Lost in Time, Space, and Meaning

An Ontology-Based Approach to Road Traffic Situation Awareness

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Abstract. Situation awareness in road traffic management[3] aims at determining the meaning of information by examining relations among traffic objects in time and space, thus being a candidate for applying ontologies. Existing ontologies for situation awareness are, however, only partly applicable, since they primarily focus on a quantitative representation of time and space and do not sufficiently attend qualitative issues which are a crucial prerequisite for road traffic management. This paper contributes a set of requirements for road traffic situation awareness derived from typical road traffic management scenarios. On this basis, an ontology for road traffic situation awareness is extended by concepts identified in existing, well-established spatio-temporal calculi. The applicability of these concepts is demonstrated using the exemplary road traffic management scenarios.

1 Introduction

Achieving *situation awareness* (SAW) or *context awareness* (CAW)[4] involves the determination of the *meaning* of information about physical objects in highly-dynamic, heterogeneous environments. By the derivation of relations[5] among these physical objects [3], they are, depending on, e.g., the application domain or the assessing agent's purpose, clustered to situations. Consequently, actions can be taken based on the identified situations. *Ontologies* have been recently regarded to be beneficial for SAW [3], since they allow, for example, a formal approach to model context [4].

[3] Our work is partly supported by the ASFINAG Traffic Telematics Ltd. which, among others, develops and operates the Traffic Management and Information System (TMIS) for Austrian's highways [1].

[4] In the scope of this paper, the notion SAW is used as a synonym for CAW; cf. Dockhorn Costa et. al. [2] for the notion of situations in CAW.

[5] The notion of relation is used with its mathematical interpretation in mind.

A prominent environment for SAW applications is the field of road traffic management, in which agents control road traffic based on the assessed traffic situations using either direct measures (e.g. by means of speed controls) or indirect measures (e.g. via warning messages) [5].

The notions of *time* and *space* are ubiquitous in road traffic management and, actually, in SAW applications in general (c.f. [6]). For reasoning about situations that involve traffic objects with their spatio-temporal locations, the *quantitative* representation of these locations (e.g. coordinates) is not sufficient; rather, *qualitative* approaches employing primitive, spatio-temporal relations (e.g. "in the area of") should be utilized [7]. As an evaluation of existing SAW ontologies has shown [8], such qualitative aspects of time and space are still not sufficiently attended.

After an overview of related work in Sect. 2, this paper provides a set of requirements for road traffic SAW derived from typical road traffic management scenarios (Sect. 3). On this basis, an ontology for road traffic SAW is extended by concepts identified in existing, well-established spatio-temporal calculi (Sect. 4). The applicability of these concepts is demonstrated using the introduced road traffic management scenarios (Sect. 5). It has to be emphasized, however, that the proposed combination of concepts in terms of an ontology is only a first step towards an actual proof-of-concept implementation in a road traffic management system. This next step is also addressed in Sect. 6, in which we summarize the contribution of the paper, state lessons learned, and describe further prospects of our work.

2 Related Work

Considering related work, it is first of all interesting to note that there are currently, to the best of our knowledge, no specialized, formal ontologies for the area of SAW in road traffic management. Consequently, in this section, we present an overview of domain-independent SAW ontologies that are applicable to road traffic management and examine their qualitative spatio-temporal concepts. In a still larger context, we also have a look at common top-level ontologies, since they naturally model all aspects of time and space.

As has been shown in our evaluation done in [8], existing domain-independent SAW ontologies scarcely support qualitative spatio-temporal concepts. An exception is the Standard Ontology for Ubiquitous and Pervasive Applications (SOUPA) by Chen et. al. [9]. SOUPA supports temporal concepts adhering to the DAML-Time[6] ontology, whereas the incorporated spatial concepts are influenced by OpenCyc[7] and OpenGIS[8]. Unfortunately, Chen et. al do not provide explicit use cases or a motivation for their chosen spatio-temporal concepts. Moreover, it is unclear how spatio-temporal reasoning is enabled and universality regarding the plurality of spatio-temporal aspects is ensured.

[6] http://www.cs.rochester.edu/~ferguson/daml
[7] http://www.opencyc.org
[8] http://www.opengeospatial.org/standards/gml

The Context Ontology Language by Strang et. al. (CoOL, [10]) is not itself an ontology for SAW; rather, it is an interoperable language for representing contexts using ontologies. CoOL is based on the ASC model (Aspect-Scale-Context) which enables the association of objects with context information in different scales and aspects. Strang et. al. provide a basic set of aspects and scales as well as mappings between different scales (e.g. between nautical miles and kilometers). These concepts include mainly quantitative spatio-temporal information, qualitative approaches that enable reasoning are not mentioned, although the open architecture of CoOL could likely allow an extensions by qualitative scales.

Since SAW ontologies hardly incorporate qualitative spatio-temporal concepts for reasoning about situations, one may suggest the direct usage of spatio-temporal concepts of top-level ontologies via importing respectively mapping them into a domain ontology for road traffic management (cf. [11] for such an approach in the domain of personal information management). In the context of our specific application domain, however, such an approach is not feasible due to three reasons. First, we want to omit the burden of a complete top-level ontology on a reasoning engine. Second, top-level ontologies may make ontological commitments that are orthogonal to the requirements of SAW in road traffic management. Finally, we want to keep our ontology as simple as possible in order to ease its usage by domain experts. Thus, we adhere to an approach also taken by SOUPA [9] and employ concepts from qualitative spatio-temporal calculi that underlie the spatio-temporal concepts in most top-level ontologies and motivate their selection on the basis of the requirements of road traffic management.

3 Requirements for Spatio-Temporal Concepts

Situation awareness in road traffic management requires specific spatio-temporal concepts. Starting with rather quantitative, spatio-temporal *locations* of traffic objects, we subsequently identify certain qualitative aspects of time and space. These *qualitative, spatio-temporal aspects* have to be expressible by appropriate *spatio-temporal relations* which form the basis for assessing road traffic situations. Each of the below requirements is motivated by real-world road traffic management scenarios.

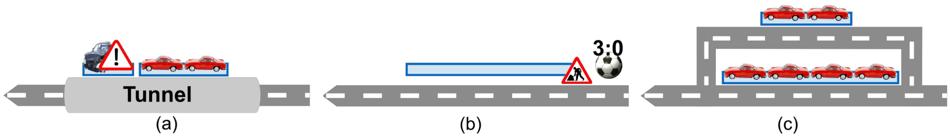

Fig. 1. Three road traffic situations depicting different spatio-temporal aspects

Locations in Time and Space. Road traffic management handles information about traffic objects in the past (e.g. a cleared accident), the presence (e.g. a measured traffic jam), and the future (e.g. scheduled roadworks or forecast black ice). In order to define the requirements for such *temporal* information, we borrow a notion from the field of temporal databases. Information about objects (e.g. the duration of a traffic jam, cf. 1(a)), their attributes (e.g. the length of a traffic jam), and relations with other objects are associated with *valid time intervals* [12]. In order to assess past and future traffic situations, one may thereby choose a corresponding time instant of assessment and examine the valid information at that moment. Regarding the *granularity* of temporal information, seconds are certainly fine enough, as even sensor measurements at every minute are very common in road traffic management[9].

Amongst others, one kind of information that evolves over time is the *spatial* location of an object. In road traffic management, traffic objects are usually located at parts of the road network (e.g. a traffic jam on a directed road segment, cf. Fig. 1(c)), i.e. the abstract structure of space for locating objects should be a *graph* representation of the road network. Regarding the *granularity* of distances in such a graph, meters are sufficient.

Qualitative Spatio-Temporal Aspects. After locating objects in time and space, we want to determine spatio-temporal relations among objects in order to assess road traffic situations at the chosen time instant of assessment. That is, these relations offer the vocabulary for describing relevant, momentary types of situations (e.g. accident "in the area of" roadworks). Such spatio-temporal relations have to express different *qualitative spatio-temporal aspects*. Although there are a lot of such aspects of time and space proposed in literature (cf. [13], [14]), many of them are not really necessary for SAW in road traffic management. The following aspects described in Cohn and Hazarika's overview of qualitative spatial reasoning [13] are motivated by our simple road traffic management scenarios[10]. However, by combining the spatio-temporal relations that express the below aspects more complex traffic situations may be constructed.

Fig. 1(a) depicts the dangerous traffic situation of an accident "in front of" a traffic jam "in" a tunnel. This leads us to the first aspect, *mereotopology*, which allows to express objects being connected with, part of, or overlapping other objects, e.g. a traffic jam "in" a tunnel. The second aspect is *orientation*, i.e. an accident "in front of" a traffic jam. Regarding the spatial orientation in road traffic management, one can implicitly determine the orientation of an object by its location on a directed route segment. The combination of both aspects contributes to the description of the above situation which would lead to a block of the tunnel in a real-world setting.

The next situation, shown in Fig. 1(b), is slightly more complicated with respect to situation assessment and involves roadworks "shortly after the end of" and "near" a football game. In such a situation the roadworks should be

[9] In fact, we focus on highway traffic management which is less granular than urban road traffic management.

[10] Although Cohn and Hazarika provide an overview of spatial aspects only, the adopted aspects of space can be interpreted with respect to time as well.

suspended in order not to obstruct leaving visitors of the football game. This example again depicts two kinds of aspects. The first one is orientation, this time from a temporal point of view, e.g. roadworks are "after" a football game. In addition, being "shortly after" and "near" indicate the aspect *distance* for time respectively space. Finally, note that temporal relations like, for example, "after" are just needed, if we want to express relations that are independent from the time instant of situation assessment, e.g. roadworks are scheduled "after" a football game.

Fig. 1(c) depicts a scenario that may lead to a rerouting of road traffic because of a traffic jam that is "shorter" than a traffic jam "on an alternative route". Whereas "on an alternative route" is a special interpretation of orientation in a road network, "shorter" deals, again from a spatial point of view, with *size*, our last aspect of interest.

Reasoning with Spatio-Temporal Relations. Concerning reasoning with spatio-temporal relations, it would in principle be possible to directly derive all relations among objects by investigating their locations. Since, however, especially space induces a high level of detail, i.e. a large number of route segments that have to be considered, the computational efforts accompanying the derivation are not feasible. Consequently, a first requirement for reasoning with spatio-temporal relations is that one should be able to *infer* relations among road traffic objects. For example, given the two relations in Fig. 1(a) involving an accident "in front of" a traffic jam and the same traffic jam "in" a tunnel, one may infer that the accident is "in" or "in front of" the tunnel.

With spatio-temporal relations that support reasoning processes at hand, the second requirement comes into play. Checking the satisfiability, i.e. determining whether a set of objects satisfies the relations described in a type of situation, has to be *computationally tractable*.

A final requirement in this category deals with *incomplete information* which is evident in road traffic management (e.g. the end of a detected traffic jam is unknown). Adequate spatio-temporal relations have to support the representation of and reasoning with such incomplete information.

4 Spatio-Temporal Concepts

In order to meet the requirements stated above, we identify and combine concepts from various spatio-temporal calculi in the following section. As a prerequisite, we briefly introduce a very basic ontology we have developed for representing traffic objects in a uniform way and extend it step by step using the identified spatio-temporal concepts.

Fig. 2 depicts this basic SAW ontology for road traffic management, which has been developed using OWL[11], and gives some specializations as needed for our scenarios described in Sect. 3. Note that similar basic concepts may be found in most domain-independent or top-level ontologies (cf. [8]).

[11] http://www.w3.org/TR/owl-features

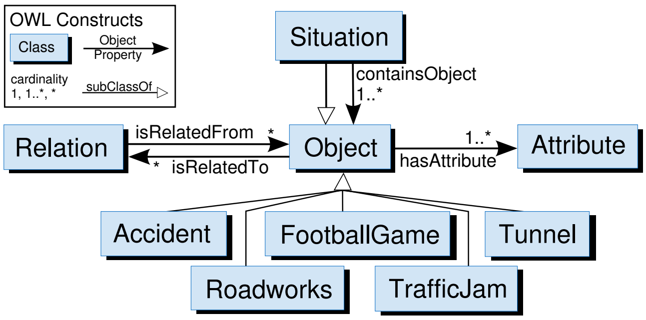

Fig. 2. Basic concepts of our ontology for road traffic SAW

A physical `Object` contributes to situations and has a stable identity (e.g. an `Accident` has, in contrast to a measured velocity, a stable identity). An object is related with other objects by instances of a binary `Relation`, whereas instances of `Attribute` represent the intrinsic characteristics of an object and provide the basic knowledge for deriving relations among objects. Finally, a `Situation` "contains" at least one object (`containsObject`) and is derived from `Object`; thus, situations may be treated as objects.

Fig. 3 shows the below discussed spatio-temporal extensions to our ontology at a glance. In order to get a small and flexible ontology, we swap out the different identified spatio-temporal calculi into ontology modules that can be plugged into the SAW ontology.

Locating Objects in Time and Space. Regarding the *temporal location* of objects, we directly utilize OWL-Time[12] in our ontology. In contrast to a complete top-level ontology, OWL-Time is a small and flexible ontology tailored to temporal concepts, for which a first-order axiomatization, which serves as the basis for deriving temporal relations, is provided. Regarding the level of *granularity*, OWL-Time enables the representation of time instants up to decimal fractions of seconds which are fine enough for our requirements. To cope with our requirement regarding *valid time intervals*, the extensions to our ontology based on OWL-Time are twofold. First, we model valid time intervals of attributes, relations, and situations by adding the object property `holds` to each of the corresponding classes. The range of this property, i.e. a valid time interval, is respresented by the OWL-Time class `ProperInterval`. Second, we add the class `Lifespan`, again borrowed from the area of temporal databases [12], and derive it from `Attribute` as well as associate it with `ProperInterval`. The lifespan, i.e. the valid time interval of the whole object, is the basis for locating objects in time and deriving temporal relations.

In order to deal with the required *spatial locations*, we follow the approach outlined by Bateman and Farrar [14]. Objects do not constitute space themselves;

[12] http://www.w3.org/TR/owl-time

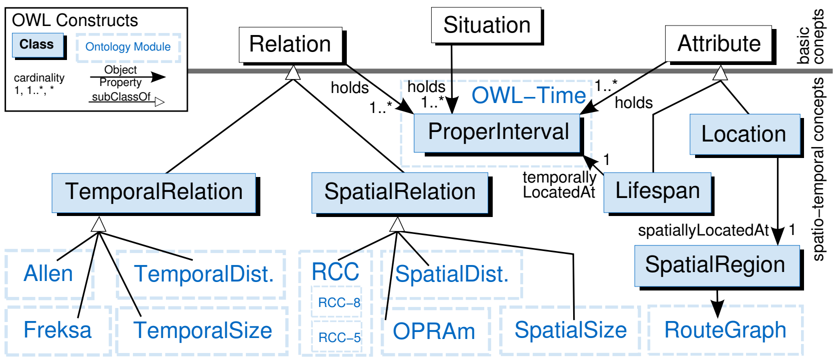

Fig. 3. Spatio-temporal extensions to our ontology for road traffic SAW

rather, they are located at spatial regions in structured space which supports the derivation of spatial relations. A structured space that meets our requirements are route graphs that, although originating from the field of agent navigation, resemble *graphs* of road networks quite well. Roads represent routes, i.e. a sequence of directed segments which are, as common in the field of road traffic management, connected by places like junctions, parking places, etc. Moreover, places have an underlying reference framework—in our case, the number of meters from the beginning of the route which satisfy our requirement regarding the *granularity* of space. In addition, we add the notion of a spatial region and define it as a non-empty set of sequences of route segments[13] that may be occupied by an object. To incorporate spatial locations into our ontology, analogously to `Lifespan`, we derive the attribute `Location` and associate it with `SpatialRegion` (cf. Fig. 3)[14].

Spatio-Temporal Relations. As mentioned in Sect. 3, spatio-temporal relations provided by our SAW ontology for road traffic management should not only express the stated aspects of time and space but also exhibit the desired reasoning capabilities[15].

First of all, the basis for extending our ontology with *temporal relations* is the choice of temporal primitives because these determine the applicable calculi. As we are mainly dealing with time intervals, we suggest time intervals as temporal primitives which are for several reasons preferable to time points [15]. A well-known theory that provides thirteen relations between time intervals (e.g.

[13] Note that we explicitly not use the notion *path*, in order to avoid confusion between position and movement.

[14] We adhere to the modeling approach of separating qualities (`Location`, `Lifespan`) and their peculiarities (`SpatialRegion`, `ProperInterval`), cf. [14].

[15] Since the subsequently introduced calculi alltogether involve more than sixty spatio-temporal relations, it is beyond the scope of this paper to describe them in detail. For an in-depth overview, we refer to related work like [13] or [14].

"before", "during") is Allen's time interval algebra [15]. Regarding the expressible aspects, these relation cover *mereotopology* and *orientation*. Moreover, Allen also provides an approach to *infer* relations based on transition tables. Although checking satisfiability has been proven to be NP-Complete in Allen's interval algebra, there exist tractable subclasses of the problem [16]. Hence, we extend our ontology by Allen's relations. When dealing with incomplete information, however, Freksa [17] argues that Allen's relations are not efficient nor cognitively adequate. Freksa provides an alternative approach based on semi-intervals, that is, relations between beginnings and endings of intervals (e.g. "older", "survives"). According to Freksa, these relations enable efficient, coarse reasoning with incomplete knowledge. Thus, we *additionally* incorporate Freksa's relations and choose the appropriate calculus dependent on the types of traffic situations we are interested in. Furthermore, we add the aspect *distance* in form of quantitative temporal relations (OWL-Time duration) respectively simple qualitative temporal relations ("shortly" and "long"). Regarding duration (*size*), we also add two simple, easily-derived, and transitive relations—an object may live longer or shorter than, respectively as long as another object, whereby equivalents to the latter case can also be found in Allen's or Freksa's relations.

Turning to *spatial relations*, the region connection calculus (RCC) [18], especially its version with eight relations (RCC-8), is well known for representing *mereotopological* relationships between spatial regions. They are similarly incorporated in most top-level ontologies and can be interpreted with respect to our route graphs. Although checking satisfiability in RCC-8 is NP-hard, recent work, especially by Renz et. al. [19], demonstrates that large tractable subclasses of RCC-8 and similar calculi exist. As with time, we additionally incorporate the RCC-5 calculus which enables coarser reasoning. Regarding *orientation*, we just consider intrinsic approaches [20], because we only need binary spatial relations between two objects without third reference points. A very generic and flexible calculus that, amongst others, enables binary relations is the oriented point relations algebra (OPRA_m) [21]. A computational advantage is that OPRA may work with different granularities which enable coarse as well as fine-grained reasoning. Although not very intuitively, the relations may be interpreted with regards to route graphs as well (e.g. two objects are "RightLeft" if they are on parallel, alternative routes to the same destination). Spatial *distance* is treated akin to temporal distance (meters respectively "close", "far", etc). Finally, spatial *size* is also handled similarly to temporal size, but we consider different levels of granularity (e.g "much larger").

Regarding our requirement for reasoning with *incomplete information*, the above calculi for time and space enable the representation of uncertainty by disjunctions of relations among objects (e.g. an accident is spatially overlapping *or* part of a tunnel). This is, however, only necessary if a fine-grained level of detail is needed; when utilizing coarse knowledge one may abstract from these disjunctions by providing specialized relations for such cases (e.g. [17]). Note that there are objects, whose temporal or spatial locations are scarcely known (e.g. the extent of a traffic jam in an area without sensors)—for such situations, disjunctions of relations or coarse relations are certainly sufficient. Even if there is more information available, we suggest that the followed approach to represent incomplete information should still serve as the basis for more sophisticated methods (e.g. the provision of probabilities for disjunctive relations).

A few final notes on *computational tractability*—all of the described calculi employ a joint exhaustively and pairwise disjoint (JEPD) set of base relations. For such arbitrary qualitative spatio-temporal calculi, Renz et. al. [19] have developed an algorithm for identifying large tractable subclasses of the *consistency problem*. In our context, we define the consistency problem as follows: "Given a knowledge base consisting of objects and a not exhaustive set of relations between them, determine whether there is an instance of a given situation type which is consistent with our knowledge base." Although there are several involved reasoning problems (e.g. minimize situation types, cf. [19]), the most important one is to derive unknown relations. As already stated in Sect. 3, the derivation of relations has to be possible without the prior computation of an exhaustive set of relations between all known objects, which is, in fact, exactly our reasoning problem. Since finding unknown relations as well as most other reasoning problems with respect to JEPD calculi can be reduced to the consistency problem in polynomial time [19], it is sufficient to restrict ourselves to tractable subclasses of the consistency problem. Such tractable subclasses restrict the possible disjunctions of relations in a calculus. For example, Renz and Nebel [22] identified a maximal tractable fragment of RCC-8 which incorporates all eight relations and, overall, allows 64 of the 2^8 possible disjunctions of these relations. For our purposes, this subclass suffices[16]. Consequently, the identified calculi can be applied to determine the satisfiability of a situation type in reasonable time.

5 Application to Road Traffic Management Scenarios

With the proposed spatio-temporal extensions to our basic ontology for road traffic SAW and the corresponding inference mechanisms at hand, we are now in a position to describe the types of situations depicted in Sect. 3. Due to its simplicity, we follow the human-readable syntax of the Semantic Web Rule Language[17] (SWRL)[18] for the following formal specification of OWL class respectively object property membership. For reasons of brevity, we suppose that the valid time intervals corresponding to the situation assessment time instant are implicitly chosen.

[16] However, the choice of a subclass is dependent on the calculus and the situation types we are interested in.

[17] http://www.w3.org/Submission/SWRL

[18] Note that SWRL does not allow variables in the consequent that do not occur in the antecedent. To be able to express our examples, we dismiss this language requirement and regard such variables as instances that have to be created in case the rule "fires".

The formalism is further explained by expressing our first scenario in Fig. 1(a):

```
/* Fig. 1(a) */
Accident(?a) & TrafficJam(?b) & Tunnel(?c) &
relatesFrom(?a, ?z) & relatesTo(?z, ?b) & rcc8:ExternallyConnected(?z)
relatesFrom(?a, ?y) & relatesTo(?y, ?b) & opra1:BackFront(?y)
relatesFrom(?b, ?x) & relatesTo(?x, ?c) & rcc5:ProperPartOf(?x) =>
  SituationA(?s) & containsObject(?s, ?a) &
  containsObject(?s, ?b) & containsObject(?s, ?c)
```

This rule, which combines concepts from different spatio-temporal calculi, should be read as follows: If between instances of the classes `Accident` and `TrafficJam` the RCC-8-relation `ExternallyConnected` as well as the OPRA_1-relation `BackFront` hold, i.e. an accident is in front of a traffic jam, and the traffic jam is related with an instance of `Tunnel` by an instance of the RCC-5 relation `ProperPartOf`, then a situation containing all three objects is created. This situation is an instance of the class `SituationA`, a derivative of `Situation` that represents the scenario shown in Fig. 1(a). In the following, the two other scenarios shown in Fig. 1 (b) and (c) are similarly formalized.

```
/* Fig. 1(b) */
Roadworks(?a) & FootballGame(?b) &
relatesFrom(?a, ?z) & relatesTo(?z, ?b) & tempDist:Shortly(?z) &
relatesFrom(?a, ?y) & relatesTo(?y, ?b) & Allen:After(?y) &
relatesFrom(?a, ?x) & relatesTo(?x, ?b) & spatDist:Near(?x) =>
  SituationB(?s) & containsObject(?s, ?a) & containsObject(?s, ?b)

/* Fig. 1(c) */
TrafficJam(?a) & TrafficJam(?b) &
relatesFrom(?a, ?z) & relatesTo(?z, ?b) & opra1:RightLeft(?z) &
relatesFrom(?a, ?y) & relatesTo(?y, ?b) & spatSize:Shorter(?y) &
  SituationC(?s) & containsObject(?s, ?a) & containsObject(?s, ?b)
```

Regarding the representation of incomplete information, we return to the first scenario and assume that the exact location of the accident is unknown. Thus, a disjunction of relations would hold among both objects (e.g. also the RCC-5 relation `PartlyOverlapping`). Nevertheless, the situation would be recognized, since the trigger `ProperPartOf` is still valid.

Finally, as shown by their application to all three scenarios, the spatio-temporal extensions to our basic ontology are capable of covering all required qualitative spatio-temporal aspects successfully.

6 Summary and Lessons Learned

In this paper, we have identified concepts from various well-established spatio-temporal calculi that meet the requirements of SAW in road traffic management.

We proposed a first approach to combine these concepts in an appropriate ontology and demonstrated its applicability to a couple of small, real-world road traffic management scenarios. The immediate benefit for a road traffic engineer is that the definition of situation types based on the suggested spatio-temporal relations are application-independent and may facilitate knowledge sharing between traffic management systems.

In the course of this work, it has been shown that the identified spatio-temporal relations should become the *working language* of a road traffic engineer for specifying relevant road traffic situations. Thus, the applied relations should be intuitive and easily understood. Although many of the utilized spatio-temporal calculi originate from the field of cognitive sciences, we believe that their combination may still be too complex. Whether a graphical user interface hiding technical issues solves this problem is an open issue.

Another interesting issue that came up is that, although we selected the spatio-temporal concepts with road traffic management in mind, we believe that they are—maybe extended by further aspects of space and time—applicable in a more general, domain-independent context. This may be achieved by factoring out all domain-independent concepts and combining them into a *domain-independent* ontology for SAW applications, which could leverage qualitative spatio-temporal concepts in contrast to related work.

Regarding future prospects of our work, we are currently incorporating our ontology into a framework for SAW in road traffic management. In the near future, we are going to deploy a prototypical implementation of this framework in a road traffic management system in order to support traffic operators achieving SAW in complex road traffic management scenarios.

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