iCity Ontology Version 1.2 Report

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# Purpose

The purpose of this document is to present the first release of the iCity ontology. This document provides a concrete outline of the concepts defined in the ontology; its purpose is to provide a point of reference to facilitate discussion and feedback on of the ontology, and to facilitate its implementation across the iCity projects and beyond. This initial release focuses on the identification of the classes and properties that will form the ontology. These classes and properties provide a clear indication of the breadth of the scope of the iCity ontology, and are thus a critical first step in the development of the final artifact. Based on this release, we may begin the process of implementation by capturing relevant information in the language defined by the ontology, and thus providing a shared, commonly understood model of the knowledge being used and generated by the various iCity projects.

HTML documentation is maintained for each ontology, automatically generated using Widoco[[1]](#footnote-1).

# Scope

The scope of this document is limited to the identification of the vocabulary within the ontology. More specifically, it is restricted to the identification of vocabulary in the Urban System Ontology; at this stage, it does not capture the application-specific concepts of the individual iCity projects. We provide an initial specification of the classes and relationships (properties) to support formalization in OWL 2 (Grau, et al., 2008). Future versions will expand on the depth of these definitions, providing more detailed semantics in a complementary logical language. This document aims only at conveying the vocabulary currently defined in the iCity ontology, implementation of the ontology shall be addressed in a separate iCity report.

# Outline

The report will begin with an introduction to the role of the ontology within the iCity project. The core concepts pertaining to the characteristics and behaviour of the urban system will then be presented in Section 5. Section 0 identifies directions for future iterations of the ontology; in particular, Section 6.2 outlines top-level concepts required for data collection, simulation, and analysis applications. At the current stage of development, we have not identified any requirements specific to the Visualization application (Theme 3 in the iCity project). It is our understanding that the Theme 3 work will interpret the iCity ontology in order to generate the required visualizations. Should this change in the future, it is likely that an extension to capture the visualization applications will also be required.

# Role of the Ontology

Given that all of the projects within iCity are situated in the urban domain, and therefore it is not surprising to find many common concepts between them. 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 ILUTE and other simulations, 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, and in some cases 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 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 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 as means of 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)[[2]](#footnote-2), created by mapping data from the iCity applications to the agreed-upon terminology defined in the iCity ontology. The architecture for the ontology’s implementation in the context of the iCity project, is illustrated in Figure 1.

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 Architecture

The sections that follow introduce the core ontology required to capture the iCity projects, in particular, to define the urban system. Beyond this, the iCity ontology may be implemented to support specific applications. Examples of this are discussed in further detail in Section 7.

# Summary of Changes from Previous Version

The “iCity-“ prefix was removed from all ontology filenames and IRIs in order to improve readability and convey generality. All other changes are summarized by ontology below.

Activity ontology:

* revised representation such that an activity is a class of occurrences (activities and occurrences are not separate entities); removal of ActivityOccurrence, definition of State instead of StateType.

Transportation Network ontology:

* added Link and LinkPD classes to serve as “containers” for multiple arcs (e.g. vehicle lanes, bicycle lanes, walkways); introduced some additional properties and changed the mode of an Arc from an invariant to variant property.
* Associated Nodes with location information.
* Links and Arcs represent access on some part of the physical infrastructure, which has an associated location. Although Nodes do not represent access in the same way, they are still associated with some physical location. A property was added to specify the *associated* location of a Node. It should be possible to infer which Transportation Complexes (e.g. road segments) meet or contain the node based on the links it is connected to. Future extensions may consider capturing the relationship between the nodes location and the location of the Transportation Complexes accessed by its related links.

Added: iContact.owl Ontology

The notion of addresses is required to represent information about buildings, parking lots, the start and end of trips, and so on. Contact information for individuals and organizations may also be required and captured for some applications.

Added: Calendar/Hours of Operation Ontology:

Beyond the representation of individual timepoints and time intervals, there is often a requirement to reference concepts from a calendar. In particular, the specification of hours of operation (e.g. fora business or transportation network policy) relies on the representation of these concepts, such as the days of the week or times of day. The Calendar Ontology is introduced to define these concepts.

Imported SSN/SOSA Ontology:

Sensor observations are an integral part of ITS operations and research. To capture these sensors and the data they generate, we import the SSN/SOSA ontology [ref].

Units of Measure Ontology:

* Extended and merged with monetary value ontology.
* Updated with new release OM 2.0
* Extend with specializations of quantities, measures, etc, as required by use cases.

Spatial Location ontology:

* Replaced original representation with geoSPARQL terminology, primarily due to it being better supported (geoSPARQL works for simple linked data but also offers the potential for specialized query abilities) and more current.   
  Features have geometry (geo:hasGeometry); geometries can be defined as simple features (points, polygons,…); these geometries can be *serialized* as WKT or GML, special purpose datatypes that allow for, e.g. a series of coordinates. Both serializations support the specification of a reference system, therefore (for now) we do not need to extend OM with NAD83 and WGS84.  
  The representation of the reference system is not ideal as in the current implementation of geoSPARQL it is appended within the same IRI as the coordinate data, (it is also not clear what code is to be used for NAD83). Future revisions should investigate a possible extension to this representation that will capture the reference system in a more convenient way (while still leveraging the capabilities of geoSPARQL).  
  Ideally, in future work we would like to look consider the spatial-location theory in more detail as it geoSPARQL provides a vocabulary and a tool but lacks a complete declarative semantics
* This change impacts many of the other ontologies within iCity (those with spatial information). Each was modified to address this.
* Extended SpatialLoc to include a hasLocation property. This allows us to separate objects from their spatial embodiment as required. Whether an object is related to geosparql:Feature or is a subclass of geosparql:Feature is a foundational ontological decision. In either case, we can describe location of these objects more precisely via the hasGeometry property.

Foundation Ontology: removed

* In the initial design Foundation is imported by all of the domain ontologies, this requires a revision to all of the Urban System ontologies. We observe that this design is not ideal as there may be cases where foundational concepts (e.g. activities or resources) are not used in a particular domain ontology. In such cases, updates to Foundation.owl will result in unnecessary updates to unaffected domain ontologies.  
  This was originally done for convenience, however we observe that it may be more clear and effective to only consider the foundational grouping conceptually, and individually import whichever ontologies are required.
* In version 1.2 of the ontology, we replace all imports of the Foundation ontology only with the ontologies that are used. In some cases, this may be equivalent to importing the Foundation ontology, however in other cases this will be a sub-theory of the Foundation ontology.

Land Use Ontology:

* Defined new subclasses of Parcel based on sample data: TrafficZone, PlanningDistrict, Municipality. It’s unclear what the logical distinction between these classes will be, but they are distinct types of parcels used by the domain experts.
* Introduced additional land use classifications, aligned with lbcs classifications where possible, based on CLUMP and AAFC systems.
* Added TrafficZone subclass of Parcel
* Added population properties for Parcels

PublicTransit Ontology:

* Added specializations of the Activity class: TransitTrip and TransitIncident
* Included some additional properties and added to the definitions of some existing classes
* Imported Transportation System ontology
* Imported Activity ontology

Time Ontology:

* Revised to reuse the new version of OWL-Time (updated via W3C in fall of 2017)

Parking Ontology:

* Based on requirements identified by CUHK use cases, the parking ontology has been extended to capture additional concepts to provide a more detailed picture of existing car parks.

# 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.

To do: include discussion on practices adopted for the reuse of existing ontologies

* Save and re-publish with new IRI to ensure availability and consistency (there may be issues if some ontologies update and do not use Version IRI metdata)
* Entities created for organization: XThing, XObjectProperty, XDataProperty…

## Foundational Ontologies

*~~http://ontology.eil.utoronto.ca/icity/Foundation.owl~~*

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.

### Spatial Location Ontology

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

**Namespace: geo**

To capture generic spatial features, we require concepts of location, but also concepts of geometry in order to describe shapes that are more complex than a single point in space. In addition, we need to be able to describe the spatial relationship between various features (e.g. containment, overlaps). To achieve this, we leverage the GeoSPARQL[[3]](#footnote-3) standard. GeoSPARQL specifies the required vocabulary of spatial relations; it is particularly attractive as it has been published as a standard by the OGC, and in addition it provides specialized functions for querying spatial data according to these relations that are supported by some knowledge base implementations. The Spatial Location Ontology also includes the property hasLocation to capture the relationship between non-spatial objects 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. In theory, GeoSPARQL supports the identification of alternate reference systems, these are captured as IRIs and concatenated with the coordinates. Currently, knowledge base support for translation between these systems is limited.

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

The ontology specifies properties for the topological relationship between spatial objects, among these are:

|  |  |  |
| --- | --- | --- |
| 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 |
| Range | geo:Geometry |
| hasLocation | Range | geo:Feature |
| associatedLocation | Range | geo:Feature |

RCC8 and Egenhofer relations are also defined.



Figure 2: Key classes in geoSPARQL.

|  |  |  |  |
| --- | --- | --- | --- |
| **TYPE** | **SHAPE** | **Geometry Class** | **SYNTAX** |
| **POINT** |  | sf:Point | POINT(longitude latitude) |
| **LINESTRING** |  | sf:LineString | LINESTRING(long1 lat1, long2 lat2, …) |
| **POLYGON** |  | sf:Polygon | POLYGON((long1 lat1, long2 lat2, … , long1 lat1)) |
| **POLYGON (WITH HOLE)** |  | sf:Polygon | POLYGON((long1 lat1, long2 lat2, … , long1 lat1), (longA latA, longB latB, …, longA latA)) |

Figure 3: An example of some basic shape encodings in WKT, from (Kolas & Battle, 2012).

To capture geometries as RDF literals, they are given the geo:WktLiteral datatype, for example: "POINT(-77.03524 38.889468)"^^geo-sf:wktLiteral.

ex:Monument1 a ex:Monument;

rdfs:label "Washington Monument";

geo:hasGeometry ex:Point1 .

ex:Point1 a geo:Point;

geo:asWKT "POINT(-77.03524 38.889468)"^^geo-sf:WktLiteral.

Ex:Park1 a ex:Park;

rdfs:label "Example Park";

geo:hasGeometry ex:Polygon1 .

ex:Polygon1 a geo:Polygon;

geo:asWKT "POLYGON((-77.05 38.87, -77.02 38.87, -77.02 38.9, -77.05 38.9, 77.05 38.87))"^^geo-sf:WktLiteral.

Figure 4: An example encoding of geospatial information for the Washington Monument, from (Kolas & Battle, 2012).

**Reused Ontologies:**

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

### Time Ontology

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

**Namespace: time**

* Temporal Entity: A Temporal Entity may refer to an instant or an interval in time.  
  A Temporal Entity may be described as being **before** or **after** some other Temporal Entity(s).  
  A Temporal Entity has a **beginning** and **ending** time Instant.  
  A Temporal Entity has a **duration**.
* Instant  
  An Instant may be **inside**some Interval.
* Interval  
  An Interval may be described as **before**, **meets, overlaps, starts, during, finishes, equals** some other Interval(s).

|  |  |  |
| --- | --- | --- |
| 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:inXSDDateTime | max 1 xsd:DateTime |
| time:Interval | subClassOf | time:TemporalEntity |
| time:before | only time:Interval |
| 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 |
| TimePeriod | subClassOf | time:DateTimeDescription |
| CalendarPeriod | subClassOf | time:DateTimeDescription |

**Update:** Note, version 1.1 updated to reflect revision to owl-time released as a W3C recommendation in October 2017.

**Reused Ontologies:**

* time: OWL-Time Ontology[[4]](#footnote-4) originally presented by (Hobbs & Pan, 2004)

### Change Ontology

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

**Namespace: iCity-Change**

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. An approach to representing changing properties, or *fluents*,that leverages the 4-dimensionalist perspective was proposed by (Welty, Fikes, & Makarios, 2006). We adopt a similar approach, , based on the design pattern presented by (ref WOP) 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.

* TimeVaryingConcept: 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 (Krieger, 2008), we view TimeVaryingConcepts as perdurants (things that occur over time, i.e. processes).  
  A TimeVaryingConcept has **Manifestations** that demonstrate their changing (variant) properties over time.  
  Different types (**subclasses**) of TimeVaryingConcept may be defined based on the Manifestations that are part of them. For example, VehiclePD[[5]](#footnote-5)s have manifestations that are Vehicles.  
  A TimeVaryingConcept **exists at** some Interval.  
  The class of TimeVaryingConcepts is equivalent to the class of things that have some Manifestations - and *only* Manifestations - in the hasManifestation relation.
* Manifestation: A Manifestation of some TimeVaryingConcept at a particular point/interval in time.  
  A Manifestation **exists at** some Instant (or possibly Interval).  
  The class of Manifestations is equivalent to the class of things that are manifestations of some TimeVaryingConcept - and *only* time varying concepts - in the manifestationOf relation.

|  |  |  |
| --- | --- | --- |
| 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 |

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

**Reused Ontologies:**

* iCity-Time

### Activity Ontology

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

**Namespace: activity**

* Activity: An Activity describes something that occurs in the domain.  
  An Activity may be further defined by **(decomposed into) Subactivities**.  
  An Activity may have **precondition and/or effect** States.  
  An Activity may be **enabled by or cause** some State~~s~~. An enabling of 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.   
  In other words, the state may not be required directly before, or cause directly after the activity, but by some more specialized sub-activity.  
  An Activity **occurs at** some point in time and space.  
  An Activity takes place **during some interval**, and so **has** some **duration**.  
  An Activity may have some Manifestations that participate in it.  
  An Activity may **occur before** some other Activity.
* State: a state refers to a class of manifestations. 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 note on complex states:**Say that a shopping activity, Activity-Shop, requires both the state of a vehicle having at least 30L of gas in the tank (let's call this state VehicleW30LGas), but also some state type wherein the mall is open, (we'll call this state OpenMall). Each state type would first be defined separately. This precondition could bet stated as:

precondition(VehicleW30LGas,Activity-Shop) AND precondition(OpenMall,Activity-Shop)

were the preconditions required disjunctively, we could state:

precondition(VehicleW30LGas,Activity-Shop) OR precondition(OpenMall,Activity-Shop)

However, in large and complex domains, there will be cases in which the above approach is undesirable. In particular, due to the complexity of the description that results as the state type becomes more detailed. In many cases it will be more natural and convenient to be able to refer to a single, aggregate state. We therefore extend the representation of States to capture aggregation, adopting the following approach used in the description of state trees in TOVE by (Fox, Chionglo, & Fadel, 1993).

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.

NonTerminalState(x) v TerminalState(x) = State(x)

A state type cannot be both non-terminal and terminal.

*TerminalState disjointWith NonTerminalState*

* A terminal state has no substates (cannot be decomposed). 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.

ConjunctiveStateType(x) v DisjunctiveStateType(x) = NonTerminalStateType(x)

A state cannot be both conjunctive and disjunctive.

*ConjunctiveStateType disjointWith DisjunctiveStateType*

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, *decomp\_of* 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.

decomp\_of(x,y) -> substate(x,y)

**A note on activity ordering:** Although we are unable to fully define the semantics, some notion of an ordering on activity occurrences must be captured in some cases. To address this, we introduce the properties: “occursBefore” and “occursDirectlyBefore” in the Activity ontology.  
An activity occursBefore another if its endOf instant is before the beginOf instant of the other activity; the occursBefore relation is transitive. An activity occursDirectlyBefore another if it occursAt an interval that meets the interval of the other activity. We cannot define this semantics in OWL, though it would be supported by an extension with rules. In OWL, we are only able to comment on the semantics, and define occursBefore as transitive and occursDirectlyBefore as a subproperty of occursBefore.

|  |  |  |
| --- | --- | --- |
| 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 |

|  |  |  |
| --- | --- | --- |
| Property | Characteristic | Value (if applicable) |
| hasSubactivity | Transitive | - |
| hasPrecondition | Domains | Activity |
| Ranges | State |
| ~~enabledBy~~ | ~~subPropertyOf~~ | ~~hasPrecondition~~ |
| hasPrecondition | subPropertyOf | enabledBy |
| hasEffect | Domains | Activity |
| Ranges | State |
| ~~causes~~ | ~~subPropertyOf~~ | ~~effectOf~~ |
| hasEffect | subPropertyOf | causedBy |
| occursAt | Domains | Activity |
| Ranges | time:TemporalEntity |
| hasParticipant | Domains | Activity |
| Ranges | change:Manifestation |
| participatesIn | inverseOf | hasParticipant |
| preconditionOf | inverseOf | hasPrecondition |
| enables | inverseOf | enabledBy |
| effectOf | inverseOf | hasEffect |
| causedBy | inverseOf | causes |
| achievedAt | Domains | State |
| Ranges | time:TemporalEntity |
| superPropertyOf | inverse(preconditionOf) o beginOf |
| superPropertyOf | inverse(effectOf) o endOf |
| superPropertyOf | inverse (hasDecomp) o conjunctiveAchievedAt o during |
| hasDecomp | Domains | State |
| Ranges | State |
| subPropertyOf | hasSubstate |
| hasSubstate | Domains | State |
| Ranges | State |
| ~~subPropertyOf~~ | ~~hasDecomp~~ |
| Transititve |  |
| beginOf | Domains | Activity |
| Ranges | time:Instant |
| superPropertyOf | occursAt o time:hasBeginning |
| endOf | Domains | Activity |
| Ranges | time:Instant |
| superPropertyOf | occursAt o time:hasEnd |
| terminalAchievedAt | subPropertyOf | achievedAt |
| subPropertyOf[[6]](#footnote-6) | existsAt |
| Domains | TerminalState |
| disjunctiveAchievedAt | subPropertyOf | achievedAt |
| superPropertyOf | hasDecomp o achievedAt |
| Domains | DisjunctiveState |
| conjunctiveAchievedAt | subPropertyOf | achievedAt |
| Domains | ConjunctiveState |
| occursBefore | range | Activity |
| domain | Activity |
| transitive |  |
| occursDirectlyBefore | subPropertyOf | occursBefore |

**Reused Ontologies:**

* iCity-Change
* iCity-SpatialLocation

### Resource Ontology

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

**Namespace: resource**

This 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 (Fadel, Fox, & Gruninger, 1994) 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*". The definition of a resource is dependent on its participation in an activity, so the Resource ontology is in fact an extension of the Activity ontology. In this sense, Resources are a class of manifestations, so that rather than have a specialized Resource-perdurant (PD) class, a Resource is a manifestation of some *other* perdurant class in the ontology. For example, an instance of a Vehicle that is a manifestation of some VehiclePD may also be an instance of a resource, whereas some other instance of a Vehicle that is some later manifestation of the same VehiclePD may not be a Resource, or it may be a *different* Resource.

* A Resource is a generic representation of some Thing that can be "used" in an Activity.  
  A Resource may have some Location, amount or availability, according to the definition of the Manifestation or TimeVaryingEntity.  
  A Resource must be **classified as** some Resource Type.  
  A Resource may **participate in** some Activity.  
  A *specific* Resource may be **used in** or **consumed in** some activity. As with the precondition and effect properties defined in the Activity Ontology, these relationships are specific to a particular activity; more general properties may be defined (analogous to enables and causes) should this be required.   
  A Resource may have some **associated location**.   
  A Resource may have some **owner**.
* A Resource may *either* be a Divisible Resource or a Non-Divisible Resource. On the surface this may seem counterintuitive -- consider a vehicle being used as a non-divisible resource for transportation, and then later as a divisible resource for scrap metal. However, 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).
* A Resource Type describes a class of Resources, (intuitively similar to the State Type class).  
  A Resource Type may be **usedBy** or **consumedBy** 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.

usedBy and consumedBy are subproperties of preconditionOf.

|  |  |  |
| --- | --- | --- |
| 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 |

|  |  |  |
| --- | --- | --- |
| Property | Characteristic | Value (if applicable) |
| usedIn | Functional | - |
| consumedIn | Functional | - |
| usedBy | subPropertyOf | preconditionOf |
| consumedBy | subPropertyOf | preconditionOf |
| hasOwner | domain | Resource |
| hasAssociatedLocation | domain | Resource |

**Reused Ontologies:**

* iCity-Activity

### Mereology Ontology

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

**Namespace: mereology**

The parthood relationship a fundamental construct that we use to describe the world. While sometimes conflated, there are distinctly different types of "parthood". The mereology ontology focuses on identifying these differences and making them explicit. In this ontology, we identify the following different types of parthood: proper-part-of, component-of, and contained-in. The distinction between these types of parthood 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.

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 [ref Bittner & Donnely] 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. We therefore omit 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.

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 provided in extensions (in or beyond the OWL representation). In addition to the aforementioned work by [ref Bittner & Donnelly], various approaches to the extension and definition of these mereological relationships in OWL have been proposed that might be used to extend the ontology presented here, such as in W3C note [https://www.w3.org/2001/sw/BestPractices/OEP/SimplePartWhole/], and also in top-level ontologies such as [ref BFO].

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| ~~Thing~~ | ~~subClassOf~~ | ~~hasProperPart exactly 0 Thing or hasProperPart min 2 Thing~~ |

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

**Reused Ontologies:**

* None directly, but reused concepts as defined by (Bittner & Donnelly, 2005), however theirs is not an officially published ontology.

**Future work:**

* Extend to capture mereotopological relations
* Extend with a first-order formalization or mereology

### Ontology of Units of Measure

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

**Namespace: om**

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. metres).

In the context of the iCity ontology, quantities, units, and/or measures that are defined with domain-specific concepts (e.g. vehicles, lanes) are defined by reusing and extending the units of measure ontology in the relevant modules.

* A quantity has some measured value
* A measured value (om:Measure) is associated with a unit of measure
* There are many types (subclasses) of units of measure, such as length, mass, speed, and currency.

om:Quantity

om:Measure

om:Unit\_of\_measure

om:hasValue

om:unit\_of\_measure\_or\_measurement\_scale

om:numerical\_value



Figure 5: Representation of populations as reused from the GCI Ontology.

In order to represent populations, we reuse the following classes from the GCI-Foundation ontology: ~~govstat:Population,~~ 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 6: 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 to core concepts of Population Size, Population Measure, Cardinality Unit, and Population, as depicted in Figure 5.

Capacity and its associated quantity and measure are defined similar to population.



Figure 6: Specialization of populations.

**Revisions:**

* Updated to OM2.0
* OM:MonetaryValue a om:Unit\_of\_measure
* Monetary Value: Monetary Values may be attributed to things such as the purchase of a dwelling, or the salary of some Job.  
  A Monetary Value has a **dollar value** relative to a particular **date** (year).  
  A Monetary Value has some associated **currency**.
* Population (via GCI): The population class is defined as a subclass of om:Quantity. It represents the quantities of counted sets. Various subclasses of Population will be defined as required, e.g. Resident\_Population, Vehicle\_Population, etc. A population has a measure (Population\_measure) in some cardinality unit
* Population\_measure
* Population\_unit\_of\_measure
* Cardinality\_unit
* Capacity: subclass of Quantity and hasUnit CardinalityUnit
* CapacityRate, e.g.
  + OM:lanecap a om:Unit\_of\_measure (vehicles/hour)
* Added quanitites: RoadOccupancy, VehicleVolume, MeanTravelSpeed
* Added aggregateOver and aggregateOf properties in order to defined aggregate quantities in greater detail

**Future work:**

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). In this approach, we are considering “degrees relative to a particular datum” as a kind of measure. In any case, it is important that we are able to distinguish between different position systems as latitudinal and longitudinal values cannot be assumed to use the same sort of system. 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.

|  |  |  |
| --- | --- | --- |
| 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 |

**Reused Ontologies:**

* ~~om: Ontology of Units of Measure[[7]](#footnote-7)~~
* om-2: Ontology of Units of Measure 2.0[[8]](#footnote-8)
* gci: Global City Indicators Foundation Ontology[[9]](#footnote-9)

### ~~Monetary Value Ontology~~

*~~http://ontology.eil.utoronto.ca/icity/MonetaryValue.owl~~*

**~~Namespace: monetary~~**

* Removed. Monetary Value now integrated with Units of Measure Ontology

### Recurring events ontology

A specification of recurring events, in particular those that are defined according to calendar dates (e.g. every Monday, every March), is required in order to capture information regarding hours of operation, road restrictions, restrictions on parking policies, etc. The design of this ontology was inspired by previous work on an ontology for city services[[10]](#footnote-10) for the Global City Indicator Ontology [ref]. The city-services definition of ServiceDeliveryEvent incorporates and references the representation of recurring events from <http://www.vertabelo.com/blog/technical-articles/again-and-again-managing-recurring-events-in-a-data-model>, however there are issues in the formalization that prevent its direct reuse:

* Specific to service events: we need a generic representation of repeating, calendar events. The notion of exceptions is specific to a kind of event (such as service delivery).
* Use of Date-time interval: owltime:DateTimeInterval defines a specific interval in time, therefore a recurring event occurs at multiple DateTimeIntervals, not one. For example, there is the interval 08:00-14:00 on August 8, 2018, and then there is *another* interval 08:-14:00 on August 9, 2018.
* Monthly events are underspecified. A monthly event repeats on a given day of the month (e.g. the 1st day of each month). There is the related notion of a repeating event that occurs with respect to some day of the week, e.g. an event occurs on the second Tuesday of each month, however this is distinct from the monthly recurring events defined here. This type of recurrence requires a specialized approach to address (e.g. accounting for week numbers) and is out of the scope of the current representation. The related concept of a “separation count” (as described in the referenced data model) that is required to define repetition such as biweekly or bi-monthly occurrences is also not currently required or addressed here.
* Missing the notion of a yearly event: a yearly event occurs on a specific day of some month.

We propose the following approach to representing recurring events, which may be extended for specializations of recurring events such as calendar dates and service events. This approach is based on the city services work, but revised to eliminate the identified issues and apply to recurring events in general. In addition, it should be noted that daily, weekly, and monthly recurring events (and their related properties) are defined, however the ontology may be extended with similar definitions of other sorts of recurring events, as required.

* Recurring events are defined based on the regular interval at which they occur; this is captures using some combination of the hasTime, dayOfWeek, hasMonth, and dayOfMonth properties. Using these properties, ontology defines the following specializations of the RecurringEvent class. Other subclasses may be defined similarly, as required.
  + A DailyRecurringEvent occurs at the same time every day. Therefore, it has exactly one associated time – the start time. No associated time indicates that there is no commitment to a recurring start time for the event. A DailyEvent does not necessarily have a recurring endtime (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.
  + 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).
* In order to define these calendar specifications (as well as to capture other sorts of recurring events), the following properties are required:
  + hasMonth: ranges over the Month class, which is defined via enumeration based on the calendar system in used
  + dayOfWeek: ranges over the DayOfWeek class, which is defined via enumeration
  + dayOfMonth: a data property to describe the day position in the calendar system. This property has an undefined range, although it could be restricted to positive integers, possible within a specific range.
  + startTime: ranges over the xsd:time datatype
* Properties to indicate the (recurring) end of a recurring activity may also be defined (e.g. endtime, endDayOfWeek), but are not required in the definition of the classes:
  + endMonth
  + endDayOfWeek
  + endDayOfMonth
  + endTime
* Optionally, timepoints to indicate when an event begins and ends recurring may be defined. For example, some weekly event may only recur during a particular year. This may be captured with the following properties:
  + beginsRecurring
  + endsRecurring
* 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.
* An instance of a recurring event represents a class of activities (e.g., all of the occurrences of a Tuesday, all of the occurrences of the weekly waste pickup). Essentially, this is the activity – occurrence distinction that is made by other approaches; a RecurringEvent *hasOccurrence* some Activity. Exactly which activities (and at what date and time) are specified by the definition of the recurring event. This relationship should be defined as an optional property for a recurring event. The Recurring Event ontology should import the Activity ontology, as the concept of an activity is central to the notion of a recurring event: the activity is the thing that is recurring.
* As with an Activity, a RecurringEvent may be decomposed into RecurringEvents at a greater level of detail. This decomposition may be specified with the hasSubRecurringEvent property.

Although intuitively similar, it should be noted that calendar concepts are distinct from recurring events. As discussed in earlier work by [Gruninger et al. KR paper on dates & durations], the semantics of calendar dates – concepts such as “Monday”, or “January” – can be interpreted using a theory of activities. For example, Monday may be described as an event that recurs every 7 days, and has a duration of 24 hours.

It is important to note that RecurringEvents 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.

|  |  |  |
| --- | --- | --- |
| 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 |



**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.

## Sensors Ontology

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

**Namespace: ssn**

The sensors ontology reuses the SSN (Semantic Sensor Network) ontology directly from <http://www.w3.org/ns/ssn/>. SOSA is the foundation for the SSN (Semantic Sensor Network) and provides the scope required for this application, however it does not specify any definitions for the terms, therefore we have opted to reuse the SSN Ontology. The SSN Ontology is a W3C recommendation that has been widely adopted to represent sensors and their observations. The relevant terms are highlighted here.

* Sensor: A Sensor is a device that makes some observation and may be triggered by some stimulus.
* Observation: 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 an observation.

Note that 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. For the domain of transportation sensors, we opt to define instances of ssn:Property at a general level; this will enable 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.

|  |  |  |
| --- | --- | --- |
| Object | Property | Value |
| Sensor | sosa:madeObservation | only sosa:Observation |
| sosa:observes | only sosa:ObservableProperty |
| ssn:detects | only ssn:Stimulus |
| 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 |
| ObservableProperty | inverse ('is proxy for') | only ssn:Stimulus |
| inverse ('observed property') | only sosa:Observation |
| sosa:'is observed by' | only sosa:Sensor |
| FeatureOfInterest | ssn:'has property' | min 1 owl:Thing and ssn:Property |
| Result | sosa:'is result of' | min 1 owl:Thing |

****

Figure 7: Example of an extension of the sensor ontology in the transportation system ontology.

**Reused Ontologies:**

* SSN
* SOSA

**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.

## 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

To do: import and extend as required for Person, Building, Organization(?) and Parking ontologies

|  |  |  |
| --- | --- | --- |
| 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.”[[11]](#footnote-11) 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[[12]](#footnote-12) (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 make 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 |
| mer:hasPart | only 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 |
| mer:hasPart | only person:Person |
| DwellingUnitPD | subclassOf | change:TimeVaryingConcept |
| 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 |
| 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 |

**Reused Ontologies:**

* schema.org
* gci: GCI-Shelter Ontology[[13]](#footnote-13)
* 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 |

**Reused Ontologies:**

* tove: The TOVE Organization ontology[[14]](#footnote-14), 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 has a market **value**.  
  A Building **has** some **Location**.  
  A Building contains one or many units.
* BuildingUnit: A BuildingUnit has a size (square footage, number of rooms)  
  A BuildingUnit may contain some Facilities, e.g. kitchen, bath.(Note that contain is distinct from the notion of including amenities, 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 |
| mereology:contains | 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 | 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 | only Facility |

**Reused Ontologies:**

* ~~iCity-Foundation~~
* Change
* Units of measure
* Mereology
* Spatial location

## 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 Infrastructure (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).

In this representation Nodes do not access the Transportation Infrastructure nor are they part of it in any way. 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[[15]](#footnote-15)) 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.

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 8: 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 |
| mereology:hasComponent | 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 |
| mereology:componentOf | 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 |
| mereology:componentOf | only Network (variant or invariant?) |
| 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 |
| 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 |
| mereology:componentOf | 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 | exactly 1 Municipality (?) tbd – where should municipalities be defined |
| 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:SpatialFeature |
| Mode | equivalentClass[[16]](#footnote-16) | {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 |
| 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.

### 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 |
| 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 |
| mereology:hasProperPart | 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 |
| (inverse hasProperPart) | 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 {0})) |

**Ontologies Reused:**

* Foundational
* 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.owl*

**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[[17]](#footnote-17) 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. For example, the relationship between its population and trips taken and vehicles used. 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)

# 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 are currently being 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 the IT-SoS Framework

The IT-SoS framework proposed by [ref Elshenawy] enables a solution for the design of transportation applications capable of dynamically executing services based on a given context. Using the framework, services can easily be added and integrated as part of applications as appropriate.

[more detail/diagram]

Ontologies play a key role in this framework. Here, we focus on the interface between the iCity ontology and the rest of the system. This interface must be well-understood and clearly defined in order to implement this framework in the context of the iCity project. In the following sections, we outline the functional requirements and describe the design of an interface to satisfy these requirements.

### Ontology Interface: Functional Requirements

More detail on the complete framework can be found in [ref]. The role of the ontology and its interface with the rest of the system is specified with the following requirements (revised from the requirements identified in [ref thesis]):

* Ontology representation of services (WFS)
  + To support discovery
  + To support composition
* Ontology representation of applications
  + To enable (context-based) composition

The above requirements are formalized and elaborated with the following use cases:

1. A user formalizes the relevant semantics of a new WFS service for the ArcGIS server, to be part of the IT-SoS framework.
2. Given a process definition and some contextual information, the system identifies the information requirements required to perform it.
3. Given an information requirement, identify which services are capable of providing the required information.

|  |  |  |
| --- | --- | --- |
| **Use Case 1** | A user formalizes the relevant semantics of a new WFS service for the ArcGIS server. | |
| **Goal in Context** | Users create new WFS services for the ArcGIS server, to be incorporated into the IT-SoS framework. | |
| **Preconditions** | WFS service designed correctly. | |
| **Success End** | WFS service created, formalized with metadata. | |
| **Failure End** | WFS service not created and/or metadata not captured | |
| **Primary &**  **Secondary Actors** | Primary: user | |
| **Trigger** | New WFS service created. | |
| **Description** | **Step** | **Action** |
| 1. | User creates new WFS service. |
| 2. | User defines additional required metadata for service. |
| 3. | User submits the service to IT-SoS. |
| 4. | Service description formalized in the language of the ontology. |
| **Extensions** | **Step** | **Branching Actions** |
|  |  |
| **Variations** | **Step** | **Branching Actions** |
| 2a. | No sources are capable of supplying all of the required data  2a1. System or user notified query is unknown... |
| **Related Information** |  | |
| **Priority** | High | |
| **Performance** | TBD | |
| **Frequency** | High | |
| **Open Issues** | What metadata is required? | |

|  |  |  |
| --- | --- | --- |
| **Use Case 2** | Given a process definition and some contextual information, the system identifies the information requirements required to perform it. | |
| **Goal in Context** | In order to perform automatic and dynamic composition of applications, the system must be able to determine what information is required in a particular context. | |
| **Preconditions** | Application process correctly formalized.  Contextual information available | |
| **Success End** | All and only the correct information requirements are identified. | |
| **Failure End** | Information requirements not (fully or exclusively) identified. | |
| **Primary &**  **Secondary Actors** | Primary: application composer | |
| **Trigger** | Application execution. | |
| **Description** | **Step** | **Action** |
| 1. | Application process selected. |
| 2. | Contextual information input. |
| 3. | Information requirements to support application process generated. |
| **Extensions** | **Step** | **Branching Actions** |
|  |  |
| **Variations** | **Step** | **Branching Actions** |
|  |  |
| **Related Information** |  | |
| **Priority** | High | |
| **Performance** | TBD | |
| **Frequency** | High | |
| **Open Issues** |  | |

|  |  |  |
| --- | --- | --- |
| **Use Case 3** | Given an information requirement, the system identifies which services are capable of providing the required information. | |
| **Goal in Context** | In order to perform automatic and dynamic composition of applications, the system must be able to determine which services are capable of satisfying which information requirements. | |
| **Preconditions** | WFS services correctly formalized.  Application process correctly formalized. | |
| **Success End** | All and only the required services are identified. | |
| **Failure End** | Required services not (fully or exclusively) identified. | |
| **Primary &**  **Secondary Actors** | Primary: application composer | |
| **Trigger** | Application execution. | |
| **Description** | **Step** | **Action** |
| 1. | User provides a set of information requirements. |
| 2. | WFS services capable of satisfying the information requirements are identified. |
| **Extensions** | **Step** | **Branching Actions** |
|  |  |
| **Variations** | **Step** | **Branching Actions** |
|  |  |
| **Related Information** |  | |
| **Priority** | High | |
| **Performance** | TBD | |
| **Frequency** | High | |
| **Open Issues** |  | |

### System Design

Illustrated in Figure 8, the creation of ITS applications using the IT-SoS framework is supported within the iCity project with three key components: the WFS creator, which supports the definition of individual services; the Application creator, which supports the definition of applications as processes; and the Application engine, which supports the automated composition and execution of services.

*The WFS Creator* (illustrated in Figure 9) supports the creation of a WFS service from some existing data source. The WFS is created and published to the ArcGIS server. Additional metadata is also collected during the creation process in order to achieve a complete description of the service (e.g. the equipment it uses, the information it provides). This description is mapped into a formal representation using terminology defined in the iCity ontology, and stored in a triplestore which may be accessed as required by other components.

*The Application Creator* component supports the definition of ITS applications – in particular the context-specific decomposition of the underlying process (including accounting for possible dependencies between sub-processes). As with the creation of WFS services, each application definition shall be mapped into an ontology-based representation in the IT-SoS triplestore.

*The iCity ITS Application Engine* (illustrated in Figure 10) is responsible for building and executing ITS applications on-the-fly, according to the definitions specified by the ITS Application Creator.

In the context of the iCity project, each application shall be accessible (buildable and executable) via the iCity dashboard. Based on the selected application and additional contextual information (supplied by the dashboard), the engine queries the triplestore for the appropriate composition in order to determine how the application shall be built. The resulting composition then serves as input for the execution engine, which combines the WGS services from the ArcGIS server in accordance with the prescribed composition in order to execute the application. Since all of the WFS services are represented using the iCity ontology, information between services may be combined easily, using the ontology as the interlingua.



Figure 9: Ontology-focused view of the iCity implementation of the IT-SoS framework.



Figure 10: Illustration of the key components within the WFS Creator.



Figure 11: Illustration of the key components within the ITS Application Engine.

### Ontology Design: Required Extensions

The iCity ontology must be extended in order to capture WFS and their possible compositions. This will be approached by formalizing some sample application definitions and compositions in order to guide the metadata that will be required to support the system’s functionality.

### Next Steps

The next steps toward implementation of this application will be to clearly define the required, ontology-based representation of applications and services within the system. This will be incorporated into a workflow that will become part of the system’s processes to add applications and services. In this way, the ontology interface to the IT-SoS system will be baked-in to the creation process, requiring no additional overhead on the part of the user. The system shall be implemented to take advantage of the ontology-based representation in order to support the automated, intelligent composition of applications as envisioned by the IT-SoS framework.

## 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 8.2.2.

# Future Work

The iCity Ontology, presented in the previous section, has been classified with the Hermit reasoner in Protegé 5.1[[18]](#footnote-18) and shown to be consistent. An initial, informal evaluation has been performed through a review of its contents with iCity project members serving as domain experts. Future iterations shall be informed by and evaluated against a more precisely defined series of competency questions to be elicited from the iCity project team.

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.

## Extensions to the Urban System Ontology

In developing a richer semantics for the iCity concepts, we will also look to identify more detailed connections between them. This will serve to facilitate shareability between the various projects and domains within iCity. Consider for example, the identification of relationship between common property types, such as hasId, memberOf. While there is likely a shared semantics between these relations in, for example the Person/Family and the Organization ontology, in this initial release, we opt to maintain a distinction between these relations (through specialized names, e.g. personId). Future work should, if required, investigate and make explicit exactly what the relationship is.

In a similar vein, future work will also look to integration of the iCity ontology with other existing vocabularies, which may provide opportunities to improve its shareability. For example, in the design of the iCity ontology we identified some vocabularies that were not directly reusable, (specified as XML schemas, for example), however based on their applications, it might be advantageous to incorporate the representations in some way. For example, GTFS [[19]](#footnote-19), the format used by Google for travel information.

## 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 8.



Figure 12: 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

**Related projects: 1.2, 1.3, 2.1, 2.2, 2.3**

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

**Related projects: 2.2, 2.3, 2.4**

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.

### Analysis of Urban Systems

**Related projects: Project 1.2, 2.1, 2.2, 2.3, 2.4**

Similar to the previous section, capturing the various analysis applications may be seen as a sort of experiment management. We must capture the concepts of analysis input, output, as well as the analysis itself: in other words, how is the output determined from the input? The following concepts may be required for the Analysis extension:

* Analysis: A set of rules or criteria applied to some Analysis Input to obtain some Analysis Output.  
  An Analysis may take only certain class(es) of instances as Input.  
  An Analysis will output only certain class(es) of instances as Output.
* Analysis Input: An Analysis Input is input for some Analysis.
* Analysis Output: An Analysis Output is output from some Analysis.

### Visualization of Urban Systems

**Related projects: All of Theme 3**

The concepts defined in the iCity ontology (and the data they define) shall be interpreted for visual renderings; to-date no additional requirements have been 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 existing, external 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.

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# 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. https://github.com/dgarijo/Widoco [↑](#footnote-ref-1)
2. Note that the data may not in fact be stored in the triple-store, but maintained in the application's own database, with mappings from the ontology to the database performed on-the-fly, as required. [↑](#footnote-ref-2)
3. http://www.opengeospatial.org/standards/geosparql [↑](#footnote-ref-3)
4. https://www.w3.org/TR/owl-time/ [↑](#footnote-ref-4)
5. 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-5)
6. equivalent property? [↑](#footnote-ref-6)
7. om:http://www.wurvoc.org/vocabularies/om-1.6/ [↑](#footnote-ref-7)
8. om: http://www.ontology-of-units-of-measure.org/resource/om-2/ [↑](#footnote-ref-8)
9. http://ontology.eil.utoronto.ca/GCI/Foundation/GCI-Foundation-v2.owl# [↑](#footnote-ref-9)
10. http://ontology.eil.utoronto.ca/city-services/city-services.owl# [↑](#footnote-ref-10)
11. http://www23.statcan.gc.ca/imdb/p3Var.pl?Function=DEC&Id=24101 [↑](#footnote-ref-11)
12. http://schema.org/ [↑](#footnote-ref-12)
13. http://ontology.eil.utoronto.ca/GCI/Shelters/GCI-Shelters.html [↑](#footnote-ref-13)
14. http://ontology.eil.utoronto.ca/tove/organization.html [↑](#footnote-ref-14)
15. http://www.pms.ifi.lmu.de/rewerse-wga1/otn/OTN.owl [↑](#footnote-ref-15)
16. More options may be added as required. This list comes from the options specified in the EMME NCS11. [↑](#footnote-ref-16)
17. Not available online [↑](#footnote-ref-17)
18. http://protege.stanford.edu/ [↑](#footnote-ref-18)
19. https://developers.google.com/transit/gtfs/ [↑](#footnote-ref-19)