Rule-based vehicle-pedestrian interaction

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Contents

This report refers to the exploitation of explicit representation of knowledge (through an ontological conceptualization) for enhancing the behavior of active system that support decisions making of autonomous driving vehicles. In particular the interactions with one or more pedestrians crossing vehicle driving path are the reference situation we are focusing on and the reduction of collisions (risk) is our vehicle performance reference behavior.

The present document collects the main results of a plausibility studied, primarily oriented at assessing the exploitation of explicit knowledge approach to conceive an ADAS (Advanced Driver-Assistance Systems) that improve the vehicle performance on road environments populated by other (non-vehicles) autonomous entities that is, pedestrians crossing the vehicle driving planned path. These activities can be summed atp as follows:

- Analysis of ADAS context and the AI technologies (specifically focused on rule-based technologies for the explicit representation of coordination knowledge involved in interactions situations of autonomous entities

- Structured library of studied research context within L.Int.Ar. documentation in sharable and open (but restricted to L.Int.Ar.);

- Proposal of a model of autonomous driving vehicle compliant with ontology-based knowledge representation and rule-based reasoning technology. The latter has been developed taking into account available state of the art in this research context and with specific reference to the autonomous vehicle developed at DISCO (by IRA lab) [1];

- Proposal of a functional component to be integrated into an autonomous driving vehicle model based on rule-based technology, to explicitly represent heuristic knowledge about pedestrian crossing behaviours. The latter results from observation studies conducted at Complex Systems and Articial Intelligence (CSAI) research center of DISCo [2].

- Development of the prototype of an ontology (as plausibility demonstration tool) for the explicit representation of the knowledge related to pedestrians' known behavioral dynamics at intersections (i.e.pedestrian crossing vehicle path on crosswalk).

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Expert competences that have been involved in Knowledge Acquisition campaign are:

- Prof. Domenico Sorrenti, Informatica e Robotica per l'Automazione (IRA) lab: he studies autonomous driving systems and developed a working hardware prototype that is able to navigate autonomously in areas shared with the presence of pedestrians;
- Andrea Gorrini, Complex Systems and Artificial Intelligence (CSAI) research center: from 2015 he has been coordinating experimental activities on pedestrain dynamics observations;
- Luca Crociani: he studies pedestrian dynamics modelling and simulation. With Luca it has been considered the plausibility of microsimulation approach to evaluate effects at macro level of the proposed vehicle-pedestrian interaction modelling;

1 Introduction to Research Context

Safe, accessible and convenient mobility has always been one of mankind's challenges. The increasing number of vehicles lead to the progressive modernisation of driving spaces with the construction of new roads, and with the installation of traffic lights, signs, round- abouts, etc. The whole is ruled by several laws and regulations, and the most common one among nations is the Vienna convention[3]. Among the most relevant issues on which automotive industries invest is the reduction of the number of fatalities and therefore the enhance of safety (see figure 1) [4]. For this purpose it is possible to distinguish passive devices, which intervenes after the accident to limit injuries on the passengers, and active systems designed to avoid accidents, or at least to reduce their effect. Whilst initial efforts were focused on passive devices such as seat belts and airbags, today's efforts focus on active systems like ABS (Antilock Braking System), ESP (Electronic Stability Program), ASR (Acceleration Slip Regulation) and ADAS (Advanced Driver-Assistance Systems). Motor vehicles are undergoing a rapid transformation from essentially electromechanical systems to computer controlled complex systems. That is, the control of vehicles is progressively being taken over by computer systems. Accordingly to the trends of automotive industry (see Figure 1), we can envision future vehicles populating our streets to become complex, software dependent, sensor-based platforms that improve their functional behavior at an accelerated pace.

The state of art define five categories of automation corresponding to the functionalities that the vehicle will be able to perform [4]. Figure 2 illustrates the five level of automation defined by SAE International. In this work we refer to the last levels where the automation is full and human intervention is no more needed for the driving task. They are listed with progressive numbers increasing along with the level of automation of the vehicle. The table is divided in two main blocks. The first one indicates the stages in which a human driver is monitoring the driving environment, indeed the onboard computer system is capable to support the driver with systems like advanced cruise control which can autonomously steer and keep lanes safely but prompts from the driver are still needed. While the second one indicates the stages in which the car is capable of monitoring the driving environment, this means that the human intervention, in level 3 is required only for emergencies or navigation, and in levels 4 and 5 is not needed at all; The passengers can be completely absent and even go to sleep. The main difference from both is that in level 4 it is possible to enable autonomous driving only under certain circumstances like traffic jams, while in level 5 the car has the ability to chose several driving modes for itself to handle every situation.

Cars have been increasingly equipped with technology, meeting the demand of people for safety, connectivity, and comfort. Upcoming technology provide access to in-car systems and web service in a personalized manner that facilitates a large array of functionalities even while driving, with other passengers also benefiting from an enhanced experience. Such intelligent applications however depend on a solid basis to be effective on personalization, adaptive human-machine interfaces, situation-aware intelligent

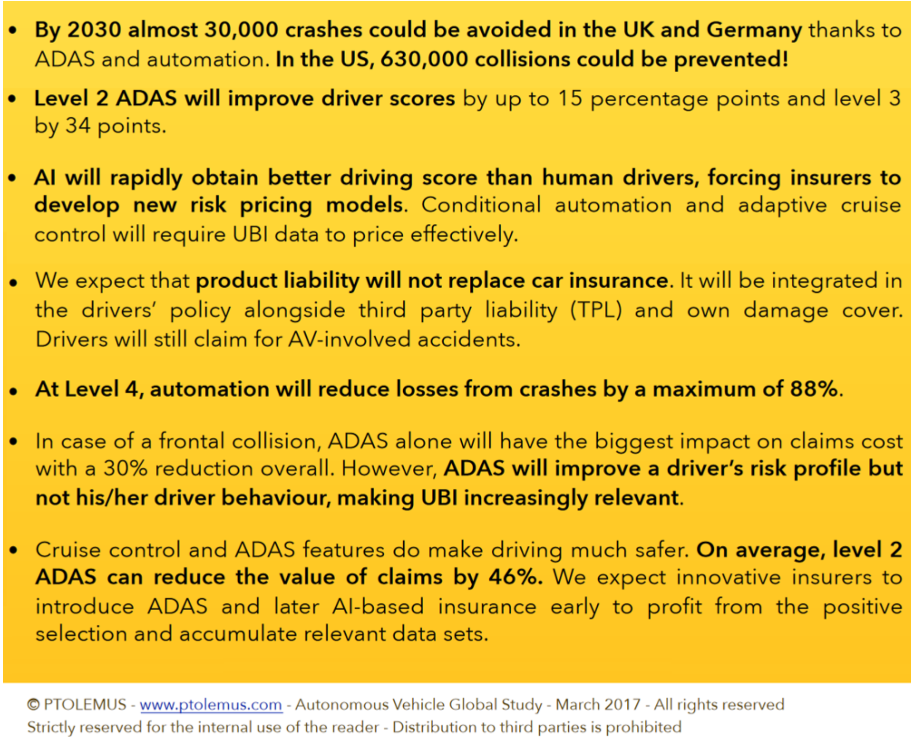


Figure 1: How will automation impact risks? [4]

systems, systems to avoid collisions. Either of those require semantic knowledge about the user, the vehicle and the current driving situation[6]. Ontology-based approach [7][8][9][10] [11] has profitably been investigated to provide the required solid knowledge representation for next generation intelligent in-car systems and formal representational languages [12] is demonstrated to be enough expressive and practicable to enable context understandig [13][14][15].

For intelligent systems, both natural and artificial, knowledge is an essential element. In that way, intelligence can be defined as the faculty to capture, process, reuse and share this knowledge. Whilst performing these tasks is a natural thing for living being gifted with intelligence, it remains complex for machines. As a technical solution, ontologies represent an Artificial Intelligence tool (AI) which enables to artificially perform these tasks. As it will be discussed in section 3, we'll exploit ontology representation of knowledge about pedestrian behaviour at intersection to improve scene understanding and decision making. The main references are: a simple ontology that includes context concepts such as Mobile Entity (Pedestrian and Vehicle), Static Entity (Road Infrastructure and Road Intersection), and Context Parameters(isClose, isFollowing, and isToReach) [13] and an ontology-based framework for assessing the degree of risk in a road scene designed to cater for risk related to several factors, such as risk from objects (vehicles, pedestrians, cyclists etc.), environmental risk (weather and visibility condition) and road

SAE Level	Name	Narrative definition	Execution of steering and acceleration/ deceleration	Monitoring of driving environment	Fallback performance of dynamic driving task	System capabilities (driving modes)
Human driver monitors the driving environment						
0	No automation	The full-time performance by the human driver of all aspects of the dynamic driving task, even when enhanced by warning or intervention systems	Human driver	Human driver	Human driver	n/a
1	Driver assistance	The driving mode-specific execution by a driver assistance system of **either steering or acceleration/deceleration** using information about the driving environment and with the expectation that the human driver performs all remaining aspects of the dynamic driving task	Human driver + system	Human driver	Human driver	Some driving modes
2	Partial automation	The driving mode-specific execution by one or more driver assistance systems of **both steering and acceleration/ deceleration** using information about the driving environment and with the expectation that the human driver performs all remaining aspects of the dynamic driving task	System	Human driver	Human driver	Some driving modes
Automated driving system (system) monitors the driving environment						
3	Conditional automation	The driving mode-specific **performance** by an automated driving systems of all aspects of the dynamic driving task **with the expectation that the human driver will respond** appropriately to a request to intervene	System	System	Human driver	Some driving modes
4	High automation	The driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task **even if a human driver does not respond** appropriately to a request to intervene	System	System	System	Some driving modes
5	Full automation	The full-time performance by an automated driving system of all aspects of the dynamic driving task **under all roadway and environmental conditions** that can be managed by a human driver	System	System	System	**All driving modes**

Source: SAE International, Blue denotes human control and green denotes machine controlled

Figure 2: Levels of automation and description.

environmental risk (road quality, road traffic signs and road types)[14]. Applying rules written in *Semantic Web Rule Language* (SWRL), the ontology is able to process human-like reasoning on global road contexts [13] .

Result of that research have inspired Toyota researchers to another related ontology, developed with the same tools and the same concepts but with a little differences, the most considerable difference is the result of the reasoning, that is a value which corresponds to a variation in speed [15]. This last research is also an extension of [13] .

2 Vehicle-Pedestrian interaction at intersections

Goals	*Resources*	*Skills*	*Situation Type*	*Category*
Compatible	Sufficient	Sufficient	Independence	← Indifference
Compatible	Sufficient	Insufficient	Simple Collaboration	
Compatible	Insufficient	Sufficient	Obstruction	Cooperation
Compatible	Insufficient	Insufficient	Coordinated Collaboration	
Incompatible	Sufficient	Sufficient	Pure Individual Competition	
Incompatible	Sufficient	Insufficient	Pure Collective Competitions	
Incompatible	Insufficient	Sufficient	Individual Resource Conflicts	Antagonism
Incompatible	Insufficient	Insufficient	Collective Resource Conflicts	

Figure 3: Types of interaction situations [5].

The research addressed in this report refers to an active module designed to reduce the risk of collision in the interaction with one or more pedestrians crossing the vehicle path. According to [5] the interaction situation occuring at intersection is recognised as obstruction.

An *interaction* occurs when two or more agents are brought into a dynamic relationship through a set of reciprocal actions. The latter can develop out of a series of actions and influence the future behaviors of agents; agents' interactions may be direct, through other agents, or through the environment.

Interaction situations are numerous and varied. As sketched in Figure 3, they are usually classified in relation to three main criteria: the objectives or intentions of the agents (*Goals*), the relationship of these agents to the resources they have available (*Resources*), and the skills available to them to achieve their goals (*Skills*).

- **Goals:** can be
  - incompatible: two goals, P and Q are *incompatible* if achieving one means the other cannot be achieved.

$$\mathrm{P} \rightarrow \neg \mathrm{Q}$$

  - compatible: two goals are *compatible* if they are not incompatible!
- **Resources:** include all the environmental and material elements that can be used in carrying out an action (e.g. space, time, access, etc.). Limited quantities of resource eventually lead to conflicts. Conflicts occur when two agents need the same resource at the same time and/or space.
- **Skills:** define whether or not any agent can carry out its tasks autonomously.

Cars on the road, airtraffic control, optimal use of resources such as scheduling use of time, stock management, placing tasks on a processors are typical examples of situation interaction named **obstruction**.

Vehicle-pedestrian interaction can be considered an obstruction situation where: any subject have individual skills to employ autonomously the available resources to accomplish their goals, and goals are compatible because pedestrians crossing the road won't compromise the capabilities of the vehicle to go straight on its way and vice versa. On the other hand, in crossing situations where the vehicle and crossing pedestrians paths overlap, both interacting agents need to coordinate their actions in order to share the use of the limited resource represented by the road lane in which the pedestrian wants to cross and the vehicle wants to go on at the same time. As any obstruction situation it requires a conflict resolution strategy to solve it [5]. In this domain, traffic regulations system represent the system of rules that grant (when not violated) successful action coordination.

2.1 Autonomous Driving Vehicle

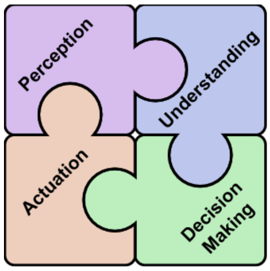


Figure 4: Driving process: major driving tasks[13].

Driving a vehicle implies the simultaneous performance of several tasks. Shortcomings on the ability to perform them often lead to risk situations, and to accidents. This section aims to provide an overview of what driving is, in order to understand how risk situations arise, and to compare human and autonomous vehicle driving process, illustrating the behaviour of the planner in each phase according to the state of art described in [18].
For most people, driving after a few years becomes a collection of mechanical tasks [13]. However, driving is complex, as different tasks are performed in parallel, each responding to the different situations ecountered. For the purpose of this work, four major tasks have been identified for a driver to safely control a vehicle: Perception, Understanding, Decision-Making and Actuation (see Figure 4). In the remaining of this section, we'll adopt this functional decomposition of driving tasks to describe the behavior of an *autonomous vehicle* that could take advantage from a rule-based component in case of intersections with pedestrians.

- **Perception**

  When driving, the first question to be answered is "*What is around my vehicle?*". The driver must be capable to observe the surroundings, to classify the scene into the relevant entities. This is done despite the clutter and occlusions that might occur. The perception task is complex, where experience enables driver to consider mainly the most relevant entities.
  Autonomous vehicle: The vechicle acquires the information about the surrounding environment through a system of sensors composed by two stereoscopic cameras, LIDAR scanner and digital maps. These data are used to build an abstract representation of the robot environment (*world model*) in the form of a set of layouts [1]. Formally:

  $$S\colon data \mapsto \sum$$

  Where S is the sensing function, *data* is the data received from sensors interface and $\sum$ is the robot internal state.

- **Understanding**

  Once the driver has a mental model of the perceived world, it is then necessary to understand the spatio-temporal relatioships between the vehicle and the perceived entities. Those which are relevant are inferred first, and the classified into entities that are in motion, and those that are likely to move. Then, road features that constrain vehicle motions like road signs are considered. Within this context, the driver takes into account all likely interactions and constraints posed by all surrounding entities on his vehicle. Drivers need to gain a full understanding of their situation wherever possibile. Failure to do this often results in driver errors, which may lead to conflicting and dangerous situations.
  Autonomous vehicle: The system associates a degree of reliability to the layouts processed in the previous phase. This probabilistic criteria to decide which is the most realistic representation of the situation is used to disambiguate situations in which some subject could be mistaken for an other, resulting in an incorrect scene evaluation. The layout with the highest likelihood will be chosen over the others to build the world model. When the entities in the scene are identified, spatio-temporal relationships betweene them are estabilished to define the internal state of the robot.

- **Decision-Making**

  Once the driver gains an understanding of his current situation by identifying the relevant entities with regard to his future direction of motion, a process of risk assessment starts. This includes the estimation of the future state of the interacting entities, his own intention, the knowledge of the vehicle capabilities, etc. The collected mental model allows drivers to decide the immediate motion of the vehicle. This implies split-second decisions, particularly in case of difficult driving situations. Extreme situations, e.g. bad weather, hazardous surrounding vehicles may lead to inappropriate decisions favoured by poor driving experience or insufficient situation awareness.
  Autonomous vehicle: All the information about the scene will be trasferred to the planner. Its main role is to provide the vehicle with a safe and collsion-free path towards its destination, while taking into account the vehicle dynamics, its manoeuvre capabilities in the presence of obstacles, along with traffic rules and road boudaries. At anytime the vehicle owns a set of attributes describing its condition in time and space (position,orientation,velocity,angular velocity) called internal *state*, that could be changed consequently to an *action* (acceleration, steering angle). *State space (St)* represents the set of all possible states that the vehicle can be in. *Action space (A)* represent the set of all possible actions that can be applied to the state space. It is possible now to define the motion function M that describes the state transactions.

  $$M\colon St{\times}A \mapsto St$$

- **Actuation**

  Once the decision on the next vehicle manoeuvre is taken, the driver acts on the vehicle controls, e.g. accelerates, brakes, turns the steering wheel. The vehicle then responds accordingly and completes the manoeuvre. This again is subject to driver capabilities, as any latency might hamper the manoeuvre and might result in hazardous situations.

  Autonomous vehicle: For every decision, output by the planner, the vehicle controller, designated to the driving task, is responsible of taking the next manouvre.

For both humans and machines, the four tasks are always simultaneously active as the vehicle response has to be adapted according to the contextual situations. More specificaly, these tasks are executed while the scene is countinuously changing its configuration. This means that a decision made at a given time could be no more valid as it could be in conflict with the new scenario. In the vehicle case, this is why the local planning scheduling is done in the order of milliseconds [18].

2.2 Crossing pedestrians profile

This section aim to define a criteria for modelling the possibile pedestrian profiles that can be met in the road context, in particular during the vehicle-pedestrian interaction, and for that purpose the behavioural model is explicitated through an ontological representation of the latters.
We simplified the profiling since the literature in this field is not rich. By the observation of [2] and [25], it emerged that there are two measurable elements allowing the classification: *age* and the presence of a *group*.

What is a group?

Two or more people who interact to achieve a shared goal [24]

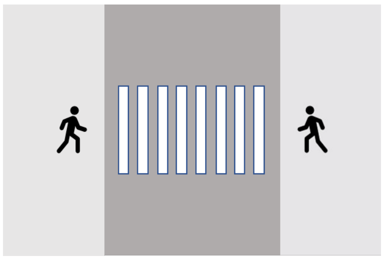


Figure 5

Considering pedestrian crossing, the shared goal is to cross the road. Figure 5 shows the possible ambiguous case, if on both sides there is more than one pedestrian it is considered to be a group and their decision making is influenced not only by their own skill and experience but also by the behaviour of others who happen to be crossing at the same time[25].

Group is defined this way because trascends the age factor of the single component.

The results of [26] indicate that pedestrians' decision making is influenced not only by their own skill and experience but also by the behaviour of others who apper to be crossing at the same time, in fact it has been observed that a risk averse pedestrian in group becomes more propense to risk, on the other hand, a risk seeking pedestrian, in group assumes an attitude less dangerousF.
Then it is possible to be classified as an unique subject in the interaction with vehicles.

The agewise classification helps to define a behavioural profile of pedestrians. Empirical research on pedestrian dynamics oservation has shown, in fact, that the single pedestrians' behaviour is strongly influenced by the age factor [26]. Elderly pedestrians were found to be more likely to die or be seriosly injured in road traffic accidents than adult people due to their body fragility [2, 19, 20] and perceptual and attentional skills likend to ageing [21, 22] requires the elderly do adapt their road crossing decision-making and behaviour. in the range of [25..50] years old.

Crossing behavior of pedestrian [2, 21, 22] can be described by five main properties:

- **Cognitive capability** to cross the road: indicates the subject's capability to estimate the other's motion properties, like distance from the subject and speed. An incorrect evaluation of these properties imply a worng estimation of the necessary time to succesfully cross the road without collisions.
- **Physical capability** to cross the road: indicates the subject's capability to move, that is the maximum speed and the ability to safely overtake obstacles.
- **Assertivity** before crossing: indicates the subject's capacity to let know his intention to cross the road.
- **Compliance** with the rules: indicates how much the pedestrian comply with the traffic rules.
- **Propensity to risk**: indicates how much a subject is willing to put himself in danger to cross the road.

Physical capability and propensity to risk are inversely proportional to the increment of age, while cognitive capability, assertivity and compliance decreases as the age diverges from the one of a reference pedestrian fully compliant to road traffic rules and with full capabilities and assertivity; for the present work, an adult person in the range of [25...50] years old.

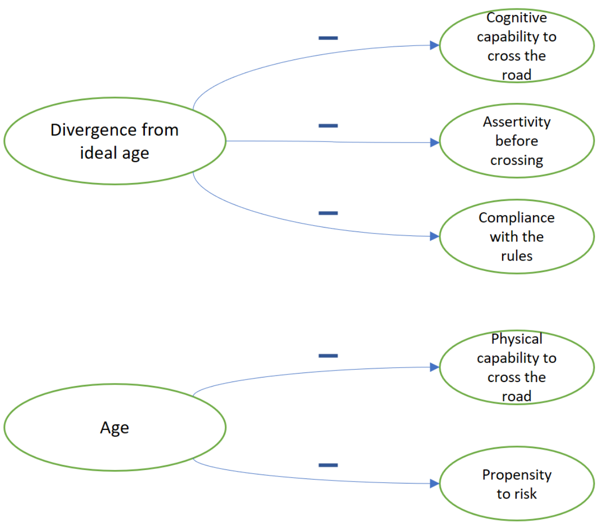


Figure 6

What is described and represented in Figures 6 and 7 is a partial work developed only for demonstrative purpose. It will need a further study on the psichology literature.

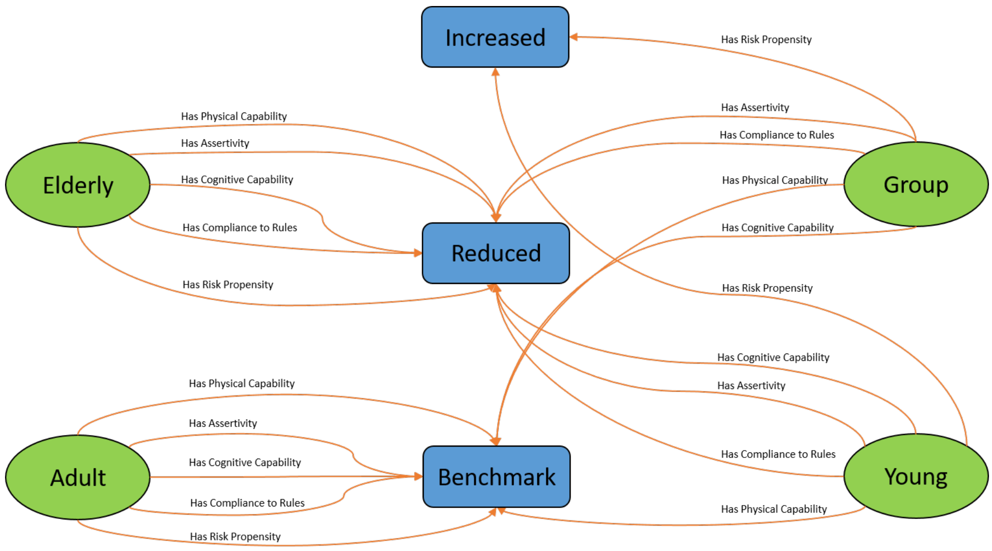


Figure 7

Result from the studies of [2] demonstrated that pedestrians' crossing decision is based on a significant deceleration in proximity of the curb (appraising), as showed in figure 8, to evaluate the distance and speed of oncoming vehicles. Once pedestrians decided to cross there an increase of speed(crossing). Elderlies walked in average 22% slower than adults among the three crossing phases, decelerating 6% more than adults while appraising. This demonstrated also the negative impact of ageing on crossing behaviour in terms of locomotion skills decline.

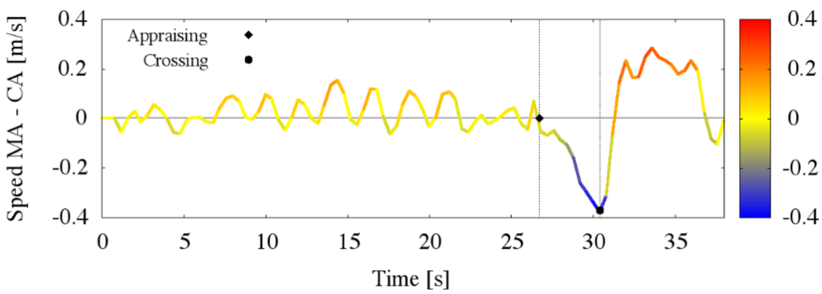


Figure 8: Chart that present the variation of speed overtime. Observe the decay of speed, that indicates the start of appraising phase. MA is Moving Avarage and CA is Cumulative Avarage.

3 Ontology

3.1 Ontologies Principles

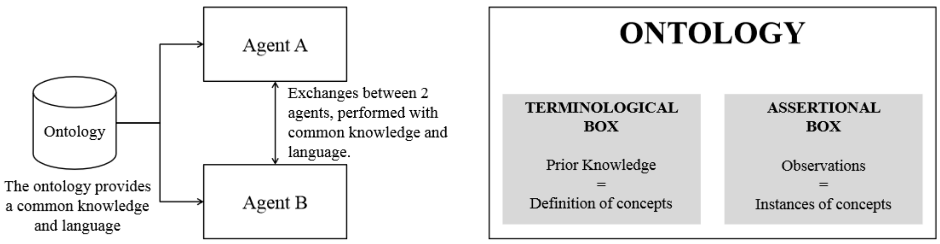
For intelligent systems, both natural and artificial, knowledge is an essential element. In that way, intelligence can be defined as the faculty to capture, process, reuse and share this knowledge. Whilst performing these tasks is a natural thing for living being gifted with intelligence, it remains complex for machines. As a technical solution, ontologies represent an Artificial Intelligence tool (AI) which enables to artificially perform these tasks. This section aims to present the principles of ontologies.

3.2 Definition

The term ontology was first introduced by the philosophers to designate the study of being of existence. It is from the beginning of research in AI that this term started to be employed by researchers of the domain to designate computational models which enable automated reasoning [23]. From this point of view, several definitions of the term were published; the three following are those which are the most often admitted by the literature:

- An ontology is an explicit specification of conceptualization [7].
- An ontology is a theory of vocabulary or concepts used for building artificial systems [8].
- An ontology is a body of knowledge describing some domain [9]

A comparison of these three definitions was done [10]. Whilst these definitions do not mean exactly the same, the principles of ontologies come down to the first definition.



(a) Ontology used by agents (e.g. software) for communication.

(b) Structure of an ontology based on description logic.

Figure 9: Ontology.

It is therefore important to understand both terms specification and conceptualization in the good way. The conceptualization of a domain is the manner how a domain is perceived and understood, and the specification of this conceptualization is actually a formal description of this conceptualization. More concretely, an ontology is a description of the concepts and relationships that are relevant to model a domain of interest. It specifies the vocabulary that is necessary to make assertions, and which may be inputs/outputs of knowledge agents (e.g. software, etc.). Moreover, it provides the language for communication between agents [11]. Figure 9(a) illustrates this definition.

3.3 Description Logic

Ontologies are based on *Description Logics* (DL) which is a formal language for Knowledge Representation [12]. A DL enables to model Concepts, Roles and Individuals through its two functional parts, namely the *Terminological Box* (TBox) and the *Assertional Box* (ABox). Figure 1b illustrates this structure, and the description of these two parts is given below.

Terminological Box (TBox)

The TBox consists of the definition of all the concepts that the ontology aims to describe. An analogy can be done between the TBox and the knowledge that human have. The knowledge that humans acquire along their life is used to understand and to interpret the world. The ontology TBox represents prior knowledge, and the definition of it is performed through the definition of Concepts, Roles and Relations. The following definitions were established after [16].

- **Concepts** (or classes) are concrete representations of the concepts of the domain that the ontology aims to describe. These concepts can be organized into a superclass-subclass hierarchy, which is generally called Taxonomy.
- **Roles** are properties which can be defined and assigned to concepts. Roles can be classified into two groups:
  - **Object Properties** aim to define axioms in the form of Triples . In other words, they are binary relationships between two concepts in the form Concept1 - Object Property - Concept2. Characteristics may be attributed to object properties, such as symmetry or transitivity with respect to other object properties.
  - **Data Properties** are used to assign properties to single classes or instances of classes in the form Concept1 - *Data Property* - Property Value.
- **Relations** between concepts are defined with taxonomic relations (hierarchical relations), axioms (classes linked by object properties) and rules. The definition of rules can be done using basic description logic axioms which only enables the definition of basic class equivalence. More sophisticated languages enable to define more complex and expressive rules. Among these languages, the Semantic Web Rule Language (SWRL) is one of the most common [17].

Assertional Box (ABox)

The ABox consists of the definition of instances of classes previously defined in the TBox. These instances, commonly called Individuals , represent real life data that the ontology aims to interpret. Again, an analogy may be done with humans as the ABox can represent objects that humans observe, and understand thanks to prior knowledge their acquired with experience (TBox). Further, in the same way as properties can be attributed to concepts defined in the TBox, Object and Data Properties can be attributed to individuals defined in the ABox.

Description Languages

Several DL languages exist, the differences between each rely on the concept constructors that they provide. Concept constructors are actually operators which enable to build complex descriptions [12]. The language AL(Attributive Language) provides foundations for most of the other DL languages. Table in figure 2 shows the operators which present the syntax of ALC (Attributive Language with Complement) which is an extension of AL.

It is proposed to illustrate the syntax and expressivity with a simple example. Let's define two atomic concepts: Human and Male. The intersection of these two concepts Human $\sqcap$ Male is a concept that describes men, that is, humans who are male. Similarly, Human $\sqcap \neg$ Male represent humans who are not male, that is, women. Now let's define hasChild as an atomic role. The expression Human $\sqcap \exists$ hasChild . $\top$ describes humans (not all) who have a child. By contrast, Human $\sqcap \forall$ hasChild . $\top$ describes all humans who have a child.

Syntax	Comment
N_C	Set of Atomic Concepts
N_R	Set of Atomic Roles
C, D	Concept Descriptions
R	Role Description
$\top$	Top Concept (Most general in Taxonomy)
$\perp$	Bottom Concept (Most Specific in Taxonomy)
$\neg C$	Negation
$C \sqcap D$	Intersection
$C \sqcup D$	Union
$\forall R.C$	Universal Restriction
$\exists R.C$	Existential Restriction

Figure 10: Table of logic syntax of ALC language.

3.4 Development tools

To check the consistency of the ontology presented in the previous section, it was edited in Protégé software version 5.2.0 [28].
We used a **top-down** development process, that is the definition of the most general concepts in the domain and subsequent specialization of the concepts. As shown in Figure 11, we organize the classes into a hierarchical taxonomy by asking if by being an instance of one class, the object will necessarily (i.e., by definition) be an instance of some other class. Namely, if a class A is a superclass of class B, then every instance of B is also an instance of A. In other words, the class B represents a concept that is a "kind of" A.

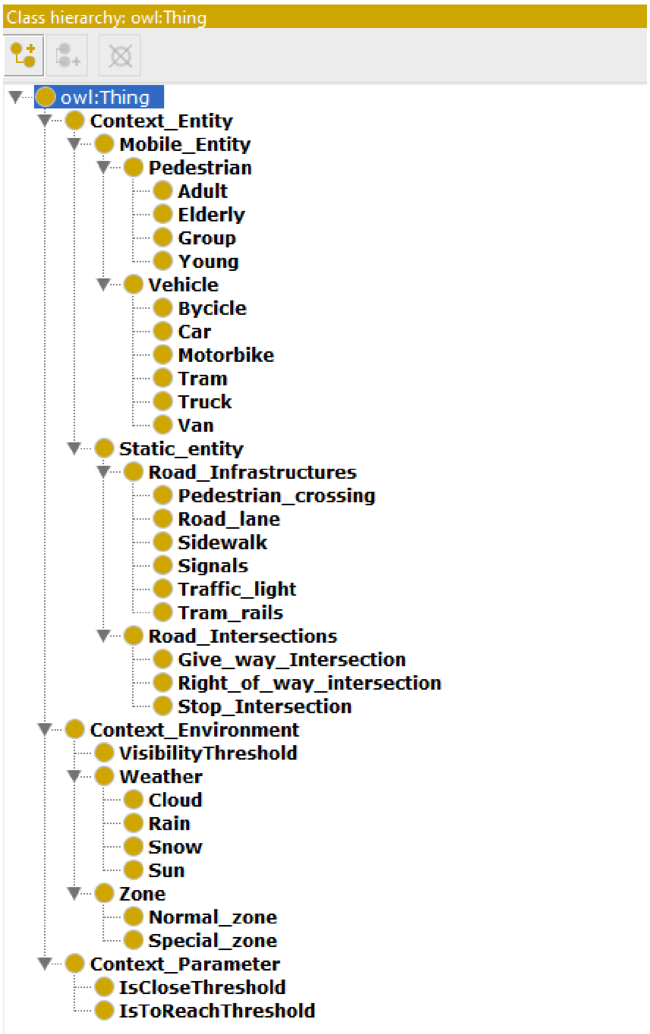


Figure 11: Implementation of the taxonomy.

But not all of the terms defined in the ontology are meant to be classes. Most of the remaining terms are likely to be properties of these classes, as the latters alone will not provide enough information. Once we have defined some of the classes, we must describe the internal structure of concepts through these properties. There are two main types of properties, **Object properties** and Data properties. Object properties are relationships between two individuals and they could be enriched through the use of *property characteristics*. These are listed as follows:

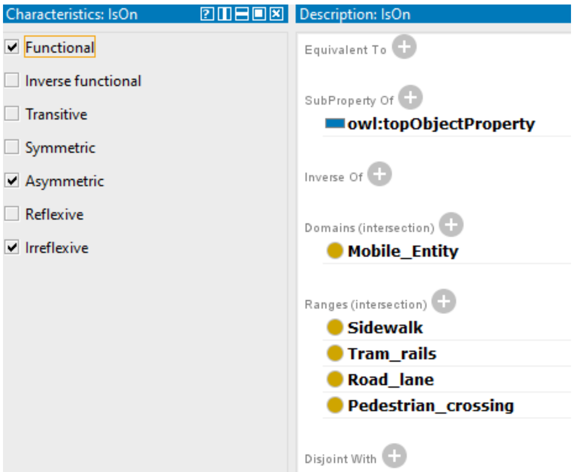


Figure 12: Implementation of *IsOn*.

- **Functional**: if a property is functional, for a given individual, there can be at most one individual that is related to the individual via the property.
- **Inverse Functional**: If a property is inverse functional then it means that the inverse property is functional.
- **Transitive**: if a property is transitive, and the property relates individual A to individual B, and also individual B to individual C, then we can infer that individual A is related to individual C via property P.
- **Symmetric**: if a property P is symmetric, and the property relates individual A to individual B then individual B is also related to individual A via property P.
- **Asymmetric**: if a property P is asymmetric, and the property relates individual A to individual B then individual B cannot be related to individual A via property P.
- **Reflexive**: a property P is said to be reflexive when the property must relate individual A to itself.
- **Asymmetric**: If a property P is irreflexive, it can be described as a property that relates an individual A to individual B, where individual A and individual B are not the same.

Further, properties may have a domain and a range specified. Properties link individuals from the domain to individuals from the range.
Figure 12 shows an example of the implementation of an object property applying the *property characteristics*.

Datatype properties link an individual to an XML Schema Datatype value or an rdf literal. In other words, they describe relationships between an individual and data values. The only *property characteristic* for this kind of properties is **Functional**.

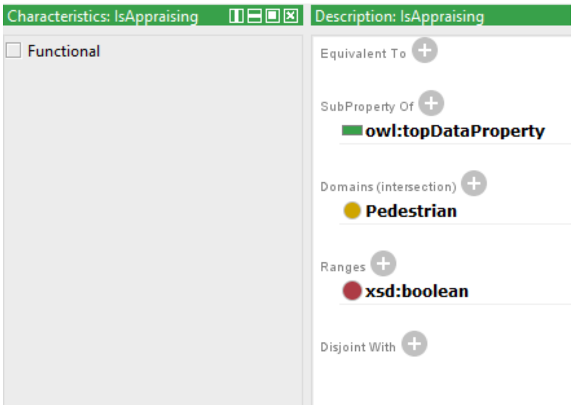


Figure 13: Implementation of *IsAppraising* data property.

The ontology should not contain all the possible information about the domain: you do not need to specialize (or generalize) more than you need for your application (at most one extra level each way), and should not contain all the possible properties of and distinctions among classes in the hierarchy. The rules were implemented with SWRLtab plug-in [29] that permits to add SWRL rules to the ontology (as Figure 15 shows).

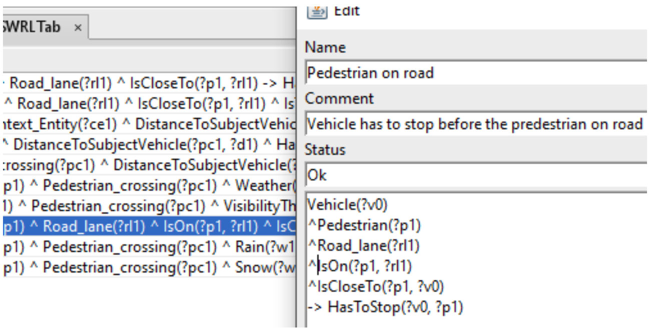


Figure 14: Implementation of one of the SWRL rules in SWRLtab.

Figure 15

4 Proposed Ontology

4.1 The Tbox

The ontology *TBox* was developed with respect to the Description Logic specifications, this means that it was designed through the definition of concepts, object and data properties, and relations. Figure in next pages shows the taxonomy which defines the ontology.

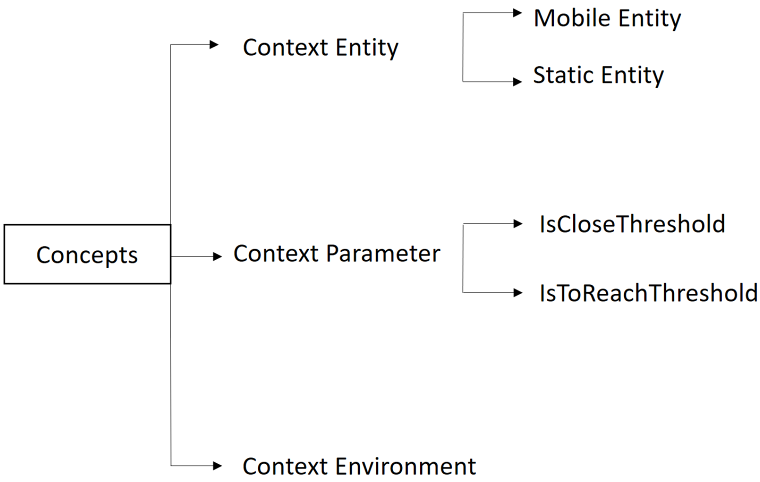


Figure 16

1. Context Entity:

   Context entity lists and classify the road entities wich may be met in a driving space. Road entities were classified into two sub-cocepts. *Mobile entity* and *Static entitity*.

2. Context Parameter:

   The *Context Parameter* defines spatio-temporal thresholds which allow to decide wheter interactions between two entities are likely to exist. To illustrate *IsCloseThreshold*, lets imagine a vehicle and a pedestrian crossing, if the ratio of the distance from vehicle to pedestrian crossing and the speed value of the vehicle is higher than the threshold, the condition "*IsCloseTo*" in *Object Property* is triggered. Following the same logic , the *IsToReachThreshold* parameter is also defined. Numerical values are given to these concepts through *Data Properties*.

3. Context Environment:

   Context Environment aims to model relevant context aspects not depending on the detected (mobile,static) entities that may populate the scene, that is, for instance, weather condition that may afflict both visibility and braking abilities of the vehicle.

4.1.1 Context Entity

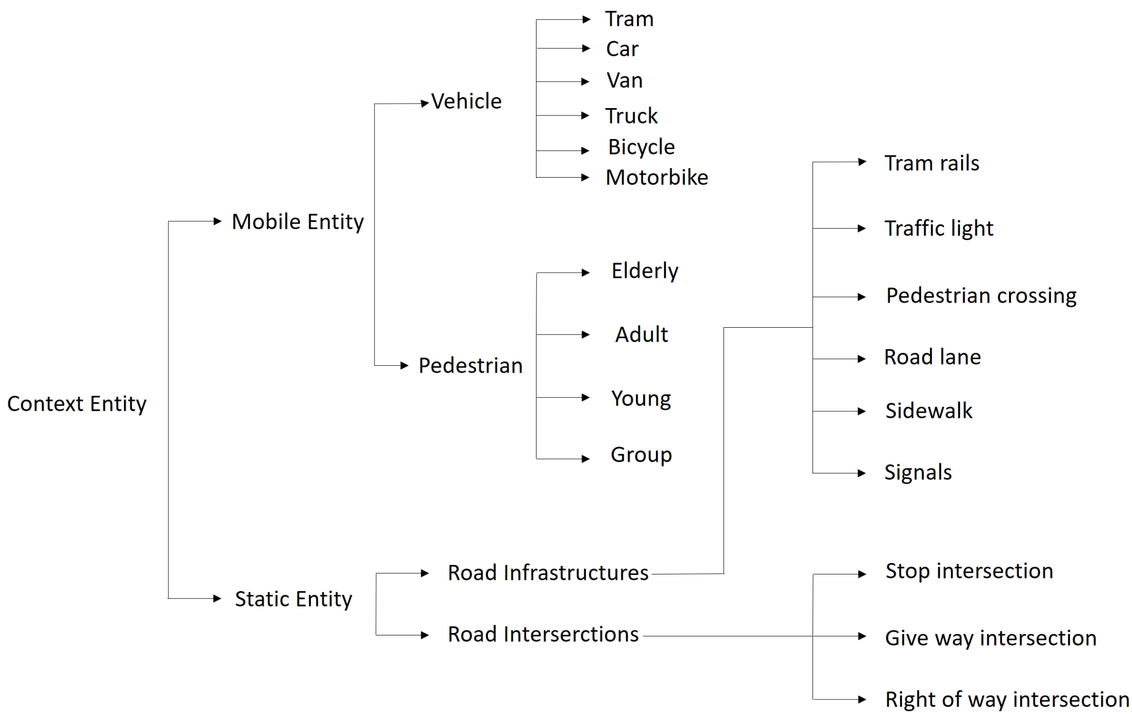


Figure 17

Mobile Entity The target of this category is to group all the entities that can change their position in the space over time, this means that their speed can be greater or equal than zero.

- Vehicle: in this category are listed the possible means of transport that we can find in the traffic.
This point is not studied in depth since it is out of the scope of this study, but it is introduced in the taxonomy because the scene evaluation comprehensive of other vehicles can influence the reasoning.

- Pedestrian: according to the criteria defined in section 3, the class is divided into four categories:

- *Elderly* over 65
- *Adult* from 25 to 65
- *Young* under 25
- *Group*

Knowing the degree of risk a priori, deducted from the criteria described in the previous section, it was possible to define these macro groups. In reasoning phase these are put in relation with two possible values of risk:

- *Normal*
- *Critic*

In particular elderly and younger pedestrians, are critical categories as a group. [26]

If the system detects a critical profile, it will settle a major care in the drive style adapting speed, braking and right of way priority.

Static Entity Static entities are those that are assumed to be part of the road network and their presence is predictable and can be stored in digital maps.
The presented ontology represents two types of *static entities*:

- Road Infrastructures: which affect the behaviour of vehicles such as pedestrian crossing and traffic light.

- Road Intersections: can be classified into three category *stop intersection*, *right of way intersection* and *give way intersections*(as proposed in [13]. There are other approaches to classify intersections, suggests to sicriminate them according to their geometric shape. This aspect is left open for future developments as the interests of the here summarized work is vehicle-pedestrian interactions.

4.1.2 Context Environment

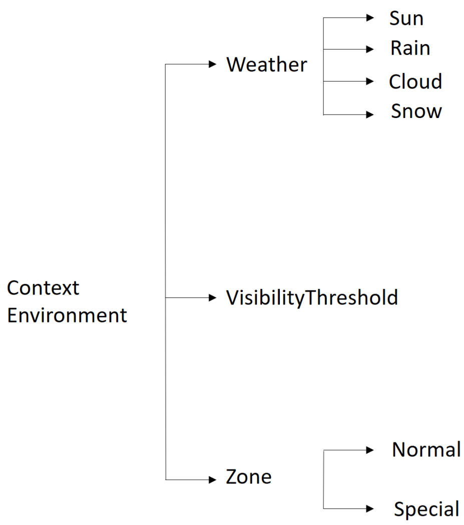


Figure 18

- Weather: this category models the weather conditions in the scene.
This choice was made mainly because, in non dry road condition, the car breaking space maybe would be longer than usual. It was noticed that the behaviour of pedestrians is influenced by the weather inducing a more risky tendency, as said in [27].

- VisibilityThreshold: this category models the visibility threshold, is linked to a numerical value, through *HasValue* in *Data Property*. That theshold is compared to a percieved visibility value. This choice is motivated by the assumption that the vehicle is equipped with sensors able to measure visibility or to infer it.
For example in a foggy environment, for every actor in the scene there is reduced capability to recognize and understand the intention of the other actors, producing an higher risk of collisions.

- Zone: this category identifies areas in which the basic traffic laws are temporarily altered or in which pedestrians are known to have risky tendencies.
For example, when the vehicle is approaching a school zone in a critical time slot, such as the end of lessons, the probability of children crossing the street is increased; this category of pedestrian is known to be critical and the vehicle must be more prudent. According to the reference literature, this information is assumed to be provided by a web service like a street map. See for instance [**?**] where is it presented a flexible probabilistic framework for outdoor urban scene understanding. It allows to exploit a broad range of information sources cameras among which digital maps. In future work it is said that it wuold be possible to retrive georeferenced information like buildings and zebra crossings.

4.1.3 Properties

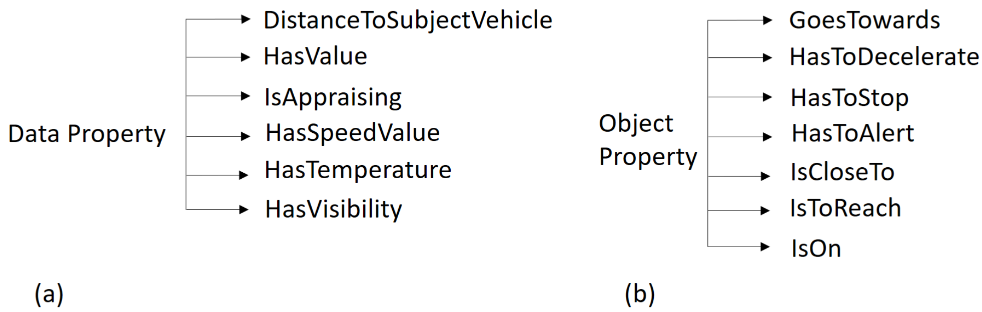


Figure 19

Data Property
In *Data Property* are defined all the unary relationships needed to evaluate the situation.

- DistanceToSubjectVehicle: the numeric value of the distance between the vehicle and any other entity.

- HasValue: specifies a numeric value where needed.

- IsAppraising: defined as the will to cross the street, it is true if the pedestrian is expressing the intention to cross, and false otherwise. An agent *intention* is an abstract concept that can hardly be represented explicitly and quantified. According to [2], a spatial area aside the pedestrian crossing called appraisal zone (area in which the pedestrian decelerates to evaluate the possibility to cross the street [2]) in which is automatically considered to appraise.

- HasSpeedValue: indicates the speed of the related entity.

- HasTemperature: this property is defined for weather entities, it was appropriate to consider the thermal contition of the environment since they significantly affect the behaviour of pedestrians [27] and the drive style of the vehicle.

- HasVisibility: this property is defined for weather and zone entities, it was appropriate to consider the visibility contition of the environment since they influence the interactions. If the visibility value is less than the threshold, the vehicle will behave in a less risk-seeking way.

Object Property
Figure 19(b) presents the ontology object properties. These properties aim to define the relationships and interactions which may happen between two concepts of *Context Entities*. There are two types: (a) can represent spatial relationship between Context Entities or (b) vehicle actions:

(a) Spatial relationships:

- GoesTowards

- IsCloseTo

- IsToReach

- IsOn

(b) Vehicle actions:

- HasToDecelerate

- HasToStop

- HasToAlert

Vehicle actions are defined as binary relationships between two entities, e.g [Car - HasToStop - StopIntersection], or [Car - HasToDecelerate - Pedestrian Crossing], or [Car - HasToAlert - Pedestrian]. This means that the given action executed by the first entity is meant to be done before the second entity in the relationship.

4.2 Rules

Rules are part of the Tbox as they determine non-hierarchical relationships between the entities stored in the taxonomy. Indeed differently from the latter, with rules we associate pairs of entities taken from any node of the taxonomic tree. This is the core part of the ontology since they provide the intelligence for the reasoning. In this work we exploit SWRL (Semantic Web Rule Language) [17] one of the most employed standard for this type of applications and the solution suggested by the state of the art of ontology-based approach applied to automated driving. For the proposed ontology we list a subset of the possible rules to illustrate the inferences that can be made between the classes.

Example of rules that infer the spatial relationship

Mobile_Entity(?me1) ∧ Context_Entity(?ce1) ∧ DistanceToSubjectVehicle(?ce1,?d1) ∧ DistanceToSubjectVehicle(?me1,?d2) ∧ IsCloseThreshold(?thresh) ∧ HasValue(?thresh,?value) ∧ swrlb:subtract(?sub,?d2,?d1) ∧ swrlb:lessThan(?sub,?thresh) → IsCloseTo(?me1,?ce1)	The distance *d1* and *d2* of the entity are known thanks to the DistanceToSubjectVehicle parameter. By performing a subtraction, it is possibile to determine the distance between both vehicles. By comparing this distance with the IsCloseThreshold, it is determined wheter mobile entity *me1* is close to context entity *ce1*.
Mobile_Entity(?me1) ∧ Context_Entity(?ce1) ∧ DistanceToSubjectVehicle(?ce1,?d1) ∧ DistanceToSubjectVehicle(?me1,?d2) ∧ IsToReachThreshold(?thresh) ∧ HasValue(?thresh,?value) ∧ swrlb:subtract(?sub,?d2,?d1) ∧ swrlb:lessThan(?sub,?thresh) → IsToReach(?me1,?ce1)	The distance *d1* and *d2* of the entity are known thanks to the DistanceToSubjectVehicle parameter. By performing a subtraction, it is possibile to determine the distance between both vehicles. By comparing this distance with the IsToReachThreshold, it is determined wheter mobile entity *me1* is to reach a context entity *ce1*.

Example of rules that apply on every type of pedestrian resulting in a vehicle stop

Vehicle(?v0) ∧ Pedestrian(?p1) ∧ Pedestrian_crossing(?pc1) ∧ IsCloseTo(?v0,?pc1) ∧ IsAppraising(?p1) → HasToStop(?v0,?pc1)	The vehicle *v0* is close to pedestrian crossing and a pedestrian *p1* is appraising to pedestrian crossing, so *p1* want to cross the road.
Vehicle(?v0) ∧ Pedestrian(?p1) ∧ Road_lane(?rl1) ∧ IsOn(?p1,?rl1) ∧ IsOn(?v0,?rl1) ∧ IsCloseTo(?v0,?p1) → HasToStop(?v0,?p1)	The vehicle *v0* and the pedestrian *p1* are on road, so *v0*, according to the road rules, has to stop before *p1*.

Example of rules that depend on the pedestrian profile

Vehicle(?v0) ∧ Adult(?p1) ∧ Road_lane(?rl1) ∧ IsCloseTo(?v0,?rl1) ∧ IsToReach(?v0,?p1) → HasToAlert(?v0,?p1)	The adult pedestrian *p1* is close to road lane and want to cross, so the vehicle *v0* alert *p1* that can't cross because *v0* is upcoming
Vehicle(?v0) ∧ Elderly(?p1) ∧ Road_lane(?rl1) ∧ IsCloseTo(?p1,?rl1) ∧ IsToReach(?v0,?p1) → HasToDecelerate(?v0,?p1)	The elderly pedestrian *p1* is close to road lane and want to cross, so the vehicle *v0* doesn't alert because elderly have be a reduced cognitive capability.*v0* has to decelerate because *p1* has a higher risk profile than the standard.
Vehicle(?v0) ∧ Young(?p1) ∧ Pedestrian_crossing(?pc1) ∧ Sidewalk(?s1) ∧ Road_lane(?rl1) ∧ IsOn(?v0,?rl1) ∧ IsOn(?p1,?s1) ∧ IsToReach(?v0,?pc1) ∧ IsToReach(?p1,?pc1) → HasToDecelerate(?v0,?p1)	The young pedestrian *p1* is to reach pedestrian crossing, the vehicle *v0* is to reach the pedestrian crossing, *v0* has to decelerate because *p1* is a risk profile of pedestrian and so is difficult to predict his action.

Some condition can influence the scene differently, for example zone and weather are two element that can change the evaluation of the scene, an example was reported in the rules below

Vehicle(?v0) ∧ Pedestrian(?p1) ∧ Pedestrian_crossing(?pc1) ∧ Sidewalk(?s1) ∧ Rain(?w1) ∧ HasTemperature(?w1,?t1) ∧ swrlb:greaterThanOrEqual(?t1,4) ∧ IsOn(?p1,?s1) ∧ IsCloseTo(?p1,?pc1) ∧ IsToReach(?v0,?pc1) → HasToDecelerate(?v0,?pc1)	The pedestrian *p1* is close to the pedestrian crossing, the vehicle *v0* is to reach the pedestrian crossing, as it is raining, *v0* must begin to decelerate because with the wet the braking space could increase.
Vehicle(?v0) ∧ Pedestrian(?p1) ∧ Pedestrian_crossing(?pc1) ∧ Sidewalk(?s1) ∧ Snow(?w1) ∧ IsOn(?p1,?s1) ∧ IsCloseTo(?p1,?pc1) ∧ IsToReach(?v0,?pc1) → HasToStop(?v0,?pc1)	The pedestrian *p1* is close to the zebra crossing, the vehicle *v0* is to reach the pedestrian crossing, as it is snowing, *v0* must begin to decelerate because with the snow the braking space could increase more than with rain.
Vehicle(?v0) ∧ Pedestrian(?p1) ∧ Pedestrian_crossing(?pc1) ∧ Sidewalk(?s1) ∧ Weather(?w1) ∧ HasTemperature(?w1,?t1) ∧ swrlb:lessThan(?t1,4) ∧ IsOn(?p1,?s1) ∧ IsCloseTo(?p1,?pc1) ∧ IsToReach(?v0,?pc1) → HasToStop(?v0,?pc1)	The pedestrian *p1* is close to the pedestrian crossing, the vehicle *v0* is to reach the pedestrian crossing, the temperature *t1* is less then 4 Celsius degrees so perhaps the street is frozen, *v0* has to stop because with the iced road the braking space could increase.
Vehicle(?v0) ∧ Pedestrian_crossing(?pc1) ∧ Weather(?w1) ∧ VisibilityThreshold(?thresh) ∧ HasValue(?thresh,?value) ∧ HasVisibility(?w1,?vi1) ∧ swrlb:lessThan(?vi1,?thresh) ∧ IsToReach(?v0,?pc1) → HasToDecelerate(?v0,?pc1)	The vehicle *v0* is to reach pedestrian crossing, the visibility condition are reduced, *v0* has to decelerate because maybe there is a pedestrian that does not see and he want to cross.

4.3 The Abox

The Abox represents the transposition of the world model into the ontology, as it is a finite set of assertion on individuals. Therefore a name should be given to the instances of the classes present in the world model to enable the reasoning on the whole ontology.

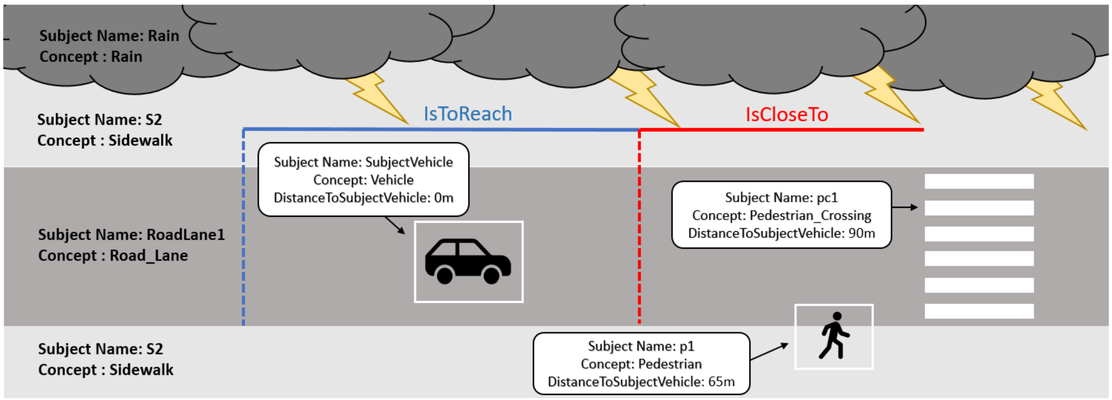


Figure 20: Illustrative picture of the *Rain* weather condition case study (scale is not respected).

Subject_Vehicle: *Object Property Assertions*: • **IsToReach** Crossing1 • **IsOn** RoadLane1 *Data Property*: • **DistanceToSubjectVehicle** 0m • **HasSpeedValue** 50 km/h	**Pedestrian:** *Object Property Assertions*: • **IsCloseTo** Crossing1 • **IsOn** S1 *Data Property*: • **DistanceToSubjectVehicle** 65m • **HasSpeedValue** 3.4 km/h
Crossing1: *Object Property Assertions*: • $\emptyset$ *Data Property*: • **DistanceToSubjectVehicle** 80m	**Rain1:** *Object Property Assertions*: • $\emptyset$ *Data Property*: • **HasTemperature** 10°C

The result of the inferences for the case study in figure 20 are detailed as follows. *SubjectVehicle* as mandatory element has *DistanceToSubjectVehicle* set to 0 as the distance from itself is null. *Pedestrian1* is inferred to be on *S1* assigning the value *true* to the property *IsOn*, and then to be close to *Crossing1* through the evaluation of *DistanceToSubjectVehicle* of both entities whom values will be subtracted and compared to the *IsCloseThreshold* to verify the condition that permits infer the *IsCloseTo* property. A similar inference is made to verify the property *IsToReach* for *SubjectVehicle* and *Crossing1*. Then, since as environemental factor, there is the presence of *Rain*, *HasTemperature* is greater than 4°C and the previous assertion are verified, lets finally infer the property *HasToDecelerate* for *SubjectVehicle* before *Crossing1*.

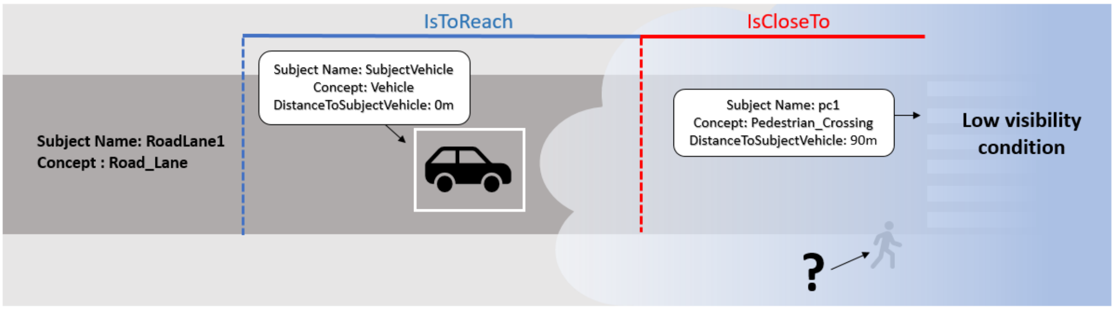


Figure 21: Illustrative picture of the *Low Visibility* environmental condition case study (scale is not respected).

Subject_Vehicle: *Object Property Assertions*: • **IsToReach** Crossing1 • **IsOn** RoadLane1 *Data Property*: • **DistanceToSubjectVehicle** 0m • **HasSpeedValue** 50 km/h	**Pedestrian?:** *Object Property Assertions*: • **?** *Data Property*: • **?**
Crossing1: *Object Property Assertions*: • ∅ *Data Property*: • **DistanceToSubjectVehicle** 80m	**Weather:** *Object Property Assertions*: • ∅ *Data Property*: • **HasTemperature** 10°C • **HasVisibility**

The case study for the low visibility condition is meaningful because it can significantly affect the correct detection of the objects in the scene with the consequence of building a distorted World Model. In foggy, steamy or dusty environments the detection of pedestrian, rather than pedestrian crossings whose presence could be detected from digital maps, is harder and mistake in this phase could cause unsolicited collisions. The result of the inferences for the case study in figure 20 are detailed as follows. *SubjectVehicle* as mandatory element has *DistanceToSubjectVehicle* set to 0 as the distance from itself is null. *SubjectVehicle* is inferred to be close to *Crossing1* through the evaluation of *DistanceToSubjectVehicle* of both entities whom values will be subtracted and compared to the *IsToReachThreshold* to verify the condition that permits infer the *IsToReach* property. Then, since as environemental factor, there is the presence of *Weather* whose *HasVisibility* value is compared with *VisibilityThreshold*, if the latter is lower than the specified threshold and the previous assertion are verified, lets finally infer the property *HasToStop* for *SubjectVehicle* before *Crossing1*.

Figures 22 and 23 show an example of the possible interactions with pedestrian.

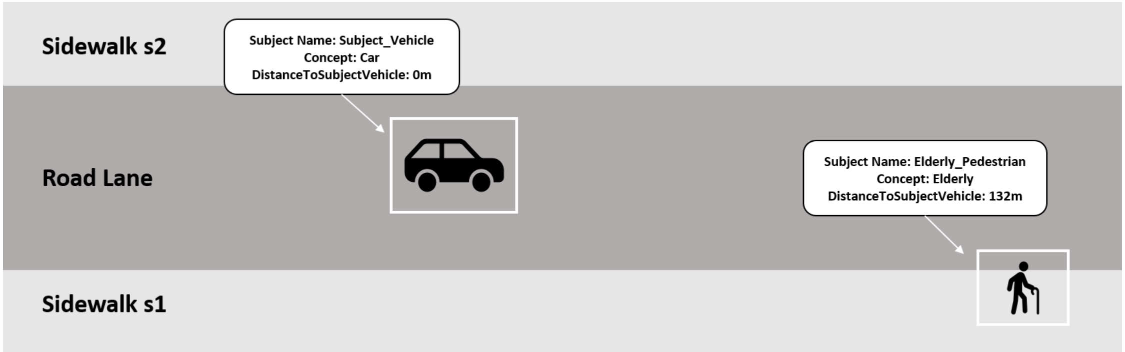


Figure 22: Example with elderly pedestrian without zebra crossing (scale is not respected).

Subject_Vehicle:	**Elderly_Pedestrian:**
Object Property Assertions: • **IsToReach** Elderly_Pedestrian • **IsOn** Road Lane *Data Property*: • **DistanceToSubjectVehicle** 0m • **HasSpeedValue** 50 km/h	*Object Property Assertions*: • **IsCloseTo** Road Lane • **IsOn** Sidewalk s1 *Data Property*: • **DistanceToSubjectVehicle** 132m • **HasSpeedValue** 3.4 km/h
Action: Subject_Vehicle *has to decelerate* before Elderly_Pedestrian	

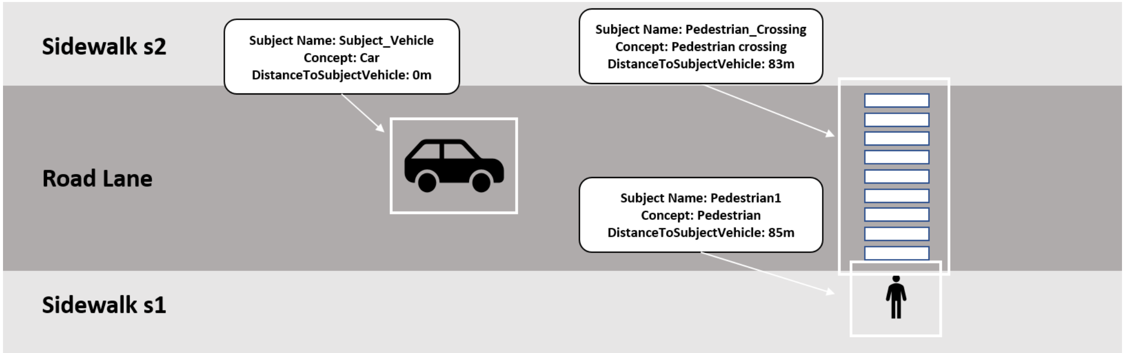


Figure 23: Example with zebra crossing(scale is not respected).

Subject_Vehicle: *Object Property Assertions*: • **IsCloseTo** Pedestrian_crossing • **IsCloseTo** Pedestrian1 • **IsOn** Road Lane *Data Property*: • **DistanceToSubjectVehicle** 0m • **HasSpeedValue** 50 km/h	**Pedestrian1:** *Object Property Assertions*: • **IsCloseTo** Road Lane • **IsCloseTo** Pedestrian_Crossing • **IsCloseTo** Subject_Vehicle • **IsOn** Sidewalk s1 *Data Property*: • **DistanceToSubjectVehicle** 85m • **HasSpeedValue** 3.7 km/h • **IsAppraising** True
Pedestrian_Crossing: *Object Property Assertions*: • $\emptyset$ *Data Property*: • **DistanceToSubjectVehicle** 83m	

Action: Subject_Vehicle *has to stop* before Pedestrian_Crossing to give the precedence to pedestrian.

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