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Review

Ontologies for transportation research: A survey

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ABSTRACT

Transportation research relies heavily on a variety of data. From sensors to surveys, data supports day-to-day operations as well as long-term planning and decision-making. The challenges that arise due to the volume and variety of data that are found in transportation research can be effectively addressed by ontologies. This opportunity has already been recognized – there are a number of existing transportation ontologies, however the relationship between them is unclear. The goal of this work is to provide an overview of the opportunities for ontologies in transportation research and operation, and to present a survey of existing transportation ontologies to serve two purposes: (1) to provide a resource for the transportation research community to aid in understanding (and potentially selecting between) existing transportation ontologies; and (2) to identify future work for the development of transportation ontologies, by identifying areas that may be lacking.

1. Introduction

Ontologies provide a means of knowledge representation; they capture a domain of interest by formally defining the relevant concepts in the domain, and the relationships between these concepts. The transportation domain stands to benefit considerably from the application of ontologies. Transportation data are varied and complex; they come from different organizations, sensors, surveys, and other means of data collection. The development of "Smart Cities", as well as more traditional applications such as research and planning face the challenge of how to integrate data from multiple, unrelated sources where the semantics of the data are imprecise, ambiguous and overlapping. This is especially true in a world where more and more data being used is being openly published on the Internet. Early successes in data "mash-ups" relied upon an independence assumption, where unrelated data sources were linked based solely on geospatial location, or a unique identifier for a person or organization. More sophisticated analytics projects that require the combination of datasets with overlapping semantics entail a significant effort to transform data into something useable. It has become increasingly clear that achieving interoperability among separate datasets requires an attention to the semantics of the underlying attributes and their values. An initial literature review reveals a number of existing transportation ontologies, however the relationship between them is unclear.

The goal of this work is to present a survey of transportation ontologies to serve two purposes: (1) to provide a resource for the transportation research community, to aid in understanding (and potentially selecting between) existing transportation ontologies; and (2) to identify future work for the development of transportation ontologies, by identifying areas that may be lacking. This overview is also intended to serve as an introduction to the application of ontologies and the opportunities they provide for transportation research and management. While there also exist ontologies that define concepts that are foundational within the transportation domain such as time and space, as well as closely related concepts in urban studies such as population and land use, such ontologies are out of the scope of this survey. Here, the focus is restricted to ontologies designed to capture transportation: its

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0968-090X/

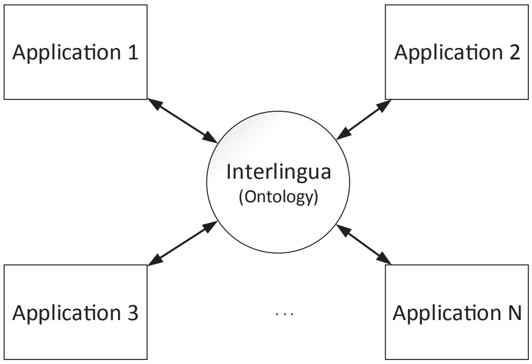

Fig. 1. Ontology as an Interlingua.

systems, infrastructure, and activities.

We begin by providing some background on the ways in which ontologies may be beneficial for the transportation research community. We then consider the cumulative scope of the identified ontologies; this serves as the basis for a comparison amongst the ontologies and also provides an indication of the scope of concepts that currently define the transportation domain. Following this we present an overview of the criteria that the ontologies will be assessed against for a more detailed comparison, before presenting and reflecting on the results.

2. Background

To motivate the relevance of this survey, a brief introduction to ontologies and the Semantic Web is necessary. We then discuss the value of ontologies, specifically for transportation research.

2.1. Ontologies: What & Why?

The most widely used definition of an ontology was presented by (Gruber, 1993) and states simply: *"An ontology is an explicit specification of a conceptualization"*. In the literature, there exist a range of artefacts that are identified as ontologies, from basic glossaries to formal ontologies specified in highly expressive logics. For the purposes of this discussion the term ontology will refer only to formal ontologies with explicitly defined semantics. This semantics can be transcribed into machine-readable languages; as a result, ontologies are able to support the various knowledge management and reasoning services described below.

Integration: precisely defined concepts provide a sort of *interlingua* (illustrated in Fig. 1) that applications can use to share and exchange information. For example, in one system a vehicle may refer to a personal, household vehicle, whereas in a transit application a vehicle may refer to a bus or streetcar. The ontology provides a common language to both distinguish and relate these concepts between the applications. This integration serves to support what is referred to as *semantic interoperability* between applications. Semantic interoperability exists between two systems when they are capable of automatically and unambiguously exchanging meaningful information.

Data validation: when data are represented with an ontology, they can be easily validated against the definitions. For example, an ontology might define a tour as something that's performed by some agent. It might also specify that all tours must start and end at the same location. In this case, if a system observes some data where the start and the end of a trip are not the same location, this data will be inconsistent with our definition of a trip and can easily, automatically be recognized as such.

Inference: we can infer new information about some data based on the domain knowledge that is encoded in the ontology. As a very simple example, say the data tells us that "AC123" is a Transit Vehicle. The definitions in a transportation ontology may specify that all Transit Vehicles are Vehicles, so it can be inferred that "AC123" is a Vehicle; this sort of inference is useful in ensuring the completeness of query results. More complex sorts of inference are also possible; for example, the definitions in the ontology state that vehicles change locations through some occurrence of travel. Given some observation of a vehicle located at one place and then located at another place a short time later, the ontology can be used to infer that some travel activity has taken place. With some additional definitions and a layout of the road network, inference about which possible route(s) was taken may also be supported.

In a given application, an ontology may be employed for one or many of these abilities. In theory, a single ontology can support all of the described services. However, in practice it is often the case that an ontology is designed with a particular service (or set of services in mind). It is in part for this reason that sometimes there are different ontologies designed to represent the same domain; this survey includes eleven different ontologies that capture the transportation domain in various ways.

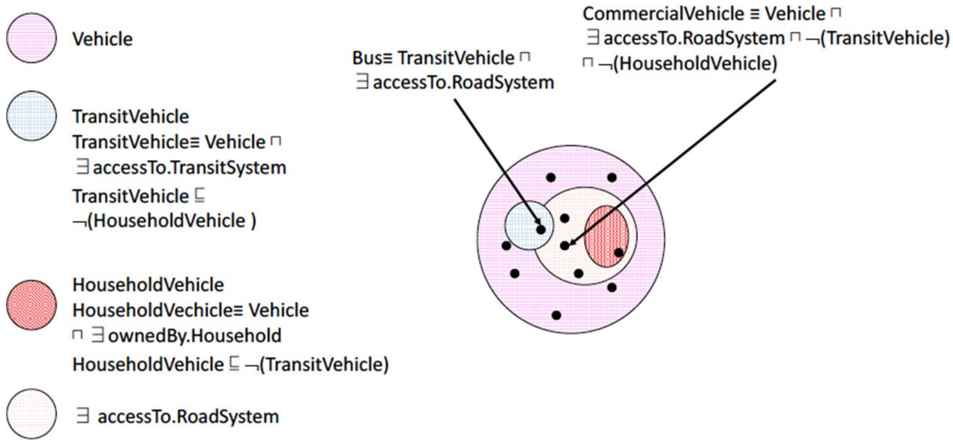

Fig. 2. Example of an OWL representation of Vehicles.

2.2. *Ontologies on the Semantic Web*

The Semantic Web is a term coined by Tim Berners-Lee to describe a vision wherein documents on the web not only capture how to visually render data, but information about its meaning (Berners-Lee, et al., 2001). On the Semantic Web, data are annotated with terms to indicate how they should be interpreted. Ontologies play a critical role in defining the meaning of these terms. Tags alone are ambiguous and insufficient to support any reasoning, but terms defined in an ontology have an explicit semantics that can be leveraged by persons or applications on the web. The Web Ontology Language (currently OWL2) (Hitzler, et al., 2012) is an ontology specification language with foundations in Description Logic (Baader, et al., 2003). As a W3C standard, it has become the *de facto* language of the Semantic Web. In practice, this means that many web pages as well as associated data stores are annotated with concepts defined in OWL2 (hereafter referred to as OWL) ontologies. These ontologies are defined in terms of classes, properties, and individuals (members of classes). The semantics of a class is defined by its relationship to other classes, via notions of subclass, conjunction, disjunction, and negation. This allows us to define the *necessary* and/or *sufficient* conditions for any individual to be a member of a particular class. For example, Fig. 2 shows the necessary and sufficient conditions for the notions of TransitVehicle and HouseholdVehicle. It indicates that transit vehicles are vehicles that have access to some transit system, whereas household vehicles are vehicles that are owned by some household. Further, household vehicles are not transit vehicles, and vice versa. From these definitions, we are able to recognize when some entity (an observation recorded in a data store, for example) is an instance of either vehicle type. Further, we are able to infer or specify other interesting information, for example we can identify new classes of objects such as Buses or Commercial Vehicles. It is also possible to make inferences regarding vehicles' access to various road systems or other transportation networks.

It is important to recognize that the formalization of an artefact in OWL does not guarantee it will provide such semantics. Simpler vocabularies may be defined in OWL while offering little in the way of actual definitions. The notion of the ontology spectrum, depicted in Fig. 3, illustrates this range of artefacts. The formal ontologies at the right of the spectrum are those of interest for the uses described here. The languages increase in expressive ability toward the right end of the spectrum, however it is important to note that this expressiveness comes at a cost for performance; we cannot guarantee that reasoning with the ontology will be scalable. On the other hand, when restrictions are imposed on the expressivity of an ontology its computational properties can be improved, allowing for some guarantees to be made about its scalability. In other words, we can still expect reasoning to be fast, though limited, when

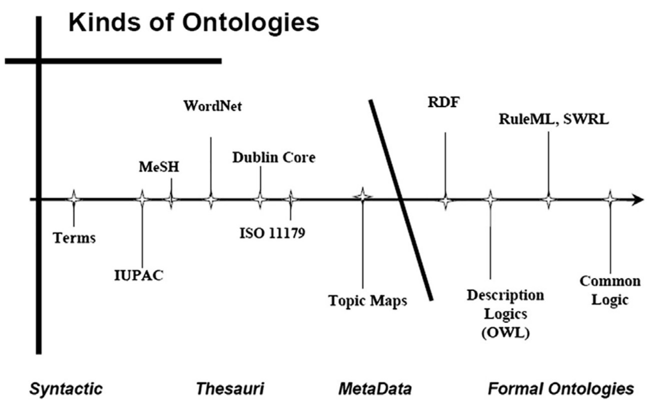

Fig. 3. The Ontology Spectrum, originally developed by Gruninger et al. (1999).

dealing with a lot of domain information. It is for this reason that this work focuses on ontologies formalized in OWL, as opposed to more expressive and possibly richer ontologies in Common Logic (ISO/IEC 24707:2007 Information technology – Common Logic (CL): a framework for a family of logic-based languages).

2.3. Ontologies for the transportation domain

As data management becomes more challenging, ontologies are a reusable tool to provide clear, understandable definitions that are critical to understanding large volumes of data from different sources. While large volumes of data may be challenging for reasoning with ontologies, ontologies that are employed as standards to support interoperability are generally not used for reasoning. On the other hand, the more expressive ontologies that are designed to support reasoning are typically much smaller in scope and are thus the challenges of scale are mitigated to some degree.

Ontologies are well-suited to address the challenges that arise due to the volume and variety of data that are found in the transportation data. Simulation is one area that demonstrates these characteristics, and plays a key role in transportation and urban studies. It is also an area where researchers have begun to recognize the potential for ontology support. Initial work in this area appears in Fox and colleagues' development of the Knowledge-Based Simulation (KBS) tool (Reddy, et al., 1985). In the KBS, a knowledge base is used to support various aspects of a simulation – in particular, to define the behaviour of the model, as well as to represent and manage the various simulations, acting as a tool for experiment management. More recently, opportunities for ontologies to complement simulations by adding semantics such that mapping from the models to the real world is explicit have been pursued. Perakath and colleagues (Perakath and Akella, 2009; Perakath, et al., 2006) advocate for the use of ontologies to aid in model interoperability and composition. Other work by Silver and colleagues (Silver, et al., 2011) and Beck and colleagues (Beck, et al., 2010) present techniques that use ontologies for model construction and automated simulation code generation. As a tool for knowledge management, ontologies provide a means of capturing simulation knowledge and communicating it unambiguously at various levels of abstraction (including code generation). In addition, an ontology-based representation is beneficial as it enables consistency checking of the models, input and output data.

The applications of an ontology extend beyond simulation support. In general, the variety of sensors and other data sources in the transportation domain make data integration a challenging task: data are published in different formats, different granularities, and with different and sometimes ambiguous properties. For example, open data and social media are also creating new and exciting opportunities for non-traditional data collection, but it's not clear how to combine all of this information coherently. Open data, especially from government organizations, is well-established and made available online through various portals[1]; a great deal of this open data pertains to transportation. Unfortunately, this data rarely adopts a standard vocabulary but instead utilizes data models specific to the publishing organizations. Linked data (Bizer, et al., 2009) improves the accessibility of this information by publishing the data with the use of shared vocabularies. There are best practices for publishing linked data (Hyland, et al., 2014), and recently more sophisticated methods focused on efficiency of access and economy of publication (Colpaert, et al., 2015). Such efforts toward data publication are critical to the success of the Semantic Web; they create opportunities for the transportation ontologies presented here: the use of ontologies to define linked data vocabularies enables semantic integration and reasoning.

The interest and progress in applying ontologies for this integration task can be seen in the Linked Open Vocabularies for Internet of Things (LOV4IoT) Ontology Catalogue.[2] At the time of this writing, the catalogue references 391 ontology-based projects for the internet of things. These projects take place across a range of domains, one of which is transportation. This integration is critical for smart city applications that typically require a combination of data from sensors and other sources. In addition, the ability to easily share and integrate data has major implications for research advancement. If datasets are more easily shared and combined, researchers will be able to get more value from a single data collection effort.

Owing to their formal semantics, ontologies are able to support integration in a number of ways. Ontologies provide a principled approach to the creation of standards. That is, they provide a formal language, (e.g. Description Logic), for defining the semantics of the concepts in a standard. Any standardization effort can benefit from an ontology engineering approach where the result goes beyond UML diagrams, to more expressive definitions of core concepts and properties. Whether implemented official standards or not, ontologies serve as a common, unambiguous language that can be used to translate messages and data between applications. They also provide a common language with which to access databases and other sources of information, for example via what is referred to as Ontology-Based Data Access (OBDA). This approach either employs either a specialized technique of query rewriting to pull results directly from the database, or materialization to translate data into instances in the ontology that can then be queried.

An ontology for transportation data can also serve as a useful tool for the analysis of transportation data. It can be employed to answer queries (straightforward lookup, or inference-based) to specific questions – such as *"What are all the sources of volume data in traffic zone X?"* – or to simply explore and learn about the domain. These types of queries are able to support both day to day transportation operations by querying real-time data, and planning activities by querying historical data.

3. Scope of transportation concepts

Unsurprisingly, the ontologies included in this survey are developed for different applications and so consider different aspects of

[1] For example: https://www.data.govhttp://open.canada.ca/enhttps://data.gov.uk1.
[2] http://www.sensormeasurement.appspot.com/?p=ontologies#transport.

the transportation domain. We do not aim to assess whether one scope is better than another, instead we consider and compare the breadth of the concepts defined by identifying the categories of sub-ontologies (domain and foundational) that manifest themselves in each ontology. This is an important first step to identify the contents of each ontology; it clarifies what concepts are being considered in the transportation domain and provides a clear understanding of the scope of each ontology relative to the others. This provides context for the assessments and discussion in the following sections.

While ontologies are developed in a variety of logical languages, this survey is restricted to ontologies formalized in the Web Ontology Language, OWL2 (hereafter referred to as OWL). This decision was made, in part to provide a more straightforward comparison of ontologies, but primarily due to the role of OWL as the *de facto* language for the Semantic Web; Transportation ontologies in other languages are less relevant for the practical applications that motivate this work. It addition, only a small minority of transportation ontologies identified during our initial search were not formalized in OWL.

Nevertheless, it is worthwhile to note that this scope decision does result in the exclusion of some well-known work, such as the GTFS (Google, 2016) and CityGML (Gröger and Plümer, 2012). While these are certainly valuable vocabularies for the transportation domain, they are encoded in XML and so are perhaps better classified as schema than formal ontologies. Many of the criteria considered in the subsequent survey are not applicable to such vocabularies, thus their inclusion would not add much value to the result.

This survey includes only transportation-specific ontologies. It was our aim to draw as clear a boundary as possible and include only ontologies directly focused on the transportation domain. While other concepts such as location, time, or even land use are related to the transportation domain, we do not consider all ontologies that define these concepts. Such ontologies may comprise a part of a transportation ontology, but they need not be directly included in this survey. We have also opted to exclude ontologies for autonomous vehicles from the scope of the survey. While certain aspects of these ontologies may be applicable to the transportation domain in general, this is a sufficiently specialized and active area to warrant its own survey. A final note is that this survey includes only ontologies with accessible encodings at the time of this writing. Several ontologies are described in the literature, but not available online and could not be obtained through contact to their authors (Barrachina, et al., 2012; Freitas, et al., 2011; Becker and Smith, 1997; Lee and Meier, 2007). These ontologies were omitted due to the fact that they could not be examined in detail, nor are they relevant in practice, as an ontology that is not available cannot be reused.

For each ontology, we summarized its high-level taxonomy of transportation-related concepts. The ontologies' varied purposes and ontological commitments have naturally resulted in different taxonomies. Depending on the design of the ontology, its taxonomy may be quite broad and not very deep, whereas some ontologies may not define any high-level concepts at all. In such cases extraction of even the top level of classes would not be very effective for our purposes, as it would not easily support a comparison with other theories, nor would it be easily digestible. To address this, for each ontology we manually derive a simple, high-level taxonomy that is representative of the scope of transportation concepts that it defines, rather than simply duplicate the first few levels of the ontologies' class taxonomy. We then aggregate the results to create a high-level taxonomy of transportation concepts. The resulting taxonomy provides an idea of what concepts are considered to be in the transportation domain. Admittedly, the approach is rather crude: we amalgamate similar concepts without consideration for the possible ontological distinctions; we choose one taxonomy structure over another (for example, the choice to a Person as a kind of Agent or Resource, or both) more or less arbitrarily. It is not the aim of this work to resolve differences or define mappings between the ontologies. Such questions are out of the scope of this work and thus not considered in the construction of this taxonomy. The purpose is to define a high-level taxonomy that is representative of the scope of the transportation domain according to the existing work, and provide a basis for comparison between the ontologies in the survey. Although foundational ontologies, such as those defining concepts of time and space, are omitted from this survey these concepts do appear in the resulting taxonomy. This should be seen as an indication of foundational concepts appearing in the surveyed ontologies, rather than an intentional focus on them. The result is illustrated in Fig. 4; the comparative summary of each ontologies' scope is captured in Table 1.

4. Comparison criteria

Beyond the scope, it is important to consider the potential capabilities of ontologies and assess the degree to which they are demonstrated by each ontology. Are they precise? Have they been formally evaluated? Do they support any sorts of knowledge management services? We also consider the characteristics of their representations which may be of particular relevance to potential users, as identified in (Fox, 1992); specifically: their generality, granularity, competence, and relative scope. In the following, criteria are defined for each capability and characteristic in order to assess the ontologies in a consistent manner.

4.1. Precision

How precisely are the concepts defined? To assign a detailed score of precision to ontologies would be far-fetched, and not a particularly meaningful metric; truthfully, the concept of precision of a given definition is relative to the semantics of the concept that is being defined. It is difficult to make any detailed claims about the precision of an ontology's axioms without complete knowledge of the intentions of the ontologies' designers. Further, we cannot *compare* the correctness of the ontologies because there is no single, explicit set of transportation requirements to verify them against. Further, whatever transportation ontology requirements we might formulate would likely vary across different applications.

On the other hand, we can compare how detailed the axioms are in general. How much semantics is explicitly stated in the axioms, versus what is implied by the documentation and left for interpretation? We approach the assessment at a relatively

- Location: where something is located, in the geographic sense.
- Space: spatial entities and their relationships, e.g. containment, contact, relative size.
- Geometry: points, lines, planes, and the shapes they can construct.
- Time: timepoints, intervals, durations, dates, and relationships between them.
- Manifestation: a 4-dimensionalist concept capturing the instance (or, time slice) of some thing at a given point in time.
- Unit of measure: the relationship between a measurement and the various values it can be described with.
    - KPI (Key Performance Indicator)
        - Indicator
        - Formula
- Land Cover and Use: description of the form or function that occupies some area.
    - Location Feature
- Activity: something that occurs in the domain; usually described by its participants, when it occurs, as well as what its preconditions and effects are.
    - Education
    - Emergency
    - Entertainment
    - Trip
    - Meteorology
    - Disruptive Event
    - Operator Action
    - Transit Event
    - Loading
    - Receiving
- Agent: something that performs some activities or has some role.
    - Organization
    - Person
    - Stakeholder
- Resource: something that's used in an activity.
    - Monetary
    - Non-Monetary
- Plan: some predefined set or series of activities.
- Objective: a desired future state, usually the outcome of a plan.
- Precondition: some state that is required to be true in order for an activity to occur.
- Effect: a change in state that results from some activity.
    - Disruptive Impact
- Transportation Network: A set of links that enable transportation from one location to another.
    - Railway
    - Road
    - Transit
    - Administrative Road
- Modes: various means of transportation.
    - Vehicle
    - Transit
    - Walking
    - Bicycle
    - Segway
- Parking: some place where vehicles or other transit modes may be stored. Usually other information is involved such as its location and policy.

Fig. 4. High-level taxonomy of transportation concepts.

superficial level by considering how the concepts and relations are defined. For this purpose, we reuse the Schema Metric of Relationship Diversity defined in OntoQA (Tartir and Arpinar, 2007), and introduce an assessment of Axiom Complexity to provide a complementary perspective on the ontologies' relative precision. On the surface, the Schema Depth metric defined in OntoQA also appears to be an attractive criterion to include in our assessment of Precision. However, closer inspection reveals that it is not an appropriate indicator. While the measure (average subclasses per class) seems to capture the structure of an ontology: intuitively, whether it is more "horizontal" or "vertical" in nature, it does not necessarily provide an accurate indication of the *semantic depth* of the ontology's definitions.

4.1.1. Relationship diversity

Relationship Diversity provides a view of the types of relationship that are defined in the ontology. The metric is defined as the ratio of the number of non-subclass relationships[3] (P), divided by the total number of relationships defined in the schema (the sum of the number of subclass relationships (H) and non-subclass relationships (P)).

We segment the range of values to provide a higher-level view of the results.

Level 0. diversity = 0 (no non-inheritance relationships)
Level 1. $0.25 > \text{diversity} > 0$
Level 2. $0.5 > \text{diversity} >= 0.25$
Level 3. $0.75 > \text{diversity} >= 0.5$
Level 4. $1 >= \text{diversity} >= 0.75$

[3] Note that data properties are excluded from this count as they capture attributes, but not *relationships* between classes.

Table 1
Scope summary.

High-level Concept	3.1 Transportation Ontology for Content Personalization	3.2 Ontology for Transportation Networks	3.3 The Transport Disruption Ontology	3.4 Ontology Based Road Traffic Management	3.5 Road Accident Ontology	3.6 Osmonto	3.7 GenCLOn	3.8 iCity Ontology	3.9 KPIOnto and Transmodel	3.10 km4city	3.11 NSO
Location	X	X			X	X		X		X	X
Space				X		X		X		X	
Geometry		X						X		X	
Time	X		X					X		X	X
Manifestation								X		X	
Unit of Measure							X	X	X	X	X
● KPI							X		X		
● Price	X							X			
Land Cover and Use		X						X			
● Location Feature		X				X				X	
Activity		X	X		X		X	X		X	X
● Education		X									
● Emergency		X									
● Entertainment		X									
● Trip	X						X	X			
● Meteorology		X								X	
● Disruptive Event		X	X		X					X	
● Operator Action			X	X						X	
● Transit Event			X								
● Traffic Event			X								
● Loading							X				
● Receiving							X				
Agent			X								X
● Organization			X	X	X			X		X	
● Person	x		X	X	X			X			
● Stakeholder							X				
Resource							X	X			
● Monetary Resource							X	X			
● Non-Monetary Resource							X				
Plan			X				X				
Objective							X				
Precondition								X			
Effect								X			
● Disruptive Impact			X								
Transportation Network	X	X				X		X		X	X
● Railway		X						X		X	X
● Road		X						X		X	
● Transit		X						X		X	
● Admin Road										X	
Mode	X							X			
● Vehicle	X			X	X			X			
● Transit	x										

(continued on next page)

Table 1 (*continued*)

High-level Concept	3.1 Transportation Ontology for Content Personalization	3.2 Ontology for Transportation Networks	3.3 The Transport Disruption Ontology	3.4 Ontology Based Road Traffic Management	3.5 Road Accident Ontology	3.6 Osmonto	3.7 GenCLOn	3.8 iCity Ontology	3.9 KPIOnto and Transmodel	3.10 km4city	3.11 NSO
● Walking	X										
● Bicycle	X										
● Segway	X										
Parking		X				X		X			

Level 5. diversity = 1 (no subclass relationships)

4.1.2. Axiom complexity

The additional criteria to complement the perspective on precision provided by Relationship Diversity is an assessment of Axiom Complexity. Since we are considering only formal, machine-interpretable ontologies, at the minimal level we must have at least a basic terminology even if it has no axioms. These terms may be more precise if defined as a taxonomy, and beyond this, the ontology may be made more precise through the use of axioms beyond the simple subclass to define a class, and beyond the sort-type axioms that define the domain and/or range of the properties. These basic levels are used to assess the complexity of an ontology – with level 0 being the least, and level 2 being the most precise. The categorization below provides some additional insight into the values of the Relationship Diversity metric, i.e. do the non-subclass relationships play a role in further defining the domain?

Level 0. No axioms, vocabulary only.
Level 1. Vocabulary defined as a taxonomy.
Level 2. Classes identified and defined with axioms beyond the taxonomy (simple subclass), and/or object properties are defined with axioms beyond domain and/or range constraints (e.g. transitivity, relationships to other relations)

4.2. Evaluation

How well are the ontologies evaluated? Here, we consider whether any evaluation was performed, and if so, the extent of its rigor. The focus is on correctness of the semantics, as opposed to performance metrics. A fundamental requirement that may be evaluated with the use of a theorem prover or model builder is consistency of the axioms. Inconsistent axioms indicate that there is some logical contradiction in the representation of the domain that must be corrected. Manual assessment tends to be less formal, but is nevertheless a useful approach to evaluation. Even if all of the axioms are consistent, it is possible that the ontologist may have misunderstood and misrepresented some aspect of the domain. Review by a subject matter expert can help to confirm that the ontology correctly captures the scope and semantics of the domain. However, even this sort of review may be subject to human error; to avoid this, ontologies can be formally evaluated against a set of requirements. These requirements, essentially competency questions (Grüninger and Fox, 1995), take the form of inferences that should be possible based on the semantics of the ontology and can be evaluated with the use of an automated theorem prover (Katsumi and Grüninger, 2010). This approach helps to ensure that there are no unintended consequences from the axioms.

Level 0. No evaluation described or referenced.
Level 1. Consistency of the axioms was assessed.
Level 2. Assessed manually in some way, for example through review by some subject matter experts, or against some authoritative document.
Level 3. Formally verified against some defined requirements/competency questions.

4.3. Knowledge management services

What sorts of knowledge management services are supported by the ontology? For each level, it is also important to consider whether the application of these services is simply discussed or if in fact the ontology has been implemented and some demonstration of the services has been provided. The basic application level simply checks the asserted facts to determine whether they satisfy the axioms. Beyond this, simple retrieval of facts may be performed to provide decision support or facilitate integration between systems and/or services. In the uppermost level the ontology provides decision support and/or integration by *inferring* new facts. In other words, it adds knowledge that was not explicitly captured in the knowledge base.

Level 0. No services defined
Level 1. Consistency checking
Level 2. Simple retrieval of facts (via SPARQL for example)
Level 3. Inferential extensions using rules (SWRL for example)

4.4. Generality

Are the concepts defined in the ontologies generally applicable to the transportation domain, or are they specific to a particular application(s)? For example, does the ontology define a trip, in general, or does it only define specific types of trips such as for bus routes? While we may not be able to provide a comprehensive score of an ontology's generality, we can identify whether or not there are application-specific concepts instead of domain specific concepts. In such cases the same representation could not easily be shared for other applications. Generality may be assessed with a simple yes or no based on a review of the concepts and their (formal and informal) definitions.

4.5. Granularity

Does the ontology support the representation of (and reasoning about) the domain's semantics at multiple levels of abstraction? The notion of granularity is distinct from the definition of taxonomic levels; rather than being concerned with, say, the definition of different modes of transportation, the focus is on if there is a representation of the entire system, and also a definition of the different parts that make up the system (e.g. lines, routes). Note that we are concerned with representation and possibly reasoning at various levels. It is not sufficient for an ontology to simply include concepts at multiple levels of abstraction. The concepts at each level should have a defined semantics; they should be examples of Level 2 Axiom Complexity. If the concepts are included superficially then the ontology can be seen as identifying other levels of resolution, however if it does not provide any semantics for these levels then it should not be considered to be granular. For example, an ontology that defines the links and nodes in a transportation network may include the concept of a network. However, in order to be considered granular, the ontology must also provide some definition of the semantics of a network beyond a superficial connection to the links and nodes; for example, can a network be owned by some entity? Can a network be part of some other network or entity? Observe that a consequence of this is that we do not consider any ontologies with an Axiom Complexity level of 1 or 0 to be granular. Granularity may be assessed with a simple yes or no based on a review of the concepts and their (formal and informal) definitions.

4.6. Competence

Does the ontology support problem-solving in the domain? Competence considers what, if any, questions the ontology is shown or claimed to be able to answer. Such questions should be explicitly identified in the ontology's documentation. They may be simple look-up queries, slightly more complicated queries that require some filtering or joining of properties, or even those more advanced queries that require the use of some inference. In any case, the questions serve as an indication of the problem-solving capabilities of the ontology. This criterion may be assessed with a simple yes or no based on a review of the ontology's documentation.

4.7. Span

How much of the scope is covered? In the previous section, we illustrated the variety of concepts that are included in the transportation domain, as well as the different ways these concepts are covered (or not) by the transportation ontologies. Span considers the *relative* span of the ontologies' scope. With this criterion, we quantify how much of the scope is covered by an ontology, relative to the set of classes that was identified in the previous section. The value returned is the percentage of classes included in the ontology; in other words, the number of top level classes defined in the ontology O_C, divided by the total number of top-level classes, S_C. According to the previous section, $S_C = 46$.

5. Comparison results

The results of the survey are detailed in the sections that follow. Summaries of the results can be found in Section 6.

5.1. Transportation ontology for content personalization

An ontology was developed and presented by de Oliveira, et al. (2013) to support the generation of personalized user content, specifically the information retrieval, in an interactive transportation system. It was designed to support information retrieval for travellers using various transportation systems. The ontology encoding could not be located online, however a copy was obtained via direct contact to the authors. The focus of the ontology is on travel planning. Transportation networks are related to transport lines, which have associated modes. A transportation journey is captured with stop points, modes, durations and costs (see Fig. 5). Using this representation, the ontology identifies different classes of journey patterns. There has been no subsequent development or application of this work since its initial publication.[4]

The ontology defines transportation concepts within the following taxonomy:

- Location
- Time
- Travel activity
- Price
- Operator
- Transportation networks
- Modes
  - o Vehicle
  - o Transit
  - o Walking

[4] Personal communication with Káthia Marçal de Oliveira on December 9, 2017.

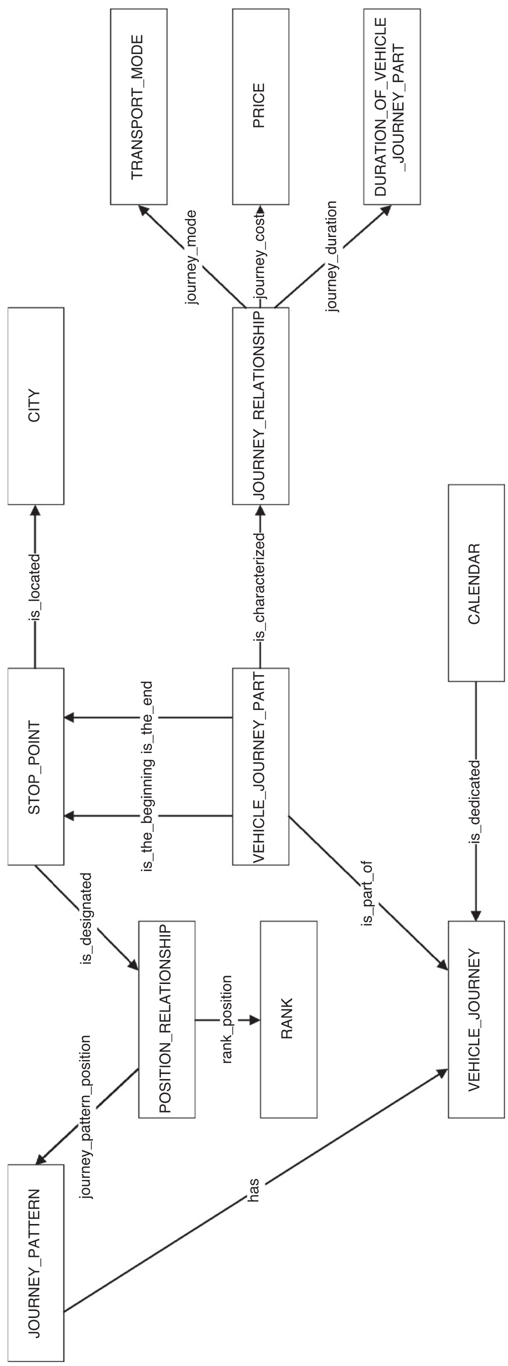

Fig. 5. High-level concepts and relationships to characterize a journey.

- o Bicycle
- o Segway

Precision:

Diversity: subclass-of axioms = 160, non-subclass relationships = 53
53/213 = 0.25
Therefore we find the ontology to have a Level 2 diversity
Complexity: The ontology includes detailed axioms, although we note they are specified in SWRL (an extension of OWL), therefore we find it to have a Level 2 complexity.

Evaluation: Level 0. No discussion of evaluation is presented. Competency questions were defined to motivate design, however no indication of evaluation of competency questions, or other criteria such as consistency, is given in the documentation.

Knowledge management services: Level 3. The authors describe the ontology's role in decision support by performing inferences, in this case via SWRL, to support the auto-fill of forms and query enrichment for a transportation information system.

Generality: General The ontology defines generic transportation concepts, however it also includes application-specific definitions of terms such as "interesting journey pattern", "pattern with little walking", and so on.

Granularity: Not granular. The classes and examples of reasoning provided are defined at a single level of granularity. The described application does not seem to warrant multiple levels of detail.

Competence: the ontology claims to support the following CQs in order to provide context-appropriate results to the user:

i What is the "transportation multi-modality"?
ii How is a transportation journey characterized?
iii How are the public transportation stop points organized?
iv What are the associated services to a journey?
v How good is the public transportation infrastructure? (e.g. are direct/indirect journeys possible?)
vi Which kinds of journeys can be offered to a passenger?

Span: 26%. The ontology captures 12 of the 46 identified classes.

5.2. *Ontology for Transportation Networks*[5]

The Ontology for Transportation Networks (OTN) was presented by Lorenz, et al. (2005) as part of the Reasoning on the Web with Rules and Semantics (REWERSE) project. Depicted in Fig. 6, OTN formalizes and extends the Geographic Data Files (GDF) standard, an ISO standard for geographic information (ISO/TC 204 Intelligent transport systems Technical Committee, 2011). While available for reuse by other projects, no subsequent work on or application of this ontology has been performed by its authors since its initial publication.[6]

The OTN defines transportation concepts within the following taxonomy:

- Geometry
- Location
- Land Cover and Use
  - o Location Feature
- Meteorology
- Activity ("Services") / Event
  - o Education
  - o Emergency
  - o Entertainment
  - o Construction
  - o Accident
- Transportation Network
  - o Railway
  - o Road
  - o Transit
- Parking

Precision:

[5] http://rewerse.net/A1/otn/OTN.owl5.
[6] Personal communication with H.J. Ohlbach on November 15, 2017.

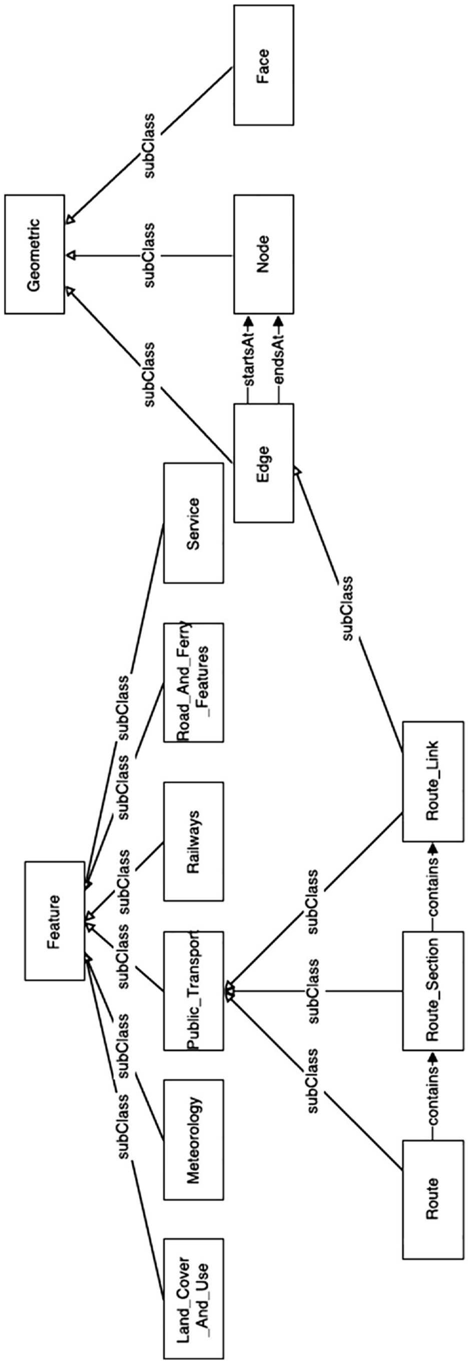

Fig. 6. A selection of some of the basic classes in OTN, and their relationships.

Diversity: subclass-of axioms = 299, non-subclass relationships = 36
36/335 = 0.11
Therefore we find the ontology to have a Level 1 diversity
Complexity: The Ontology demonstrates axioms beyond the basic taxonomy, therefore we find it to have a Level 2 complexity.

Evaluation: Level 0. No evaluation is described or referenced.
Knowledge management services: Level 0. No services are defined or described.
Generality: General The concepts defined in the ontology are generic and not specific to a particular application(s).
Granularity: Granular We find some levels of granularity present; the network is captured at the level of edges and nodes but also aggregated into concepts such as roads and routes, based on various perspectives of the network.
Competence: None. No competency questions are described or demonstrated.
Span: 32%. The ontology captures 15 of the 46 identified classes.

5.3. The Transport Disruption Ontology[7]

The Transport Disruption Ontology, presented by (Corsar, et al., 2015) is designed to capture and aid in data integration to recognize events that can have a disruptive impact on travel (see Fig. 7). The ontology was applied in Social Journeys project[8] – a project to explore how social media can be used to provide information to public transportation passengers. It was also used in the TravelBot system – a system designed to provide travel advice based on information extracted from social media (Corsar, et al., 2015).[9]

The ontology defines transportation concepts within the following taxonomy:

- Time
- Activity (Event)
  - o Disruptive Event
  - o Operator Action
  - o Transit Event
  - o Traffic Event
- Agent
  - o Organization
  - o Person
- Plan
- Disruptive Impact

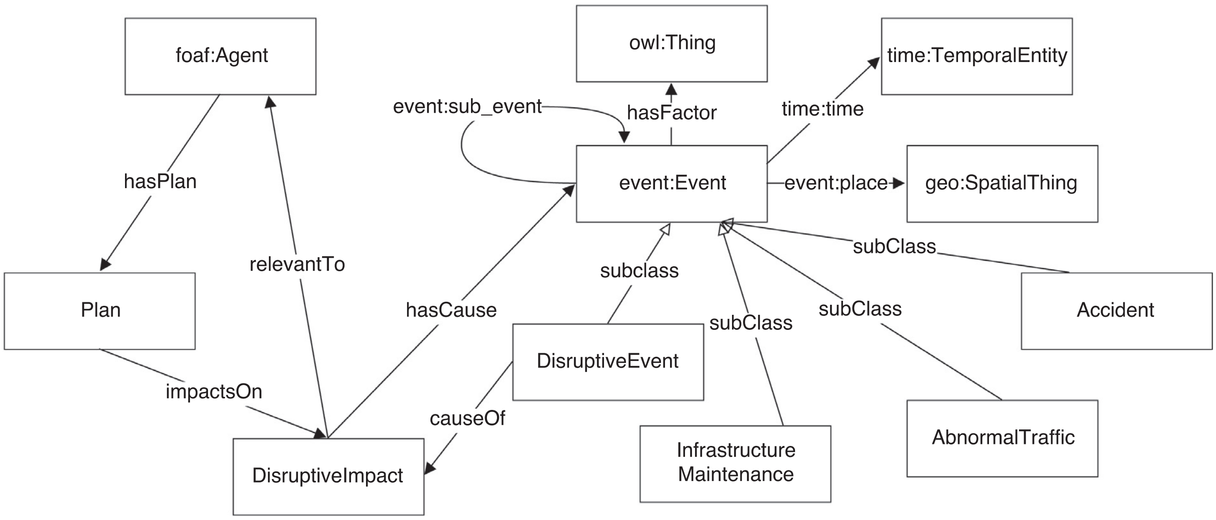

Fig. 7. Depiction of the Transport Disruption Ontology, redrawn from Corsar et al. (2015). Reused classes are indicated with prefixes.

[7] http://purl.org/td/transportdisruption#.
[8] http://www.dotrural.ac.uk/socialjourneys/.
[9] Personal communication: David Corsar on November 17, 2017.

Precision:

Diversity: subclass-of axioms = 472, non-subclass relationships = 85
85/557 = 0.15
Therefore we find the ontology to have a Level 1 diversity.
Complexity: The ontology demonstrates axioms beyond a basic taxonomy, however we note that there are only 2 instances of classes defined with axioms more complex than subclass-of (excluding cases from the imported owl-time ontology). Regardless, this classifies the ontology as a Level 2 complexity.

Evaluation: Level 0. No formal evaluation of the axioms described or referenced; though the authors note future evaluation "through use cases".

Knowledge management services: Level 2. Use of SPARQL queries is described as a means of identifying potential disruptive impacts to travel.

Generality: Not general. The concepts defined in the ontology are specific to the issue of transport disruptions.

Granularity: Not granular. We speculate that the intended application does not require representation or reasoning at multiple levels of granularity.

Competence: An example of the query "Are there any possible disruptions for my planned journey?" is formalized in SPARQL. The authors discuss other possible formalisms for this query, none of which are demonstrated.

Span: 24%. The ontology captures 11 of the 46 identified classes.

5.4. Ontology based road traffic management

The ontology, presented by Bermejo, et al. (2013), was developed to provide decision support for drivers, with the overall aim of clearing an effective path for emergency vehicles (see Fig. 8). The ontology is designed as an extension of the A3ME (Agent-based Middleware approach for Mixed Mode Environments) ontology (Herzog, et al., 2008), which introduces classes for devices and sensors; however, it does not directly reuse it. The ontology defines two key object properties: doesAction and isActionDoneBy to relate vehicles to possible driving actions. In addition, data properties are defined to capture information about a vehicle's position and speed. Beyond the decision support system described in the paper, there have not been any subsequent applications of the ontology.[10]

The ontology defines transportation concepts within the following taxonomy:

- Driving Action (accelerate, decelerate)
- Organization
- Person
- Spatial Position
- Vehicle

Precision:

Diversity: subclass-of axioms = 21, non-subclass relationships = 2
2/23 = 0.09
Therefore we find the ontology to have a Level 1 diversity.
Complexity: The ontology demonstrates some axioms beyond simple subclass and domain/range, and SWRL rules are also present. The ontology has a Level 2 complexity.

Evaluation: Level 0. An evaluation is presented; however, it employs a very restricted scope (considering two scenarios) and focuses on inference speed as opposed to correctness. No direct, formal evaluation of the ontology is discussed or presented, (consistency checking and informal evaluation are likewise absent).

Knowledge management services: Level 3. Example implementation of decision support via inferred driver suggestions is presented.

Generality: Not general. The concepts defined in this ontology are specific to the application, defining only specific types of actions and attributes relevant for the task of vehicle (re-)distribution.

Granularity: Not granular. We speculate that the intended application does not require multiple levels of detail.

Competence: No competency questions are explicitly defined; however, the described test implementation indicates that the ontology infers suggested actions (a class in the ontology) based on knowledge given about the current scenario.

Span: 11%. The ontology captures 5 of the 46 identified classes.

[10] Personal communication: José Javier Astrain Escola on November 20, 2017.

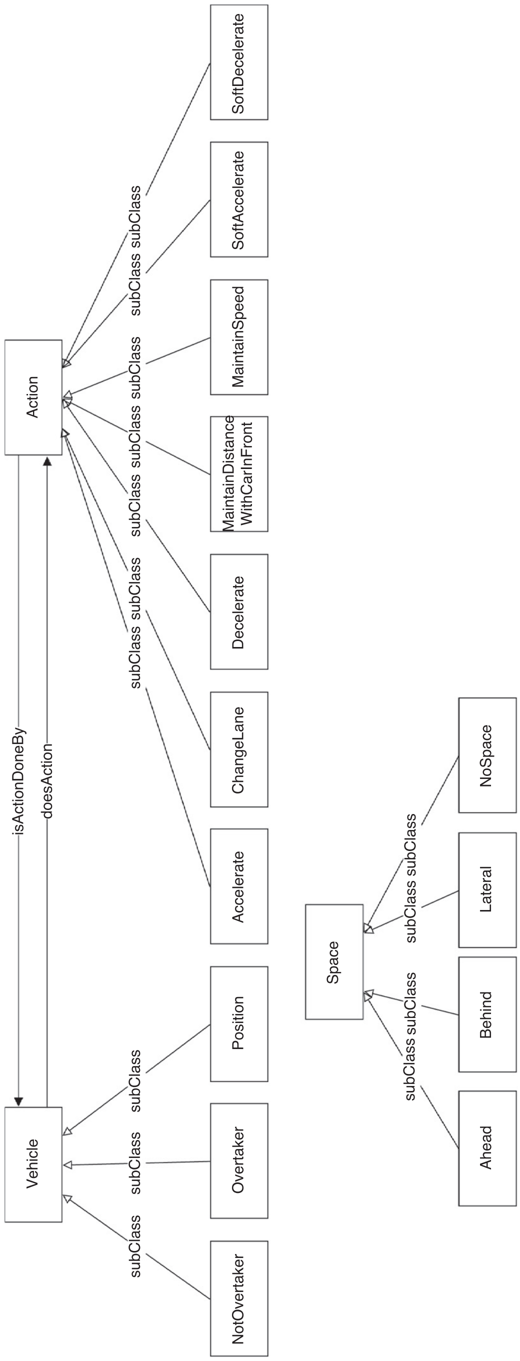

Fig. 8. Depiction of the ontology for road traffic management.

5.5. Road Accident Ontology[11]

Published as a W3C Draft, the Road Accident Ontology (Dardailler, 2012) is designed to capture road accidents and their relevant information, such as location, cause, involved parties, and so on (see Fig. 9). The ontology has not been applied in practice, nor has any subsequent development occurred since publication of the draft.[12]

The ontology defines transportation concepts within the following taxonomy:

- Person
- Organization
- Event
  - o Road Accident
- Location
- Vehicle

Precision:

Diversity: subclass-of axioms = 21, non-subclass relationships = 17
17/38 = 0.45
Therefore we find the ontology to have a Level 3 diversity.
Complexity: The ontology does not include definitions beyond the taxonomy, therefore we find it to have a Level 1 complexity.

Evaluation: Level 0. No formal evaluation is discussed or presented.
Knowledge management services: Level 0. Some services of interest are mentioned but not defined.
Generality: General No application-specific concepts are included.
Granularity: Not granular. The domain of road accidents is presented at a single level of detail.
Competence: No competency questions are claimed or shown to be satisfied.
Span: 13%. The ontology captures 6 of the 46 identified classes.

5.6. Osmonto[13]

Osmonto is an ontology presented by (Codescu, et al., 2011) to define OpenStreetMap[14] tags. The ontology, depicted in Fig. 10, is meant to providing an organization structure for the community-curated set of tags. This organization facilitates browsing and understanding of the tags, identification of similarities between existing tags, and relating tags to concepts defined in other ontologies. Essentially, the intention of the Osmonto is to make OSM tags easier to access and leverage. Osmonto was implemented in a web service for an activity-based route planning tool for OpenStreetMap (Codescu, et al., 2012).

The ontology defines transportation concepts within the following taxonomy:

- Location
- Spatial Location
- Transportation Network
- Location Features (e.g. shop, theatre, military…)
- Parking

Precision:

Diversity: subclass-of axioms = 583, non-subclass relationships = 29
29/612 = 0.05
Therefore we find the ontology to have a Level 1 diversity.
Complexity: The ontology defines its concepts as a taxonomy, without additional axioms, therefore we find it to have a Level 1 complexity.

Evaluation: Level 0. No formal evaluation of the ontology's contents is described. Given that the ontology directly captures the OpenStreetMap tags, the authors explicitly recognize there may be errors. No means of evaluating the correctness or completeness of tag representation is described; the task of maintaining the ontology (through automation or manually) with respect to OpenStreetMap is left for future work.

[11] Personal communication: Daniel Dardailler on November 14, 2017.
[12] Personal communication: Daniel Dardailler on November 14, 2017.
[13] https://raw.github.com/doroam/planning-do-roam/master/Ontology/tags.owl.
[14] https://www.openstreetmap.org.

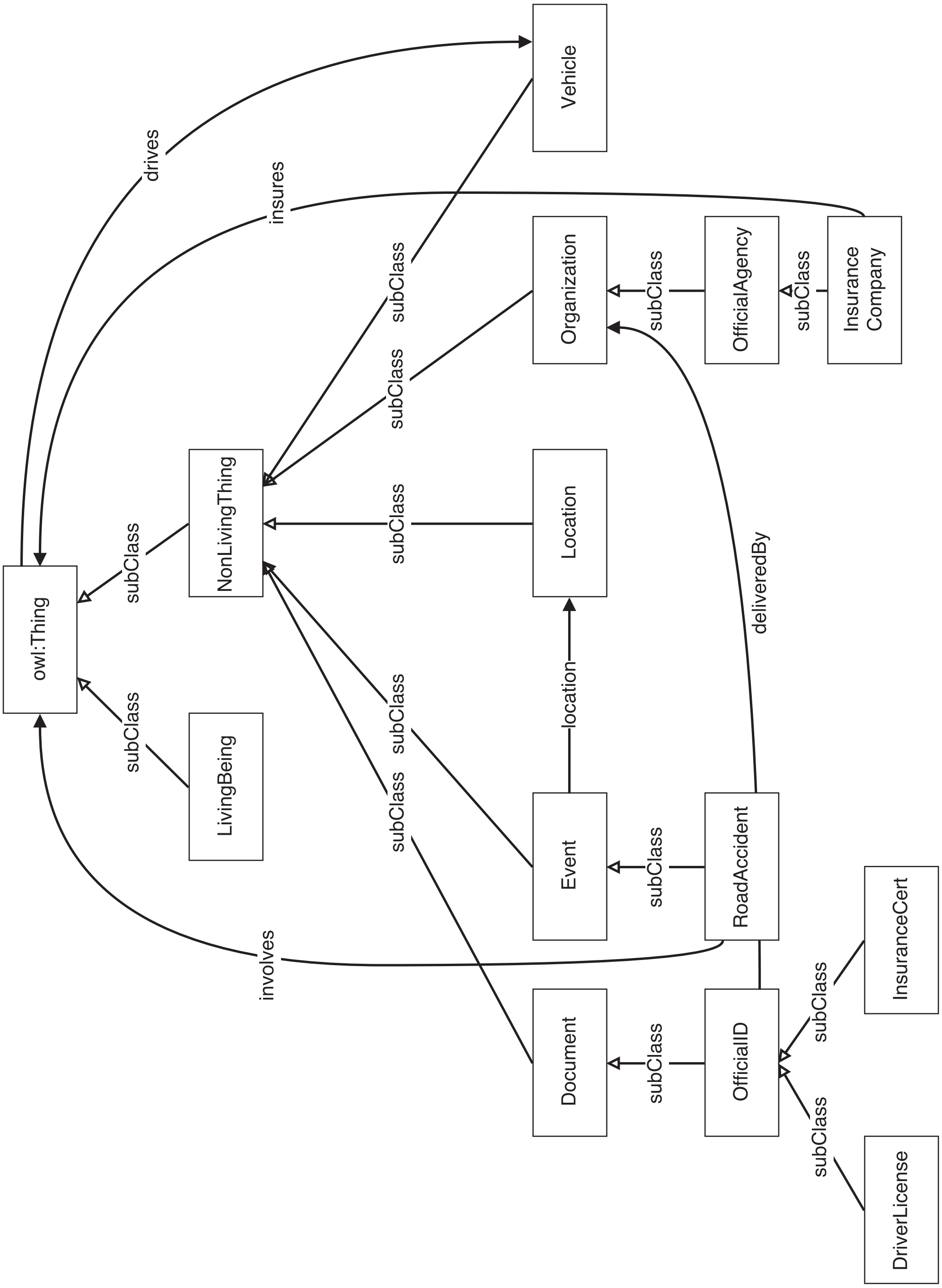

Fig. 9. Depiction of the core classes and properties in the Road Accident Ontology.

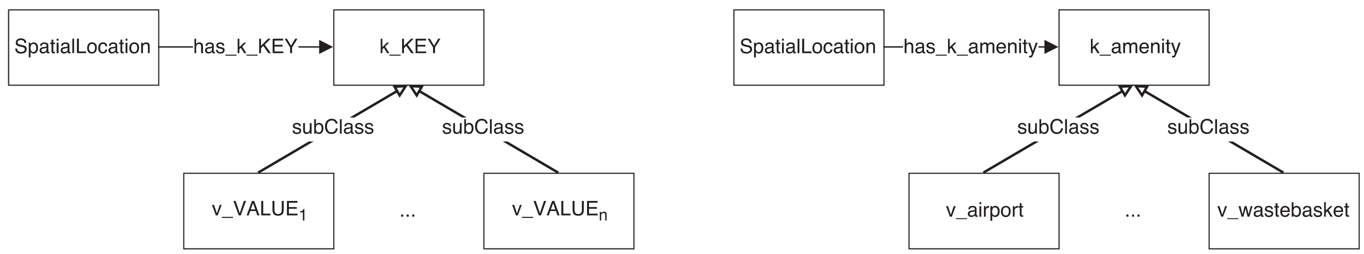

Fig. 10. The generic structure (left) and an example (right) of the Osmonto representation of OSM keys.

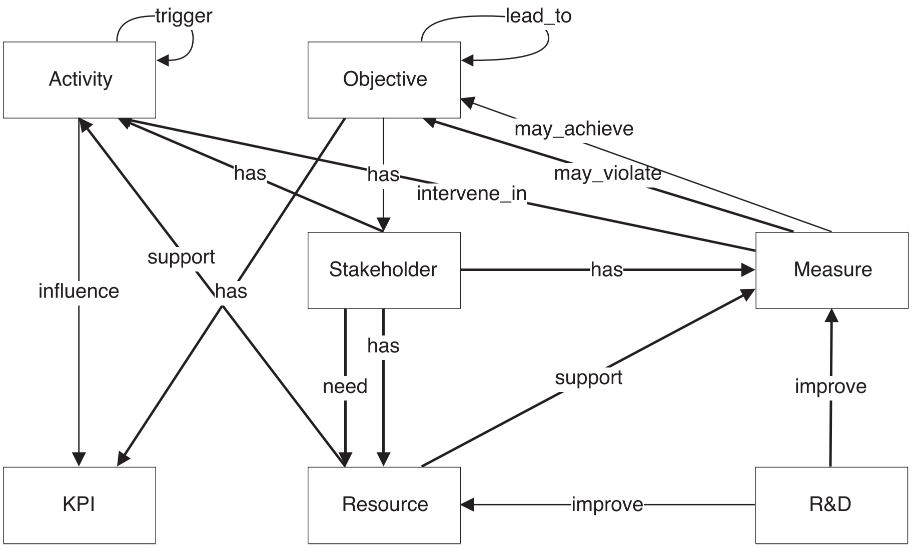

Fig. 11. Top-level classes of GenCLOn, redrawn from Anand et al. (2012).

Knowledge management services: Level 2. The ontology is applied to integrate and access OpenStreetMap data to support a route-finding application: DO-ROAM. The application is intended to calculate a route based on some desired activities that the user would like to perform along the way.

Generality: Not general. The ontology is defined entirely to capture the OpenStreetMap tags.

Granularity: Not granular. The ontology is defined with a relatively level of concepts based on the tags of map elements.

Competence: No competency questions claimed or shown to be satisfied.

Span: 11%. The ontology captures 5 of the 46 identified classes.

5.7. GenCLOn

GenCLOn was developed and introduced by (Anand, et al., 2012) as an ontology for city logistics – the freight domain in an urban context. The ontology encoding could not be located online, however a copy was obtained via direct contact to the authors. GenCLOn, depicted in Fig. 11, is intended to support the sharing and reuse of models developed to predict the behaviour of various stakeholders involved in city logistics. Unsurprisingly, the concept of the stakeholder is central to the ontology. Stakeholders have objectives, can perform activities, and have measures that they can take (e.g. to achieve their objectives). A version of GenCLOn was used in the development of a knowledge base to support a case-based reasoning system to provide itineraries for urban freight transport problems (Bouhana, et al., 2015).

The ontology defines transportation concepts within the following taxonomy:

- Activity
  - o Trips
  - o Loading
  - o Receiving
- Metric
  - o KPI (Key Performance Indicator)
- Plan (“Measure”)
- Objective
- Stakeholder
  - o Public Actor
  - o Private Actor
- Resource
  - o Monetary
  - o Non-Monetary

Precision:

Diversity: subclass-of axioms = 1452, non-subclass relationships = 50
50/1452 = 0.03
Therefore we find the ontology to have a Level 1 diversity.

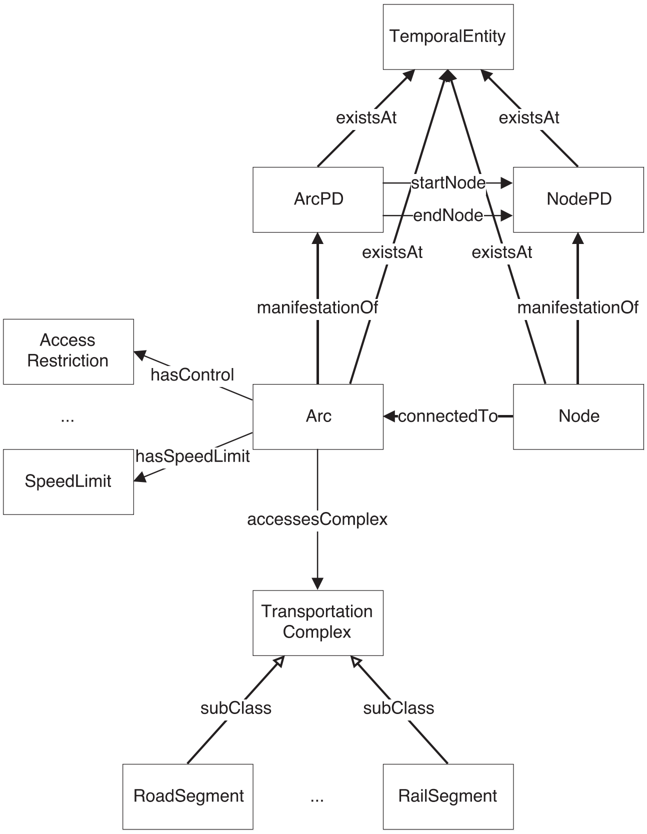

Fig. 12. Structure of the iCity transportation network, redrawn from Katsumi and Fox (2017).

Complexity: The ontology defines its concepts as a taxonomy along with additional axioms, therefore we find it to have a Level 2 complexity.

Evaluation: Level 2. The authors evaluated the ontology by comparing it to a model and two case studies on city logistics. The purpose of the assessment is to confirm whether the ontology is capable of capturing the model, and whether it is capable of capturing the real-world concepts that arise in city logistics scenarios.

Knowledge management services: Level 3. While not implemented in practice, use of the ontology to support query answering (while not leveraging SWRL rules but using classification) is discussed.

Generality: General Defined concepts are generally applicable to the transportation domain; however, the ontology also includes of logistic-specific concepts such as "E_retailer_doing_own_account_delivery".

Granularity: Not granular. We speculate that the intended application does not require reasoning at multiple levels of detail.

Competence: Competency questions not identified.

Span: 26%. The ontology captures 12 of the 46 identified classes.

5.8. *iCity Ontology*[15]

The iCity Ontology (Katsumi and Fox, 2017) is under development[16] as part of a project on urban informatics that requires the development of a set of ontologies to define the urban system (Miller, July 14, 2014). In this project, the ontologies provide a means of maintaining a knowledge base to capture all of the concepts and data collected and generated about the urban system; naturally, transportation is a core theme and so the ontology contains several sub-ontologies that are directly related to the transportation domain. In particular, the Transportation System sub-ontology[17] defines the core concepts of the transportation network, as illustrated in Fig. 12. The network flow and the physical infrastructure that comprise the network are captured distinctly using the concepts of Nodes and Arcs which have access to the physical infrastructure. The physical infrastructure is represented via the Transportation Complex class. This class is based on the concept introduced CityGML (Gröger and Plümer, 2012); it can be further specified based on mode and road type. Separate sub-

[15] https://w3id.org/icity/iCity-UrbanSystem.
[16] This survey considers Version 1.0 of the ontology.
[17] https://w3id.org/icity/TransportationSystem/.

ontologies capture concepts related to parking and travel activities.

The ontology defines transportation concepts within the following taxonomy:

- Space
- Location
- Geometry
- Time
- Manifestation
- Resource
  - o Person
  - o Monetary Value
- Units of measure
- Land Cover and Use
- Mode
  - o Vehicle
- Transportation network
  - o Transit
  - o Road
  - o Rail
- Activity
  - o Trip (e.g. transport from one location to another)
- Precondition
- Effect
- Parking

Precision:

Diversity: subclass-of axioms = 1632, non-subclass relationships = 362

362/1632 = 0.22

Therefore we find the ontology to have a Level 1 diversity.

Complexity: The ontology defines its concepts as a taxonomy along with additional axioms, therefore we find it to have a Level 2 complexity.

Evaluation: Level 2. The documentation indicates that the ontology has been evaluated for consistency, and informally reviewed by subject matter experts.

Knowledge management services: Level 0. While not yet implemented in practice (and thus not supporting any services), use of the ontology for consistency checking, query answering, and inference is discussed.

Generality: General Defined concepts are generally applicable to the transportation domain.

Granularity: Granular The domain is defined at varying levels of granularity, such as transportation networks and individual arcs.

Competence: Competency questions not identified.

Span: 50%. The ontology captures 23 of the 46 identified classes.

5.9. KPIOnto[18] and Transmodel[19] integration

Recent work by (Benvenuti, et al., 2017) integrates KPIOnto and Transmodel ontologies to support monitoring of public transportation systems. KPIOnto captures generic concepts related to Key Performance Indicators (KPIs), whereas Transmodel corresponds to a representation of the TDM: Transmodel Data Model, a European reference model (a public transport data model). In effect, Transmodel is a meta-level transportation ontology that defines three classes for the conceptual modelling of public transport information systems: packages, the classes they contain, and the basic types of data that are stored in a particular class. Transmodel and KPIOnto are linked by connecting the Basic Data classes in Transmodel with indicators from KPIOnto. KPIOnto and Transmodel are part of a proposed framework for a system to support the design and analysis of a management system for public transportation systems. Although applications are discussed, no implementations of the ontology have been completed yet[20].

While related to the transportation domain, the concepts in Transmodel (see Fig. 13) are in fact descriptions of information systems. The KPIOnto ontology, depicted in Fig. 14, defines transportation concepts within the following taxonomy:

- KPI
  - o Indicators
  - o Formulas

[18] http://w3id.org/kpionto.

[19] https://github.com/KDMG/tmo note that the Transmodel ontology was not yet officially released and made available online at the time of writing.

[20] Personal communication: Emanuele Storti on November 27, 2017.

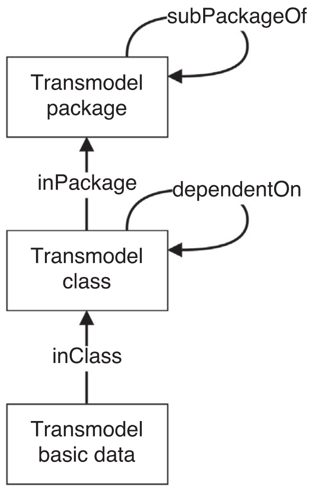

Fig. 13. Depiction of the Transmodel ontology, redrawn from Benvenuti et al. (2017).

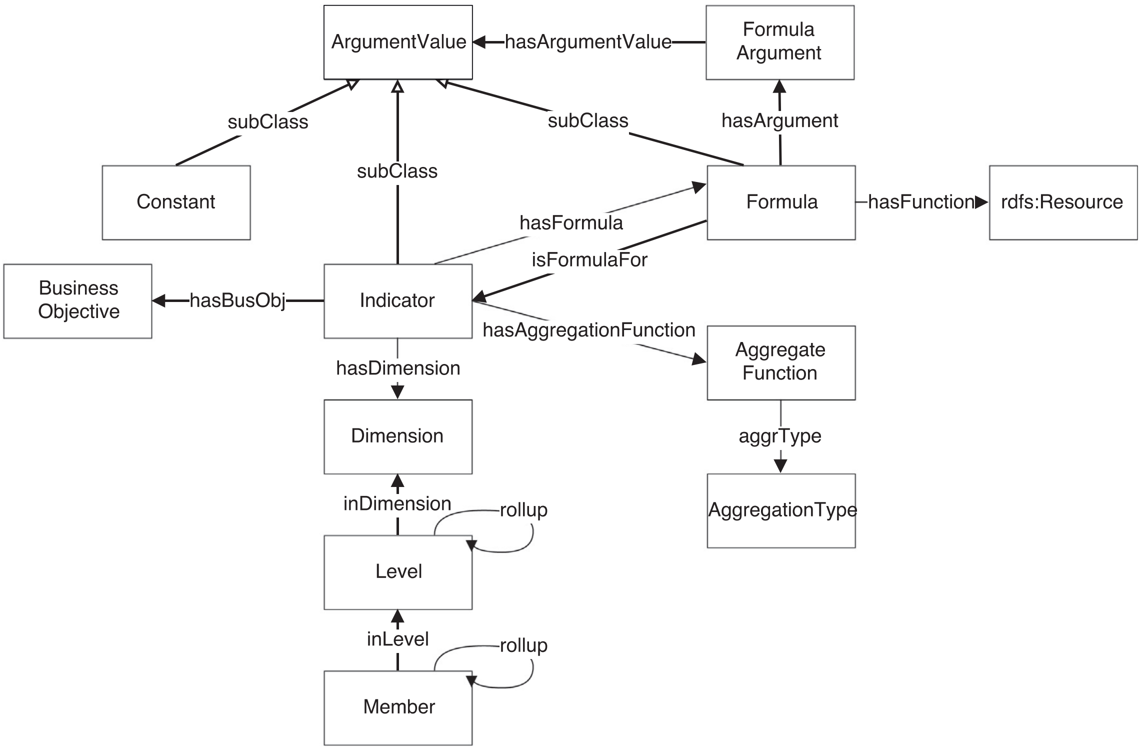

Fig. 14. Depiction of the KPIOnto ontology, redrawn from Benvenuti et al. (2017).

Precision:

Diversity: Combined across both ontologies:
subclass-of axioms = 0, non-subclass relationships = 11
11/11 = 1
Therefore we find the combined ontology to have a Level 5 diversity.
Complexity: The ontologies define its concepts at a single level (no subclasses) and without additional axioms, therefore we find it to have a Level 0 complexity.

Evaluation: Level 3. The documentation indicates that the ontology has been evaluated for consistency, and a functional evaluation has been performed on its implementation in with the logic programming language Prolog (Bratko, 2001).

Knowledge management services: Level 3. The ontology supports reasoning with Prolog.

Generality: General The defined KPIOnto concepts are general, as are the individuals defined in the Transmodel ontology. However, it is worth noting that the classes defined in the Transmodel ontology are specific to the reference data model (e.g. Packages) and so in this sense the definitions are not generally applicable to the transportation domain.

Granularity: The Transmodel ontology is not granular, while KPIOnto does provide the structure to define indicators at varying levels of granularity, the ontology itself does not define concepts at varying levels of granularity.

Competence: The competencies are indirectly specified in a review of reasoning functionalities and a discussion of the potential applications for a performance monitoring system. At a high-level, they are: manipulation of formulas, dependency analysis between indicators and data, and assessment and comparison of indicators.

Span: 4%. The ontology captures 2 of the 46 identified classes.

5.10. km4City[21]

The km4City ontology, presented by Bellini, et al. (2014) is part of a larger smart city effort. Its aim is to facilitate the verification and integration of city data, and through this to make data more accessible for applications as well as general query answering. The ontology is designed to address seven main areas, termed “macroclasses”: administration, street-guide, point of interest, local public transport, sensors, temporal, and metadata. A representation of the street guide is illustrated in Fig. 15. Note that several classes from the Ontology for Transportation Networks are reused here (prefixed with “otn:”). The ontology is implemented for data integration as part of the Km4City Platform which aims to generate value from data, for example with the generation of dashboards for monitoring indicators, the provision of services to engage city users, and the provision models for administration.

The ontology defines transportation concepts within the following taxonomy:

- Location
- Space
- Geometry
- Time
- Manifestation
- Unit of Measure
- Location Feature
- Meteorology
- Activity
  - o Disruptive Event
  - o Operator action (maneuvers made on a road)
- Organization
- Transportation Network
  - o Rail
  - o Road
  - o Transit
  - o Administrative Road

Precision:

Diversity: subclass-of axioms = 692, non-subclass relationships = 104
104/692 = 0.15
Therefore we find the ontology to have a Level 1 diversity.
Complexity: The ontology defines its concepts with a taxonomy and specifies some additional axioms, therefore we find it to have a Level 2 complexity.

Evaluation: Level 0. No evaluation of the axioms was described or referenced in the documentation

Knowledge management services: Level 2. The ontology supports query answering with SPARQL.

Generality: General The defined km4City concepts are generally applicable to the transportation domain.

Granularity: Granular Some areas of the domain (e.g. roads) are defined at multiple levels of abstraction.

Competence: Competency questions are not specified or assessed, although it is clear from the discussion of its implementation that the ontology is capable of answering a range of queries.

Span: 37%. The ontology captures 17 of the 46 identified classes.

[21] http://www.disit.org/km4city/schema.

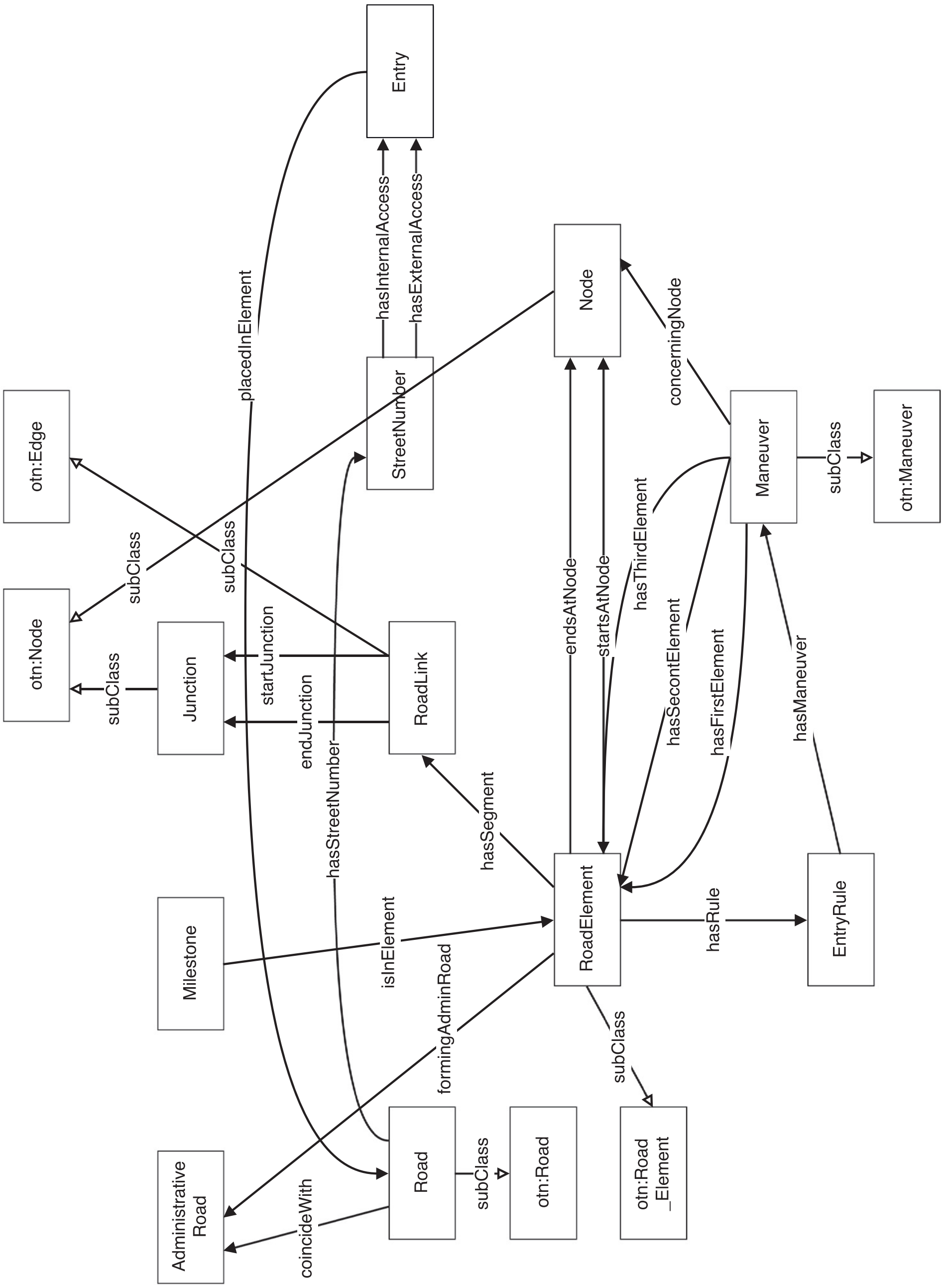

Fig. 15. Depiction of the street-guide macroclass,). reproduced from Bellini, et al. (2014

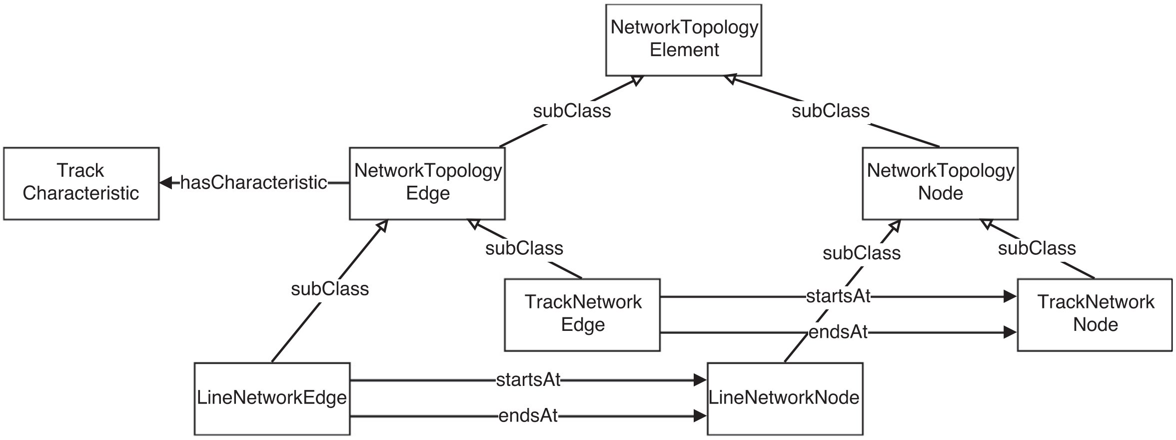

Fig. 16. A high-level view of the Network Statement Checker ontology,).
reproduced from Verstichel et al. (2011

5.11. Network Statement Checker Ontology

The Network Statement Checker Ontology (NSO) is a result of the InteGRail project (Verstichel, et al., 2011; InteGRail Consortium, 2009) (see Fig. 16). A network statement refers to the information required to check the feasibility of running a train on a given track. The purpose of the NSO is to integrate information contained in the network statements from different railways. The ontology encoding could not be located online, however a copy was obtained via direct contact to the authors.

The NSO is an extension of the InteGRail core ontology. Although it is specific to railways, the ontology identifies many generic transportation network concepts. The ontology captures both a logical and physical representations of the network, e.g. distinguishing between train lines and the physical tracks. It is then extended to capture information associated with these network elements, as defined by different railway organizations. The ontology has been implemented in a network checker proof of concept application to integrate network statements from The Netherlands and Belgium. The ontology defines transportation concepts within the following taxonomy:

- Location
- Time
- Unit of Measure
- Activity
- Transportation Network
- Railway

Precision:

Diversity: subclass-of axioms = 216, non-subclass relationships = 53
53/216 = 0.25
Therefore we find the ontology to have a Level 2 diversity.
Complexity: The ontology defines its concepts with a taxonomy and specifies some additional axioms, therefore we find it to have a Level 2 complexity.

Evaluation: Level 3. The ontology was formally verified against a set of queries. What's more, the processing time for the queries was assessed for different implementations of the ontology.

Knowledge management services: Level 2. The ontology is demonstrated in an implementation to support the retrieval of facts via SPARQL.

Generality: General Though primarily restricted to the railway, the ontology defines concepts that are generally applicable for transportation domain.

Granularity: Granular The ontology defines the domain at various levels – at the network-level and also at the level of the individual edges that make up different connections in the network.

Competence: Though not explicitly defined as competency questions, the following queries are used in the evaluation of the ontology:

- Query 1: retrieve all LineNetworkEdges from the repository.
- Query 2: retrieve all the nodes interconnecting these LineNetworkEdges.

Table 2
Results summary.

Ontology	Relationship Diversity Level	Axiom Complexity Level	Evaluation Level	Knowledge Management Services Level	Generality	Granularity	Competence assessed or specified? (Y/N)	Span
5.1 Transportation Ontology for Content Personalization	Level 2	Level 2	Level 0	Level 3	General (mixed)	Not granular	Yes	26%
5.2 Ontology for Transportation Networks	Level 1	Level 2	Level 0	Level 0	General	Granular	No	32%
5.3 The Transport Disruption Ontology	Level 1	Level 2	Level 0	Level 2	Not general	Not granular	Yes	24%
5.4 Ontology Based Road Traffic Management	Level 1	Level 2	Level 0	Level 3	Not general	Not granular	Yes (indirectly tested)	11%
5.5 Road Accident Ontology	Level 3	Level 1	Level 0	Level 0	General	Not granular	No	13%
5.6 Osmonto	Level 1	Level 1	Level 0	Level 2	Not general	Not granular	No	11%
5.7 GenCLOn	Level 1	Level 2	Level 2	Level 3	General (mixed)	Not granular	No	26%
5.8 iCity	Level 1	Level 2	Level 2	Level 0	General	Granular	No	50%
5.9 KPIOnto and Transmodel	Level 5	Level 1	Level 3	Level 3	General	Not granular	Yes	4%
5.10 km4City	Level 1	Level 2	Level 0	Level 2	General	Granular	No	37%
5.11 NSO	Level 2	Level 2	Level 3	Level2	General	Granular	Yes	15%

- Query 3: retrieve all characteristics of the track sections.

Span: 15%. The ontology captures 7 of the identified 46 classes.

6. Discussion

This survey of existing ontologies provides an indication of some possible implications of this technology for the transportation community. Yet in view of the capabilities of ontologies discussed in Section 2.1, the full extent of these opportunities is yet to be explored. To continue to develop this area requires further work on the part of the ontologists, and continued cooperation with the transportation research community.

A comparison of the ontologies' scope coverage is summarized in Table 1, and a comparison of the assessment criteria results is summarized in Table 2. The variations in scope, as well as characteristics such as granularity and generality are easily explained by the diverse applications of these ontologies. The integration of transportation information from various sources is a common focus. This is likely due to the variety of sensors and other sources of transportation knowledge. The integrated information may be processed further, or simply retrieved on the fly in order to provide travel guidance to users at an individual level, as seen in the ontologies for content personalization (de Oliveira, et al., 2013), transport disruption (Corsar, et al., 2015), and road traffic management (Bermejo, et al., 2013) for example. In other instances, location and sensor information is integrated for a more general-purpose analysis, to provide a better understanding of some part of the transportation or to formally define some existing standard, such as Lorenz et al. (2005) and Codescu et al. (2011).

With so many application-driven ontologies, it is no surprise that overall the transportation ontologies rated high for knowledge management services. The applications also serve to explain the range of diversity and complexity results that were found; the ontologies' varied applications result in varied requirements for the semantics and scope. Consequently, we have found that coverage of the transportation domain is distributed; there is no single ontology that covers all of the concepts relevant for transportation research. This leads to an important distinction in the ontologies' breadth and depth: while most of the scope is *collectively* covered by the ontologies in the survey, varied levels of complexity and diversity indicate that not all of the scope is satisfactorily defined for all ranges of applications. For example, while the Road Accident Ontology has a high level of relationship diversity, it only covers the concepts of Vehicles, Transportation Network, Time, and Space. Ontologies that cover the other concepts do so with a relatively lower level of relationship diversity. Granularity and generality too, cannot be found consistently for the entire scope.

Few ontologies demonstrated a high level of evaluation or competency questions. It is possible that evaluation was performed but the details were omitted from the publications, nevertheless, this omission may be a barrier for those looking to reuse these ontologies for their own applications. This is not a new issue; however, it is perhaps symptomatic of the range of time over which this existing work has been published. It is only relatively recently that some publications have begun to make the availability and evaluation of ontologies mandatory for submissions.

Consideration of the Span values in comparison to the other criteria yields an interesting observation. There is a general trend of higher Span percentages corresponding to lower scores in the other criteria. Conversely, transportation ontologies that score high for diversity, complexity, evaluation, and services tend to have more restricted scopes. This is not surprising, as it is certainly easier (and more reasonable, for a single project) to develop a robust ontology for a restricted scope than to attempt to address the entire domain. It does however, point to opportunities for improvement.

While the survey does not reveal any glaring omissions of transportation sub-domain ontologies, (though we certainly do not claim that there are none) these scores point to issues of completeness in both breadth and depth. To address this, it might be suggested that the ontologies with higher Span percentages should be extended to increase the robustness of their content. An alternate approach might be to attempt to combine the ontologies with smaller scopes, but higher diversity, complexity, evaluation and services scores. For either approach, we observe that there will still be holes that will need to be addressed, whether in terms of the robustness or the scope of the ontology. However, such an integrated ontology would likely be of immediate use for linked data applications; it would capture the connections between the reused transportation ontologies, and so would provide a means of linking data resulting from previous work.

Unfortunately, crafting such a combination of ontologies is not a straightforward task. Although the collective scope of these ontologies is quite comprehensive, there is also considerable overlap. Each of these ontologies was created with a different application in mind, so in places where the scope overlaps it is not immediately clear how the semantics are related. A critical direction for future work in the ontology community will be in ontology alignment (Ehrig, 2006; Euzenat and Shvaiko, 2007) between these existing ontologies. Ontology alignment refers to the task of defining semantic correspondences between terms in different ontologies. As an example, what is defined as an "Auto" in one ontology may be the same as what is defined as a "Car" in another ontology, (on the other hand, the meaning may also differ). This is critical in order to ensure the shareability of information that captured with the ontologies, and to improve their reusability in the future.

7. Conclusion

This work provides a comprehensive survey of existing transportation ontologies to serve as a useful resource for both the applied ontology and transportation research communities. The results of this survey may be extended by future efforts in a number of directions.

It may be interesting to identify the formal relationship between these ontologies via more precise techniques of ontology mapping. For ontologies that capture the same concepts, *what semantics are shared between them? What semantics differ?*

The results of this survey could also be extended with the consideration of perspicuity. Perspicuity raises the question: how clear and easy to understand is the ontology? It is a characteristic identified by Fox (Fox, 1992) that we have not assessed in this survey. The names given to the classes and properties as well as the way in which the axioms are defined are all contributing factors. As a subjective characteristic, it's not clear how best to evaluate perspicuity, especially in specialized areas such as transportation research. One possibility might be to assess the percentage of terms (classes and properties) that appear as terms in DBPedia (Lehmann, et al., 2014) or some other standard source of terminology. Alternatively, an approach involving subject matter expert review may be more effective. Either approach makes the somewhat naive assumption that the most clear and easy to understand representations are those that use common, recognizable concepts, as opposed to those that introduce new or obscure terminology. While the terms used to define classes and properties do not guarantee that the definitions or the (intended) semantics themselves are easily understood, it is these terms (along with any documentation) that provide the basis for someone to attempt to gain an understanding of the semantics. Further consideration should be given to assessing this attribute as it is an important quality of ontologies, however this is a more general research question for the ontology community and is outside the scope of the survey we present here.

Most importantly, this survey identifies opportunities to expand and build on ontologies for transportation research. No single ontology captures the entire high-level transportation taxonomy. The results of this survey, and feedback from the transportation community shall serve as input for the continued development of transportation ontologies. As the breadth and depth of these resources is developed, opportunities for interesting applications within the transportation domain can be expected to increase.

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