. The following additional concepts may be required for the data collection extension:

* Data Entity: A Data Entity refers to some instance that is defined within the urban system, according to some source.  
  A Data Collection is a type of (**subclass of**) Data Entity.  
  A Data Collection **contains** one or many Data Entities.  
  A Data Entity **is generated by** some Collection Activity.  
  A Data Entity may be found **at some Location**.
* Data Entity: A Data Entity is any instance **contained in** some Dataset.
* Collection Activity: A Collection Activity indicates the origin of the data; i.e. how was it collected?  
  A Collection Activity **starts** and **ends** at some Time  
  There are different types (**subclasses**) of Collection Activity: Survey Activity, Sensor Activity, Data Fusion Activity, Simulation Activity, etcetera.  
  A Collection Activity may be found **at some Location** (e.g. location of the sensor or survey, could be physical or virtual).
* Data Fusion: A Data Entity may be the result of the Fusion of two or more Data Collections.  
  Data Fusion **is informed by** at least 2 Collection Activities.
* Data Collection Agent: The agent responsible for some Collection Activity.  
  A Collection Activity may be **associated with** some Data Collection Agent.  
  A Data Entity may be **attributed to** some Data Collection Agent.

### Simulation of Urban Systems

Capturing the simulation activities that occur within the iCity project, at this stage, appears to be very much an effort of experiment management. We need to be able to represent the simulation runs that are performed -- but also, more specifically the model(s) that was used, as well as the results that were obtained. The following additional concepts may be required for the Simulation extension:

* Simulation: A Simulation is an execution of some Model System.  
  A Simulation **executes** some Model System.  
  A Simulation has some **input** and **output** Dataset(s)  
  A Simulation has an **initial** State, **sequence** of States, and **final** State.  
  A Simulation has a **run date** and **duration**.
* State: A State is **comprised of** some instantiation of (part of) the urban system, at some specified point in time.
* Model System: A Model System is some configuration of model(s) that has been designed for simulation.  
  A Model System **contains** some Model(s)  
  A Model System may contain rules for how the Model(s) interact. (sequentially, in parallel, etcetera).
* Model: A Model is a means of advancing some current state within a Simulation.  
  A Model **applies to** some classes in the domain.  
  There are different types (**subclasses**) of Models, identified based on their perspective: State-oriented Model, Event-oriented Model, Activity-oriented Model, PD-oriented Model.  
  A Model **has** some **Parameter**(s).  
  A Model may **execute** **in parallel with** some other Model(s).  
  A Model may **execute** **directly after** some other Model(s).
* State-oriented Model. There are different types (**subclasses**) of State-oriented Models that can be defined, according to the application.  
  A State-oriented Model has some State Space  
  A State-oriented Model has some Event Set  
  A State-oriented Model has some Time Set  
  A State-oriented Model has some Transition Function to transition between states.  
  A State-oriented Model has some Clock Function to advance "time".  
  A State-oriented Model has some Initial State.

# Acknowledgements

This project is supported by the Ontario Ministry of Research and Innovation through the ORF-RE program.

# Bibliography

Bittner, T., & Donnelly, M. (2005). Computational ontologies of parthood, componenthood, and containment. *Proceedings of the 19th international joint conference on Artificial intelligence (IJCAI).* Morgan Kaufmann Publishers Inc.

Fadel, F. G., Fox, M. S., & Gruninger, M. (1994). A Generic Enterprise Resource Ontology. *Third Workshop on Enabling Technologies: Infrastructure for Collaborative Enterprises* (pp. 117-128). IEEE.

Fox, M. S., Barbuceanu, M., Gruninger, M., & Lin, J. (1998). An Organization Ontology for Enterprise Modelling. In K. C. M. Prietula, *Simulating Organizations: Computational Models of Institutions and Groups* (pp. 131-152). Menlo Park CA: AAAI/MIT Press.

Fox, M. S., Chionglo, J. F., & Fadel, F. G. (1993). A Common Sense Model of the Enterprise. *Proceedings of the 2nd Industrial Engineering Research Conference*, (pp. 425-429). Norcross GA.

Grau, B. C., Horrocks, I., Motik, B., Parsia, B., Patel-Schneider, P., & Sattler, U. (2008). OWL 2: The next step for OWL. *Web Semantics: Science, Services and Agents on the World Wide Web*, 309-322.

Hobbs, J. R., & Pan, F. (2004). An ontology of time for the semantic web. *ACM Transactions on Asian Language Information Processing (TALIP)*, 66-85.

Krieger, H.-U. (2008). Where temporal description logics fail: Representing temporally-changing relationships. *Annual Conference on Artificial Intelligence* (pp. 249-257). Springer Berlin Heidelberg.

Lorenz, B., Ohlbach, H. J., & Yang, L. (2005). *Ontology of transportation networks.*

Montenegro, N., Gomes, J., Urbano, P., & Duarte, J. (2011). An OWL2 Land Use Ontology: LBCS. *International Conference on Computational Science and its Applications* (pp. 185-198). Springer Berlin Heidelberg.

Welty, C., Fikes, R., & Makarios, S. (2006). A reusable ontology for fluents in OWL. *Formal Ontology in Information Systems (FOIS)*, (pp. 226-236).

[1] E. J. Miller and P. A. Salvini, "The integrated land use, transportation, environment (ILUTE) microsimulation modelling system: Description and current status," *Travel behaviour research: The leading edge,* pp. 711-724, 2001.

[2] N. F. Noy and D. L. McGuinness, "Ontology development 101: A guide to creating your first ontology," ed: Stanford knowledge systems laboratory technical report KSL-01-05 and …, 2001.

[3] M. Uschold and M. Gruninger, "Ontologies: Principles, methods and applications," *The knowledge engineering review,* vol. 11, no. 2, pp. 93-136, 1996.

[4] R. Battle and D. Kolas, "Linking geospatial data with GeoSPARQL," *Semant Web J Interoperability, Usability, Appl. Accessed,* vol. 24, 2011.

[5] *Time Ontology in OWL*, O. W3C, 2017. [Online]. Available: <https://www.w3.org/TR/owl-time/>

[6] J. R. Hobbs and F. Pan, "Time ontology in OWL," *W3C working draft,* vol. 27, p. 133, 2006.

[7] C. Welty, R. Fikes, and S. Makarios, "A reusable ontology for fluents in OWL," in *FOIS*, 2006, vol. 150, pp. 226-236.

[8] H.-U. Krieger, "Where temporal description logics fail: Representing temporally-changing relationships," in *Annual Conference on Artificial Intelligence*, 2008: Springer, pp. 249-257.

[9] M. Katsumi and M. Fox, "A Logical Design Pattern for Representing Change Over Time in OWL."

[10] M. Katsumi and M. Fox, "Defining Activity Specifications in OWL," in *WOP@ ISWC*, 2017.

[11] R. Kowalski and M. Sergot, "A logic-based calculus of events. NewGeneration Computing 4," ed, 1986.

[12] M. S. Fox, "Constraint-Directed Search: A Case Study of Job-Shop Scheduling," CARNEGIE-MELLON UNIV PITTSBURGH PA ROBOTICS INST, 1983.

[13] A. Sathi, M. S. Fox, and M. Greenberg, "Representation of activity knowledge for project management," *IEEE Transactions on pattern analysis and machine intelligence,* no. 5, pp. 531-552, 1985.

[14] M. S. Fox and M. Gruninger, "Enterprise modeling," *AI magazine,* vol. 19, no. 3, pp. 109-109, 1998.

[15] M. Grüninger, "Using the PSL ontology," in *Handbook on Ontologies*: Springer, 2009, pp. 423-443.

[16] M. S. Fox, "A foundation ontology for global city indicators," *University of Toronto, Toronto, Global Cities Institute,* 2013.

[17] F. G. Fadel, M. S. Fox, and M. Gruninger, "A generic enterprise resource ontology," in *Proceedings of 3rd IEEE Workshop on Enabling Technologies: Infrastructure for Collaborative Enterprises*, 1994: IEEE, pp. 117-128.

[18] T. Bittner and M. Donnelly, "Computational ontologies of parthood, componenthood, and containment," in *International Joint Conference on Artificial Intelligence*, 2005, vol. 19: Citeseer, p. 382.

[19] H. Rijgersberg, M. Van Assem, and J. Top, "Ontology of units of measure and related concepts," *Semantic Web,* vol. 4, no. 1, pp. 3-13, 2013.

[20] I. I. J. I. technology, "Information technology - An upper level ontology for smart city indicators," ISO. [Online]. Available: <https://www.iso.org/standard/72325.html>

[21] S. Cox, A. Cuthbert, R. Lake, and R. Martell, "Geography markup language (GML) 2.0," *URL:* [*http://www*](http://www)*. opengis. net/gml/01-029/GML2. html,* 2001.

[22] C. A. Knoblock and P. Szekely, "Exploiting Semantics for Big Data Integration," *AI Magazine,* vol. 36, no. 1, 2015.

[23] M. Katsumi and M. Fox, "An Ontology-Based Standard for

Transportation Planning," in *To appear in: Formal Ontologies Meet Industry (FOMI)*, Graz, Austria, M. Grüninger and W. Terkaj, Eds., 2019: CEUR.

1. https://github.com/dgarijo/Widoco [↑](#footnote-ref-1)
2. AllegroGraph-generated nD datatype for lat-lon location data [↑](#footnote-ref-2)
3. https://www.w3.org/TR/owl-time/ [↑](#footnote-ref-3)
4. Note: in order to avoid confusion that may result from the use of the "-Process" suffix (e.g. VehicleProcess,OrganizationProcess), we opt instead to use the suffix "PD", i.e. short for "Perdurant". [↑](#footnote-ref-4)
5. http://ontology.eil.utoronto.ca/tove/activity.owl [↑](#footnote-ref-5)
6. http://ontology.eil.utoronto.ca/city-services/city-services.owl# [↑](#footnote-ref-6)
7. om: http://www.ontology-of-units-of-measure.org/resource/om-2/ [↑](#footnote-ref-7)
8. http://ontology.eil.utoronto.ca/GCI/Foundation/GCI-Foundation-v2.owl# [↑](#footnote-ref-8)
9. <http://www.w3.org/ns/ssn/> [↑](#footnote-ref-9)
10. http://www23.statcan.gc.ca/imdb/p3Var.pl?Function=DEC&Id=24101 [↑](#footnote-ref-10)
11. http://schema.org/ [↑](#footnote-ref-11)
12. http://ontology.eil.utoronto.ca/GCI/Shelters/GCI-Shelters.html [↑](#footnote-ref-12)
13. http://ontology.eil.utoronto.ca/tove/organization.html [↑](#footnote-ref-13)
14. http://www.pms.ifi.lmu.de/rewerse-wga1/otn/OTN.owl [↑](#footnote-ref-14)
15. More options may be added as required. This list comes from the options specified in the EMME NCS11. [↑](#footnote-ref-15)
16. Not available online [↑](#footnote-ref-16)
17. http://www.w3.org/2006/time#January [↑](#footnote-ref-17)
18. https://www.w3.org/TR/sparql11-overview/ [↑](#footnote-ref-18)
19. This and subsequent queries may be easily repurposed to retrieve trips with a particular end zone by replacing trip:startLoc with trip:endLoc. [↑](#footnote-ref-19)
20. http://usc-isi-i2.github.io/karma/ [↑](#footnote-ref-20)
21. http://ontology.eil.utoronto.ca/icity/Observations [↑](#footnote-ref-21)
22. http://ontology.eil.utoronto.ca/icity/TransportationSystem [↑](#footnote-ref-22)
23. As defined by the W3C standard for XML Schema Definition Language: https://www.w3.org/TR/xmlschema11-2/#dateTimeStamp [↑](#footnote-ref-23)
24. http://ontology.eil.utoronto.ca/icity/TransportationSystem [↑](#footnote-ref-24)
25. http://ontology.eil.utoronto.ca/icity/OM [↑](#footnote-ref-25)
26. http://ontology.eil.utoronto.ca/icity/Time [↑](#footnote-ref-26)
27. http://usc-isi-i2.github.io/karma/ [↑](#footnote-ref-27)
28. https://github.com/usc-isi-i2/Web-Karma/wiki/Batch-Mode-for-RDF-Generation [↑](#footnote-ref-28)