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RESEARCH ARTICLE

# VRU Safety at Road Intersections: An Ontology-Driven Digital Twin

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**ABSTRACT** Although the role of optimization in transportation systems is widely recognized as key to future sustainable development, alarming statistics related to accidents and deaths continue to be overlooked. Among the various components of road networks, road intersections pose the greatest safety challenges for smart and human cities. Digital twins (DT) have emerged as a promising alternative to assist intelligent transportation system (ITS) decision-makers in recent years. However, a critical component is still lacking in developing DTs for ITS: a robust information modeling framework that effectively integrates the physical world with cyberspace in these intricate and dynamic environments. Furthermore, the current emphasis on the efficiency of ITS solutions often overshadows pressing safety concerns for vulnerable road users (VRUs). This paper tackles the challenge of modeling transportation scenarios to enhance VRU safety, focusing on a crucial element: a *road intersection*, in particular, the semantic issues of such elements when addressing VRU safety. For the first time, we propose an ontology-based information modeling method for road intersections using recent advancements from market-driven, regulatory, and standardization bodies. It specifies the information classification, content to be modeled, and modeling methodology. Nevertheless, inexpensive, swift, and friendly prototyping remains a bottleneck for innovation in this area. Practitioners currently require more means and methods to realize ontology-based DTs for ITS. Another contribution is to provide information model instantiation, visualization, and simulation, as well as fully based open-source tools, as a case study.

**INDEX TERMS** Digital twins, information modeling, ontology, road intersection, vulnerable road users, FIWARE, CARLA simulator.

## I. INTRODUCTION

The role of transportation systems is critical for the sustainable development of modern society. The United Nations 2030 Agenda presents 17 Sustainable Development Goals (SDGs). Sustainable transport is related to i) the care of life and well-being of people through the road safety approach (SDG 3.6); ii) the reduction of polluting emissions (SDG 3.9); iii) the creation and use of sustainable infrastructure (SDG 9.1); and iv) the conception of sustainable transport systems that allow access to transport in a safe and affordable way to improve road safety (SDG 11.2). These goals explicitly show concerns for current transport problems and road safety [1].

Vulnerable road users (VRU) are central in intelligent transportation systems (ITS) [3]. VRUs are formally defined

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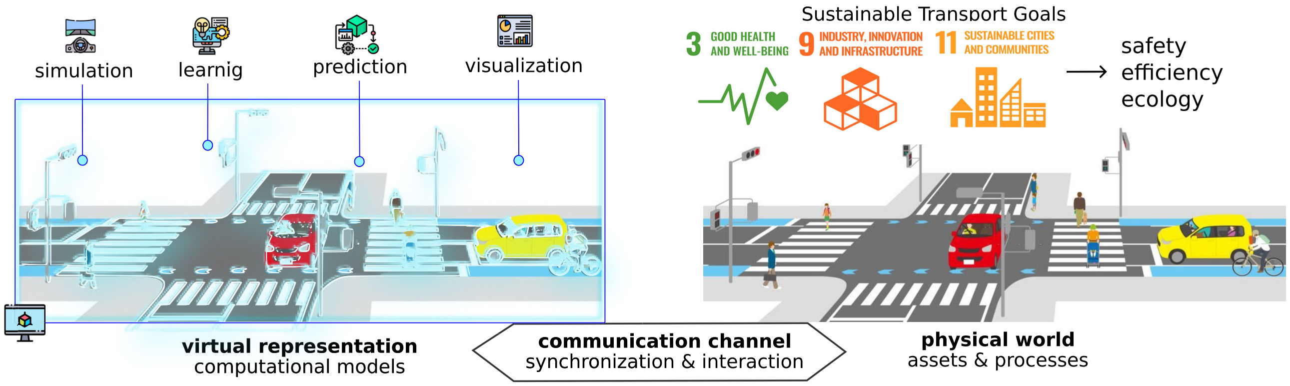



**FIGURE 1.** Digital twins paradigm. [2].

as "non-motorized road users, such as pedestrians and cyclists, motorcyclists, and persons with disabilities or reduced mobility and orientation" [4]. The likelihood of a pedestrian suffering serious consequences from a collision event is almost 300 times more than drivers [5]. However, VRU safety is dependent on multiple players, not only on drivers. Outdated roadside infrastructure, technological limitations of vehicles, and even inconsequential behaviors from VRUs themselves are also to blame for 20 to 50 million accidents with non-fatal injuries, and 1.19 million fatal ones, at road traffic crashes every year, according to statistics from the World Health Organization (WHO) [6]. This situation drives efforts toward VRU-centered ITS designs, and further research is fundamental at road intersections, where these participants (including VRUs, drivers, and vehicular systems) will interact closely. Note that they will act and react to each other's strategies for dynamically sharing a physical space, where occlusions and multiple blind spots are present like no other road segment. Among other measures involving VRU-awareness algorithms, collision avoidance in conflict zones, at roadside equipment, or on virtual assistants embedded in vehicles, is urgently needed to improve VRU safety.

Note that road intersection scenarios prove to be highly complex in terms of the semantic representation of many agents and interaction scenarios. Agility for acting and preventing unwanted states involving VRUs in transport systems, such as those recently defined by [7], is becoming an elusive goal in spite (or perhaps because) of recent technological advances. The proliferation of data and diverse data formats from roadside equipment, transferred using various protocols and processed either at the edge or in the cloud with advanced artificial intelligent (AI) capabilities, along with the emergence of connected and automated vehicles, introduces new challenges for network routing.

Alternatively, digital twins (DT) may not only help ITS deal with such semantic complexity but also unlock its wealth. The current abundant information in ITS and its latent potential for providing better public services need to be unleashed. In brief, as illustrated in Fig. 1, the key architectural concept is that a given physical asset can be properly mapped into a digitized counterpart entity in a DTs. They use a communication channel (and appropriate methods) to enable their physical and virtual parts to interact and co-evolve with each other [8]. Various sensors and scanning technologies, entities, actuators, behaviors, and knowledge of relationships in the physical world are used to create high-fidelity virtual models. Several well-known problems in transportation systems, such as safety and efficiency, can be addressed in favor of their sustainability. Virtual models rely on real-world data to formulate real-time parameters, conditions, and dynamics, thereby improving the likelihood of reflecting corresponding physical entities. With such models, it would be possible to simulate and analyze *what-now*, *what-next*, and *what-if* scenarios to obtain quick and trustworthy answers, allowing them to act accordingly in physical transport scenarios. In other words, DT may foresee problems and be proactive across different dimensions of ITS, including when dealing with safety issues for VRUs. In this context, digital twins can play the role of technology orchestrators in enabling VRU risk mitigation solutions.

On the other hand, the downside of DTs lies in the fact that modeling a vertical transport application is still heavily domain-dependent, that is, it requires deep knowledge of the application intricacies for properly implementing a DT [9]. The development of DT-based transport applications is still in its very early stages, and this is partly due to the absence of effective methodologies for representing their knowledge domains in proper semantic models. This paper argues that the development of ontology-driven modeling is crucial for pushing forward DT solutions in next-generation ITS applications.

Ontology engineering here is understood as the representation, naming, and adequate definition of the categories, properties, and relations between the concepts, data, and entities of a given domain of interest [10]. In DT, proper modeling of a system's physical (or virtual) entities will be useful for understanding its parts and duly representing the system's complex interactions. Thus, the use of domain ontologies also facilitates the interoperability and exchange of information between different DT components [11].

This paper proposes, for the first time, a pragmatic yet comprehensive approach involving ontology to model the intricacies of physical systems and implement a smart data model for road intersection scenarios, focusing on VRU issues in DTs. Note that this ontology-based approach may serve as a template for DT capabilities to fulfill the "data services module" by the Digital Twins Consortium [12]. Within such modules, DTs for road intersections, as well as other segments, can manage knowledge graphs and ontologies, allowing the DT-based solution to interpret heterogeneous data directly from the transport domain ontology as well. Thus, structured information can be exchanged and shared among the stakeholders.

Furthermore, efforts to unlock the instantiation of DTs in ITS, besides addressing semantic issues, are needed. Our proposal connects: i) recent advances in collision cases definitions according to the European New Car Assessment Program [7]; ii) information models such as next-generation service interfaces-linked data (NGSI-LD) [13] for publishing, querying, and subscribing to context information; and iii) the use of a market-driving open-source platform, i.e., FIWARE, to demonstrate implementation of such data models so that compatibility with IoT and other context information management and big data services in the cloud can be taken into consideration [14].

The remainder of this paper is organized as follows. Section II discusses the semantic issues in digital twins for ITS, highlighting the main gaps in creating DT information models in ITS. Section III introduces the Road Intersection Ontology, a domain ontology to perform reasoning that allows DT-based intelligent road intersections (DT-RI) to implement applications to improve the safety of VRUs. Section IV outlines the use of the proposed ontology to develop a smart data model and subsequently instantiate road intersection digital twins within the FIWARE framework. Finally, Section V concludes the study and proposes future work.

## II. THE SEMANTIC ISSUES IN DIGITAL TWINS FOR ITS

Digital Twins for Intelligent Transportation Systems, specifically for intelligent intersection solutions, can be broadly defined as the digital representation of the diverse components, including i) the intelligent infrastructure (roads, traffic lights, and roadside elements in general), ii) traffic participants (vehicles, non-vehicles, and vulnerable road users), iii) traffic behavior (departure, destination, path, etc.), and iv) the surrounding environment (urban functional area, weather conditions, etc.) [15]. Successful representation and reliable virtual models significantly improve common problems of transportation systems, including safety at road intersections, even with the early discovery of such issues. Thus, short–, medium–, and long-term strategies can be designed to support decision-making at intersections, transforming them into safer environments for VRU.

It is widely believed that gathering more comprehensive information from roads, vehicles, and drivers can significantly enhance awareness of hazardous traffic and road conditions. Depending on weather conditions and traffic congestion, they may become adverse to VRU and drivers. It is expected that diverse verticals will tap into this wealth of information for safety and efficiency in the ITS. As depicted in Fig. 2, real-time and detailed road and traffic information may allow road authorities to exercise more precise traffic control via new adaptive and dynamic smart traffic light systems to improve safety and traffic efficiency at road intersections [16], [17]. By utilizing diverse IoT devices, including (wearable) devices for VRUs and drivers, combined with digital maps and road infrastructure information models, it is possible to build accurate DT of road traffic systems and infrastructure assets. These digital representations enable real-time monitoring and effective analysis, such as event prediction, which are crucial for the safety [18] and efficiency [19] of intelligent transportation systems.

However, there are still considerable gaps in the current structured understanding of data, flow representation, and reasoning layers in transportation verticals [20]. No best practices have been established for organizing such a system as a proper DT for road intersections, which is possibly the most critical element of the ITS. Only well-designed ontologies can address this complexity effectively. For instance, dividing the system's static information, such as the geometric infrastructure of the road network and the various situations, from the dynamic elements of the system provides a logical basis for reasoning about the system's behavior, which can be represented more accurately in the data model used by the digital twin in its prediction, analysis, and visualization tasks.

Regular state graphs, which are often used in software engineering to represent the behavior of complex systems, such as the Unified Modeling Language (UML), perhaps disadvantageous as the number of situations to be considered in ITS grows, owing to its closed world assumption (CWA) [5]. In other words, UML assumes a complete representation of all knowledge in the domain, whereas a semantic model based on ontology tolerates partial knowledge about a domain; therefore, if a statement cannot be inferred as true or false about an object, it is assumed to be unknown. Thus, ontologies not only allow unknown system situations but also a kind of semantic modeling that learns from complexity by accumulating knowledge observed in new scenarios. This is why the large community dealing with AI subscribes to ontologies as a preferred model of knowledge representation and reasoning [21]. Recently, initiatives have

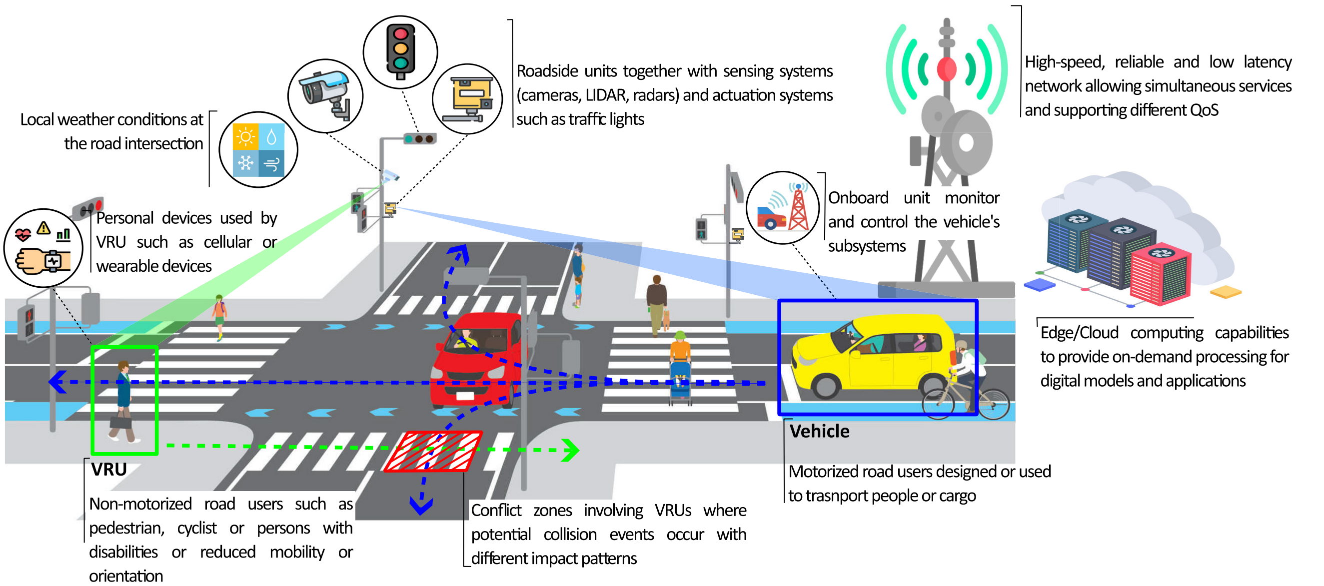



**FIGURE 2.** **Elements for information gathering, transporting, and processing for ITS unified management and control over roads, vehicles, and human interactions.**

been designed to represent and integrate taxonomies, such as Common Core Ontologies (CCO), toward generic classes and relations across different domains of interest for an integrated, consistent, and semantically interoperable monolithic piece [22]. For further discussions on DT interoperability and the central role of ontologies in semantically uniting DT and AI for building cognitive DTs, readers are referred to [20].

### A. RELATED WORKS

In the context of transportation systems, it is worth highlighting a review of early efforts focused on systematic and reliable methods for capturing semantic information through ontologies [23]. The proposal of sustainability metrics, with dynamic features, for the coverage of open fleets can be found in pioneering ITS ontologies [24]. A recent review of ontology-based approaches for diverse issues related to smart city services [25]. In the context of identifying elements and the effort to group common characteristics into categories, a taxonomy was established for modeling and developing new context-aware ITS [26].

For the structured categorization of traffic environments, Scholtes et al. proposed a 6-Layer Model (6LM) [27] that defines the elements from the road network and roadside structures to the dynamic and digital elements of the traffic environment. The 6LM has been widely used since its publication in different proposals in the transport domain, largely because it is a formal basis for building ontologies using Web Ontology Language. However, the model is limited to the elements of each layer and does not address the properties and relationships the between elements within and between the layers. To meet safety goals, Westhofen et al. [28] proposed, a 6LM-based ontology for modeling and formalizing critical factors associated with autonomous vehicle environments. The authors created the Automotive Urban Traffic Ontology (A.U.T.O.) with a modular approach to enable reasoning about criticality in urban traffic scenarios, which was evaluated using a large-scale drone data set of traffic scenarios. Based on the A.U.T.O. ontology, Zhang et al. made further extensions and adjustments to obtain a more complete traffic scenario perspective, updating the ontology based on the fusion results of a small-scale knowledge graph [29].

In addition, focusing on safety in traffic scenarios, Reich et al. [30] proposed a metamodel for cross-domain safety analysis of autonomous vehicle systems. The model allows the creation of an Operational Domain Design (ODD) in a structured manner, enabling cross-domain learning and representing a starting point for the ontological modeling of the transport domain from a safety engineering perspective. Ruchiga et al. [31] proposed a generic ontology and a framework for describing and generating critical scenarios. The proposed ontology combines the description of the scenario, environment, and dynamic elements' condition and behavior for both humans and autonomous vehicles, all of which are required to have a successful mixed traffic scenario model. Although this last work provides one of the most complete ontologies found in the literature for the analysis of safety-critical scenarios, the methods for its implementation in real data platforms have not been described. Another ontology for collaborative navigation in traffic scenarios involving autonomous vehicles, drivers, and pedestrians was proposed by Syzdykbayev et al. [32], but without the corresponding implementation through data models.

The association of perceived information with contextual information to infer non-safe situations in traffic scenarios can be complex. Armand et al. [33] proposed an ontology-based context-awareness framework to understand and interpret a context when perceived by vehicle sensors. In this solution, the ontology permits the establishment of different relationships between road entities to infer their behavior in both the medium and long terms. Besides, a long-term prediction framework, that considers the chain reactions among road users, was proposed by Fang et al. [34] using an ontology-based reasoning approach. The proposed ontology was defined with a knowledge base that can be applied to various traffic scenarios and reduces computation time compared to traditional methods.

Although physical assets in a transport system, such as infrastructure, vehicles, and even pedestrians, are modeled based on ontologies, there is a gap in representing vulnerable road users in traffic scenarios. To address the lack of descriptive language for road users and drivers, Dodoiu et al. [35] proposed a methodology for incorporating human factors into scenario descriptions to test autonomous driving systems. The methodology considers a wide range of characteristics relevant to human road users but does not address the analysis of their interactions. The challenge of modeling comprehensive VRU data and their interactions with other elements of transportation systems remains an open issue.

In summary, Table 1 presents three main features discussed in this work, compared with the set of related works described above, to highlight our contributions. Here, we are interested in i) whether VRU is considered in their ontology approach as an important element within the transport system, ii) to what extent a corresponding information model for the ontology is proposed, and finally, iii) whether an implementation for their information model is presented according to market-driven platforms.

Although the VRU must be a central element of future ITS solutions, Table 1 highlights gaps in such ontology-based approaches as VRU's safety issues are only partially addressed. Moreover, most studies have failed to propose information models for their ontologies. In this field of expertise, abstract speculations are usually preferred rather than spending energy, determining how such abstractions could be brought closer to real-life implementations by using current enabling technologies. It is also remarkable that important efforts, such as market-driven test protocols regarding VRUs, have been overlooked when implementing DT-ITS data models.

Although ontology-driven modeling is a necessary step toward next-generation ITS applications, it is not sufficient on its own. Proper data models and their compatibility with de facto industry standards for providing meaningful and swift prototype implementations are also important for unlocking virtuous cycles of innovation. This work, for the first time, bridges these three phases. The DT road intersection use case demonstrates such a prototyping process.

**TABLE 1. Summary of the evaluation of related works and our proposal.**

| Reference | VRU-centric ontology | Information model | Market-driven implementation |
|---|---|---|---|
| Scholtes et al. [27] | ◐ | ○ | ○ |
| Westhofen et al. [28] | ◐ | ○ | ○ |
| Zhang et al. [29] | ◐ | ○ | ○ |
| Reich et al. [30] | ○ | ● | ● |
| Ruchiga et al. [31] | ◐ | ○ | ○ |
| Syzdykbaye et al. [32] | ◐ | ○ | ○ |
| Armand et al. [33] | ◐ | ○ | ○ |
| Fang et al. [34] | ○ | ○ | ○ |
| Dodoiu et al. [35] | ● | ● | ○ |
| Our proposal | ● | ● | ● |

## III. PROPOSAL FOR AN ONTOLOGY FOR VRU SAFETY IN A ROAD INTERSECTION DOMAIN

For the accurate and timely development of DT-based applications in intelligent road intersections (DT-RI), we proposed a systematic framework composed of four layers due to extensive surveying work [2]. At the bottom of the framework, the physical layer for intelligent intersection solutions can be defined as the digital representation of intersection components, including smart infrastructure, traffic participants, traffic behavior, and the surrounding environment. These physical entities serve as data sources for virtual models. The definition of physical entities within DT standards varies markedly between domains as they are adapted to specific application scenarios. To accelerate the development and adoption of DT-based transportation applications, the use of layer or dimension ontologies in the DT-RI framework [36] is critical.

The semantic module of the DT-RI framework is implemented in the data and model layers, as shown in Fig. 3. The aggregated data from the Physical Layer is stored in the cloud to perform semantic operations in the Data Layer. To achieve semantic interoperability, the semantic module must comprise ontologies that provide semantic annotations to the aggregated data and convert them into semantic data, enabling the creation of virtual models in the Model Layer for instantiating our DT-RI.

### A. THE INFORMATION MODELING METHOD OF ROAD INTERSECTION DATA

Road intersections have heterogeneous data from multiple sensors dispersed throughout the scenario of interest. When discussing information modeling, a common practice is to create an ontology model written in a language that supports semantic richness, enabling a greater capacity for exchanging machine-readable content. Thus, the fundamental concepts of road intersection operations to improve the safety of VRUs can be clearly and unambiguously defined through the formal description of entities and their relationships.

A DT-RI is a set of virtual information constructs that fully describe an actual physical road intersection. In the bottom layer of the DT-RI framework, the presence of ontology is essential since it plays a critical role in enabling the

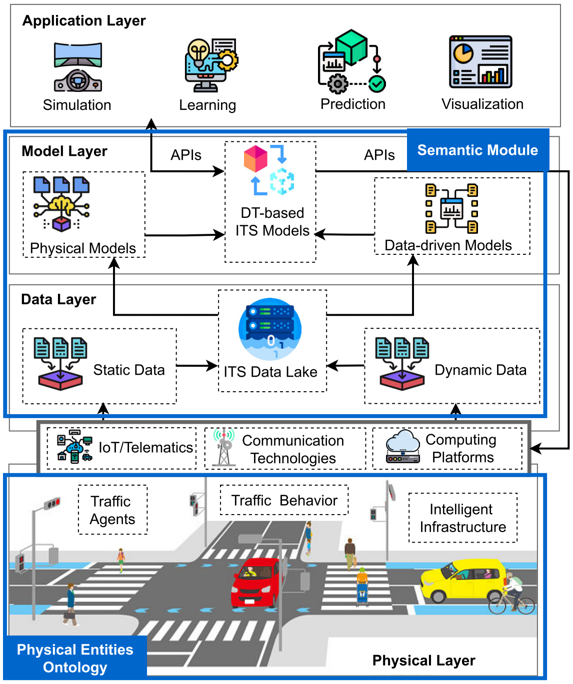



**FIGURE 3. Semantic Module in the DT-ITS reference framework. Adapted from [2].**

effective modeling of the DT-based road intersection. At this layer, a well-defined domain ontology enables the accurate representation of physical entities for the DT-based road intersection.

Our Road Intersection Ontology proposal defines more precisely what the DT's virtual entity will be concerned with regarding the concepts in the domain, their relationships, properties, and possible constraints. We aim to identify the main concepts and relationships in the transportation system, specifically road intersections, to address VRU safety DT-based applications. An ontology model can be described as a set of concepts or classes, individual instances, and relations between classes. After analyzing the existing ontologies in the intelligent transportation domain, we propose a domain ontology to perform reasoning that allows DT-RI to implement applications to improve the safety of VRUs.

Our proposal is based on the SAREF4AUTO core [37] ontology as the primary reference, and a description logic ontology using Web Ontology Language (OWL) focused on the automotive domain. In addition, new elements have been incorporated into road intersection scenario to meet many dangerous situations for VRU agents.

The ontology is structured modularly using a semantics-driven approach [38], which enables expressivity requirements to be easily handled and provides scalability for the evolution and maintenance of the ontology. As the base cell of the road network in urban and non-urban areas, every road intersection has the same dynamic and static structural information. Once both the dynamic and static information modeling of the road intersection are detailed, combining these two parts can create a complete DT-based road intersection. The ontology was implemented and evaluated using Protégé software.[1] The evaluation demonstrates that the presented ontology can process human-like reasoning in road intersection contexts. For visualization of the ontology, we used OWLGrEd software.[2]

For clarity, our ontology proposal has been divided into two main modules: static physical information of the road intersection and dynamic physical information of the road intersection. These modules are formed by different terminology classes merged into a complete ontology. In Fig. 4 and 5, squares denote classes, straight blue arrows represent the subclass relationship between two classes (the source of the arrow is the subclass of the destination class of the arrow), and dashed red arrows represent OWL properties used to assert relationships between classes (or instances).

### *B. INTERSECTION STATIC INFORMATION MODELING*

The road intersection static ontology is defined in Fig. 4 to map the non-moving elements in Fig. 2 into their DT representation. An *intersection* class was created at the center of the topology to define the main objects of interest for VRU safety. This class is related to the *Topology* class through the *consistsOf* property. The road topology comprises spatial objects at the intersection, including their geometric features and defines the spatial relations among the objects. The *consistsOf* property describes the spatial entities that can compose the intersection, while *belongTo* property describes the administrative area where the road intersection is placed. Because DT-RIs will be part of macro smart city solutions, the unique identification of such road intersections is necessary so that the authorities responsible for the smart intersection can detect and isolate faults and perform management tasks efficiently. The *TrafficCenter*, *State*, *City*, *Neighborhood* are all subclasses of the *AdministrativeArea* class. The *TrafficCenter* class serves as the central hub for monitoring the key actions related to VRU safety. It provides services to road users, facilitates data-driven road traffic management, and provides essential information regarding the mobility and operational management of road intersections.

A *Topology* class is created to represent the static characteristics of the intersection. Some aspects of the GeoSPARQL [39] ontology have been reused to represent spatial objects, and define their spatial features and geometries. The road intersection geometry is described by the hasGeometry property. The *Geometry* class represents any spatial entity, being or having a shape, position, or extent. Any of these entities at the road intersection has features related to a *Geometry*, based on *Point*, *Line*, and *Curve* classes in the road intersection space. A point is a geometric

[1]https://protege.stanford.edu/
[2]http://owlgred.lumii.lv/

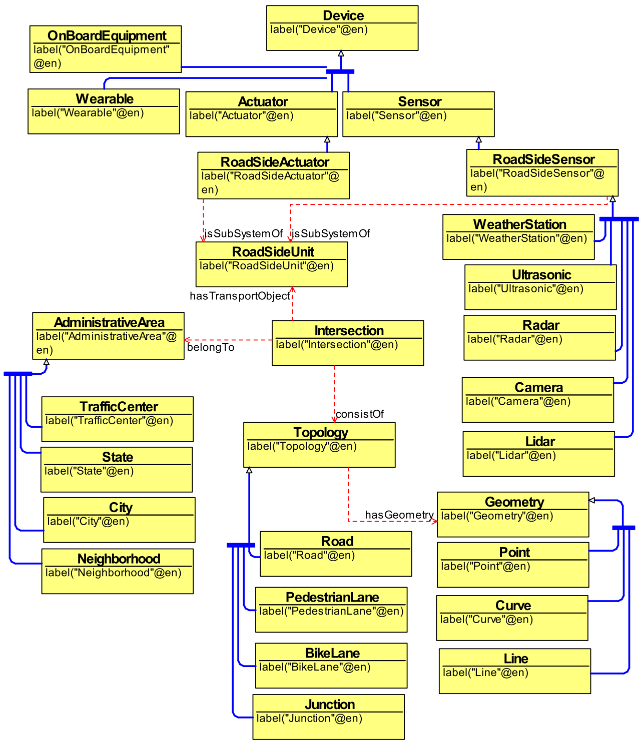



**FIGURE 4.** **Static information modeling for road intersection digital twins.**

object representing a single location in a Cartesian coordinate space. A Line is a curve with linear interpolation between exactly two points, and a curve is a geometric object stored as a sequence of points. They all serve as a reference for describing the topological features of the road intersection, e.g., roads, lanes, and junctions.

As an important part of DT-RI, simulations employ software that requires a detailed topological representation of the civil characteristics of the scenario to be modeled. Understanding the semantics of this information is essential for constructing more realistic worlds used in simulations for VRU safety applications. For this we define the i) *Road* class, a broad pathway leading from one location to another, typically with a specially designed surface for vehicle use; ii) *BikeLine* class, a designated section of a road intended for use by cyclists; iii) *PedestrianLane* class, a walkway on one or both sides of a road designed for pedestrians; and iv) *Junction* the point where roads intersect or converge. This topological information allows us to understand the global context of the road intersection, allowing the participants of the transportation system to be located (including the VRUs) to execute simulations involving such participants to analyze, predict, and resolve eventual safety conflicts among them.

The *Device* class, defined in the SAREF Ontology [40], has been reused to specify sensors and actuators specific to transportation systems. Then, the *RoadSideSensor* and *RoadSideActuator* classes are related through the *isSubSystemOf* property with the *RoadSideEquipment* class, which is a main part of the road intersection. Roadside sensors, including cameras, radars, lidars, and ultrasonic devices, are deployed along intersections to monitor the behavior of traffic agents, as illustrated in Fig. 2. Actuators are devices deployed along intersections that produce signals based on the output of the analyses carried out by specific DT-based applications. It is also considered the Electronic Control Unit (ECU), which is part of the vehicle's onboard equipment. For this purpose, the *OnBoardEquipment* class is created, being a subclass of the *Device* class. Onboard equipment is any embedded system in automotive electronics that monitors and controls one or more of a vehicle's electrical systems or subsystems. Various and heterogeneous sensors and devices in the vehicle to provide measurements and control properties. Moreover, wearable devices primarily used by the VRU were considered. Passengers or drivers of vehicles may use personal devices, but these are considered different devices from the vehicle onboard unit.

### C. INTERSECTION DYNAMIC INFORMATION MODELING

An ontology model also needs to address the challenge of representing the dynamic characteristics of a road intersection, as illustrated in Fig. 2, into representative elements of a DT's virtual world. As expected, the complexity in Fig. 5 organically reflects the challenge faced by an ontology that focuses on the dynamic scenarios related to VRU safety.

The *Intersection* class is related to the *TrafficAgent* and *Weather* classes through the *hasTrafficAgent* and *hasWeather* properties, respectively. These last two classes represent the dynamic elements of interest in road intersection for developing VRU safety applications. The *TrafficAgent* class represents any entity present at the intersection, including any vehicle type and VRUs. For any traffic safety application, the vehicle and VRU must be located in the intersection topology from the static information modeling, for which the hasAbsolutePosition and hasRelativePosition properties are created. The *hasRelativePosition* property is the relationship between a traffic agent to represent its relative position in front of a VRU, and the *hasAbsolutePosition* property is the relation between a traffic agent to represent its absolute position in the road intersection scenario. The *TrafficAgent* class has the *hasaRoute* property, a relation to express the route of an entity (e.g., a vehicle or a VRU) whose route is defined by the *Route* class in the SAREF4AUTO ontology.

The *VRU* class describes road users, such as pedestrians, cyclists, motorcyclists, and other persons with disabilities or reduced mobility and orientation problems. We classified the VRUs into various profiles: i) profile 1 is the *Pedestrian* class, which includes adults, children, elderly persons, blind persons guided by a dog, and riders off their bikes; ii) profile 2 the *Bicyclist* class, that includes users of bicycles, wheelchairs, skaters, scooters, or horse riders; iii) profile 3 the *Motorcyclist* class, that addresses users of two wheels vehicles which are equipped with engines that allow them to move on the road.

The DT-RI obtains the physical scenario data through sensors (described in the static information ontology in Fig. 4)

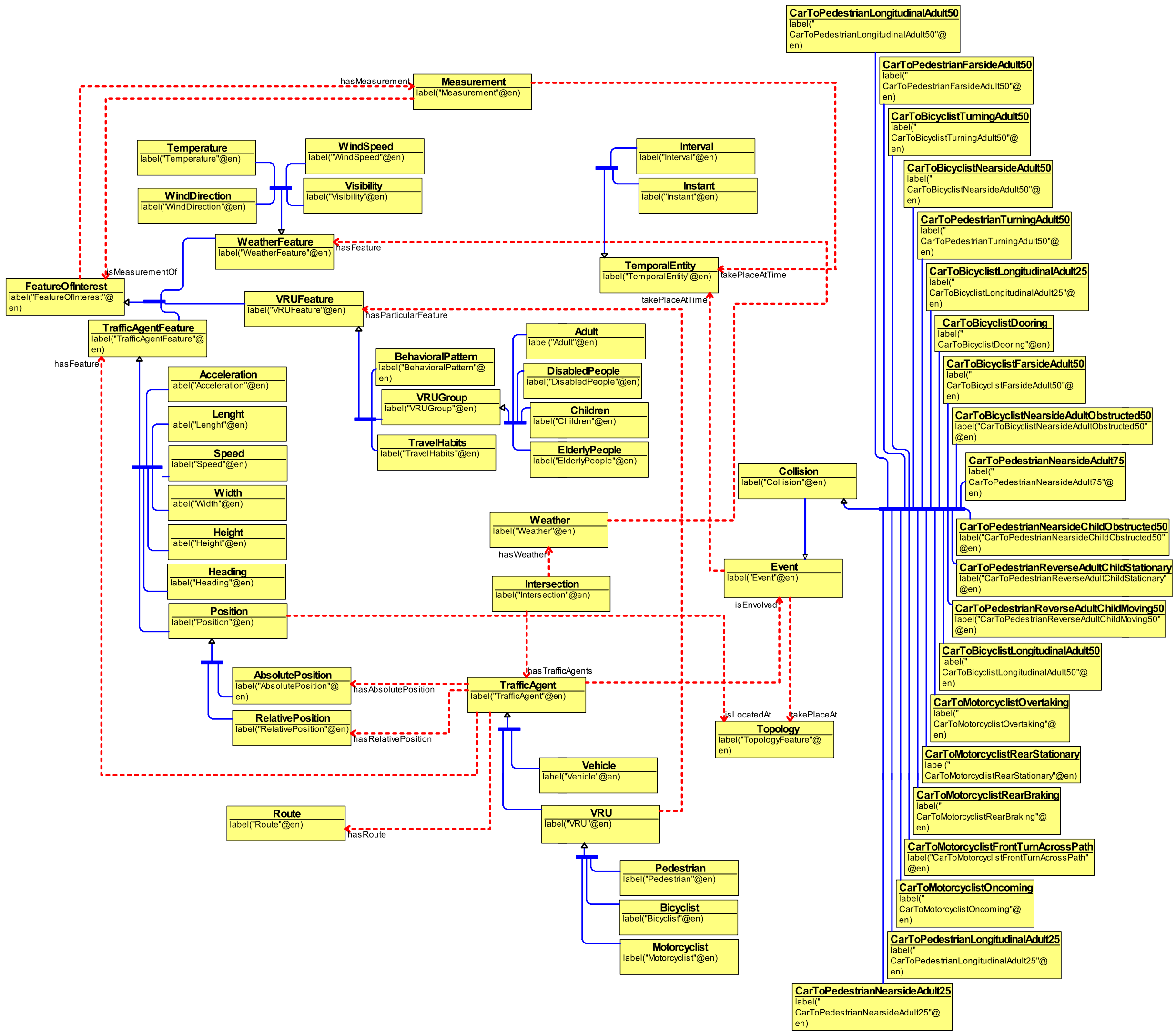



**FIGURE 5.** Dynamic information modeling for road intersection digital twins.

to keep the digital models synchronized and the actuators to intervene in the physical road intersection represented by the DT. The sensors provide the necessary measurements to obtain the features of interest for creating the DT-RI instances used by VRU safety applications. The *FeatureOfInterest* class covers all features of the road intersection divided into the subclasses *TrafficAgentFeature*, *VRUFeature*, and *WeatherFeature*. The *TrafficAgentFeature* class considers the common mobility characteristics of traffic agents, such as speed, acceleration, and heading, among others, and regarding the traffic agents' geometry such as length, width, and height. In addition, the *VRUFeature* class includes all the specific features of the VRUs, such as the behavioral pattern, groups belonging to the VRU, and their travel habits.

Specifically, events that involve any participants of the transit are monitored through the *Event* class of the SAREF4AUTO ontology, using the *takePlaceAt* property to define the relationship between an event and the road topology facility in which it takes place, and the *takePlaceAtTime* property for the relationship between an event and the temporal entity in which it occurs (or in which it is foreseen to occur). The main event case of our proposal is the *Collision* event class when a vehicle collides with another vehicle, pedestrian, animal, or other moving or stationary obstruction. This results in injury, disability, death, and property damage as well as financial costs for both the society and the individuals involved. As collision cases can be the most varied, we only considered cases involving the VRU. An exhaustive list of VRU collision cases of interest is adopted according to the recommendations of The European New Car Assessment Program, which is listed in Table 2 [7].

The listed cases incorporated the main groups of collision scenarios based on real accident databases [41]. Vehicle maneuvers and conflict situations were identified in the accident database to create groups of collisions. These scenarios are used by protocols to test collision avoidance mechanisms

**TABLE 2.** Summary of VRU collision cases (adapted from [7]).

| Class | Definition |
|---|---|
| *CarToBicyclistDooringAdult* | A collision between the vehicle's door or an occupant exiting a vehicle and a bicyclist traveling alongside the vehicle. |
| *CarToPedestrianFarsideAdult50* | An adult pedestrian crosses the vehicle's path from the farside, and the vehicle strikes the pedestrian at 50% of the vehicle's width. |
| *CarToPedestrianNearsideAdult25* | An adult pedestrian crosses the vehicle's path while walking from the nearside, and the vehicle strikes the pedestrian at 25% of the vehicle's width. |
| *CarToPedestrianNearsideAdult75* | An adult pedestrian crosses the vehicle's path while walking from the nearside, and the vehicle strikes the pedestrian at 75% of the vehicle's width. |
| *CarToPedestrianNearsideChildObstructed50* | A child pedestrian crosses the vehicle's path, running from behind and obstruction from the nearside, and the vehicle strikes the pedestrian at 50% of the vehicle's width. |
| *CarToPedestrianLongitudinalAdult25* | An adult pedestrian walking in the same direction in front of the vehicle and the vehicle strikes the pedestrian at 25% of the vehicle's width. |
| *CarToPedestrianLongitudinalAdult50* | An adult pedestrian walking in the same direction in front of the vehicle and the vehicle strikes the pedestrian at 50% of the vehicle's width. |
| *CarToPedestrianTurningAdult50* | A vehicle turns toward an adult pedestrian crossing its path, walking across a junction, and the vehicle strikes the pedestrian at 50% of the vehicle's width. |
| *CarToPedestrianReverseAdultChildMoving50* | A vehicle travels rearwards toward an adult or child pedestrian crossing its path walking from the nearside, and the vehicle strikes the pedestrian at 50% of the vehicle's width. |
| *CarToPedestrianReverseAdultChildStationary* | A vehicle travels rearwards toward an adult or child pedestrian standing still, and the vehicle strikes the pedestrian at 25, 50, or 75% of the vehicle's width. |
| *CarToBicyclistNearsideAdult50* | A bicyclist crosses the vehicle's path cycling from the nearside and the vehicle strikes the bicyclist. |
| *CarToBicyclistNearsideAdultObstructed50* | A bicyclist crosses the vehicle's path cycling from the nearside from behind an obstruction, and the vehicle strikes the bicyclist at 50% of the vehicle's width. |
| *CarToBicyclistFarsideAdult50* | A bicyclist crosses the vehicle's path cycling from the farside, and the vehicle strikes the bicyclist at 50% of the vehicle's width. |
| *CarToBicyclistLongitudinalAdult25* | A bicyclist cycling in the same direction in front of the vehicle and the vehicle strikes the cyclist at 25% of the vehicle's width. |
| *CarToBicyclistLongitudinalAdult50* | A bicyclist cycling in the same direction in front of the vehicle and the vehicle strikes the cyclist at 50% of the vehicle's width. |
| *CarToBicyclistTurningAdult50* | A vehicle turns towards a bicyclist crossing its path, cycling in the opposite direction across a junction, and the vehicle strikes the cyclist at 50% of the vehicle's width. |
| *CarToMotorcyclistRearStationary* | A vehicle travels toward a motorcyclist, and the vehicle strikes the motorcycle's rear. |
| *CarToMotorcyclistRearBraking* | A vehicle travels forward toward a motorcyclist traveling at a constant speed and then decelerates, and the vehicle strikes the rear of the motorcycle. |
| *CarToMotorcyclistFrontTurnAcrossPath* | A vehicle turns across the path of an oncoming motorcyclist traveling at a constant speed, and the vehicle strikes the front of the motorcycle. |
| *CarToMotorcyclistOncoming* | A vehicle drifts out of the lane and into the path of a motorcyclist traveling in the opposite direction in the adjacent lane. |
| *CarToMotorcyclistOvertaking* | A vehicle drifts out of the lane and into the path of a motorcyclist traveling in the same direction in the adjacent lane. |

in new driver assistance systems. Two major scenarios are generally addressed: crossing accidents between the VRU and the same nearside or farside vehicles, and longitudinal accidents where the VRU and the vehicles move in the same direction. Therefore, we understand that the same scenarios are those that our DT-RI must anticipate to act on the road intersection as a whole and avoid or mitigate the effects of a collision between vehicles and VRUs. Furthermore, these scenarios and the corresponding risks to VRUs can even assist integrated ethical decision-making mechanisms, for instance, [42], when choosing a sequence of actions to minimize harm in unavoidable collisions [43].

Furthermore, as shown in Fig. 5, the weather conditions are closely linked in our dynamical model to the collision scenarios discussed above. Environment-aware digital twins have recently been highlighted in critical domain applications [44]. Weather extremes have become more frequent and severe, and the importance of building weather, climate, and environmental information elements into digital twins of critical systems such as cities, ports, flood barriers, energy grids, and transport networks. Thus, the *Weather* class was defined for local weather conditions in the neighboring area of the road intersection. The weather describes the state of the atmosphere at a particular place and time, collecting features of interest such as precipitation, temperature, humidity, visibility, and wind, all of which are extremely important in modeling vehicle movement characteristics given that they directly influence the general perception of the road intersection for traffic participants and how the participants themselves (or cyber-physical systems) act on the road intersection.

### *D. ROAD INTERSECTION TRAFFIC MODELING*

In the context of the DT-based ITS model shown in Fig. 3, a traffic model is understood as the framework used to represent and analyze vehicular traffic flow. These models support traffic management, control strategies, and mobility optimization in urban and highway networks. These can be broadly categorized into microscopic and macroscopic models. Microscopic models simulate individual vehicle behaviors, such as acceleration and lane changes, whereas macroscopic models describe traffic as a continuous flow, focusing on aggregate variables such as density and speed [45].

Although it is beyond the scope of this paper to define a full-fledged traffic model, it should be stated that our DT-RI will employ a microscopic model once individual behaviors and interactions between vehicles and VRUs are defined in our ontology framework presented in Figs. 4 and 5. Both static (e.g., road geometry) and dynamic (e.g., real-time position) data inputs need to be integrated into all permitted movement groups for vehicles and VRUs, as defined by local transit rules and regulations and validated by traffic engineering experts.

#### 1) CONNECTING INFORMATION AND TRAFFIC MODELING

As an illustrative exercise for the functionalities of the DT-based ITS model in Fig. 3, Fig. 6(a) outlines a four-way road intersection with two lanes per approach. It (partially) shows the permitted movement groups for vehicles originating from road $r_1$, used here as a reference for defining movement for vehicle $v$. Given a two-lane configuration, two movement groups, $G_1$ and $G_2$, are defined for each source lane. The groups include specific movements between source and destination lanes, such as $\left(m^v_{1,1}, m^v_{1,2}, m^v_{1,3}\right) \in G^v_1$ and $\left(m^v_{2,1}, m^v_{2,2}, m^v_{2,3}\right) \in G^v_2$. Similarly, the traffic model defines permitted movements for VRUs, considering the likely paths for pedestrians and cyclists through the intersection [46]. Figure 6(b) depicts these movements for two exemplar VRUs: $vru_1$, a pedestrian $p$, and $vru_2$, a cyclist $c$. Their movement groups are denoted as $\left(m^p_{1,1}, m^p_{1,2}\right) \in G^p_1$ and $\left(m^c_{1,1}, m^c_{1,2}\right) \in G^c_1$, respectively. Pedestrian-type VRUs are assumed to walk along sidewalks and cross near corners, whereas cyclists follow dedicated bike lanes or ride near curbs when such infrastructure is absent.

By connecting information and traffic models, the so-called "What-if Analysis" capabilities from DTs can be unleashed at the Application Layer. In our case, the DT-based ITS "Prediction Application" in Fig. 3 will not only focus on potentially critical events for VRUs, but it will also match them to the collision cases detailed in in Table 2. Evidently, faster-than-real-time simulation [47] will be needed for this "Prediction Application". It is well-known the fact that DTs deal with the dynamics of complex physical structures, for example mobile cranes [48], by using kinematic models. They are fed by the agent's present state, so that a DT can evolve them in time faster than real-time to do predictions. Therefore, in addition to the movement groups discussed above, the agent's present state, such as location, velocity within the road intersection and prevailing weather conditions. Those parameters are obtained from Fig. 5, as well as other (static) physical constraints from Fig. 4 for those kinematic models.

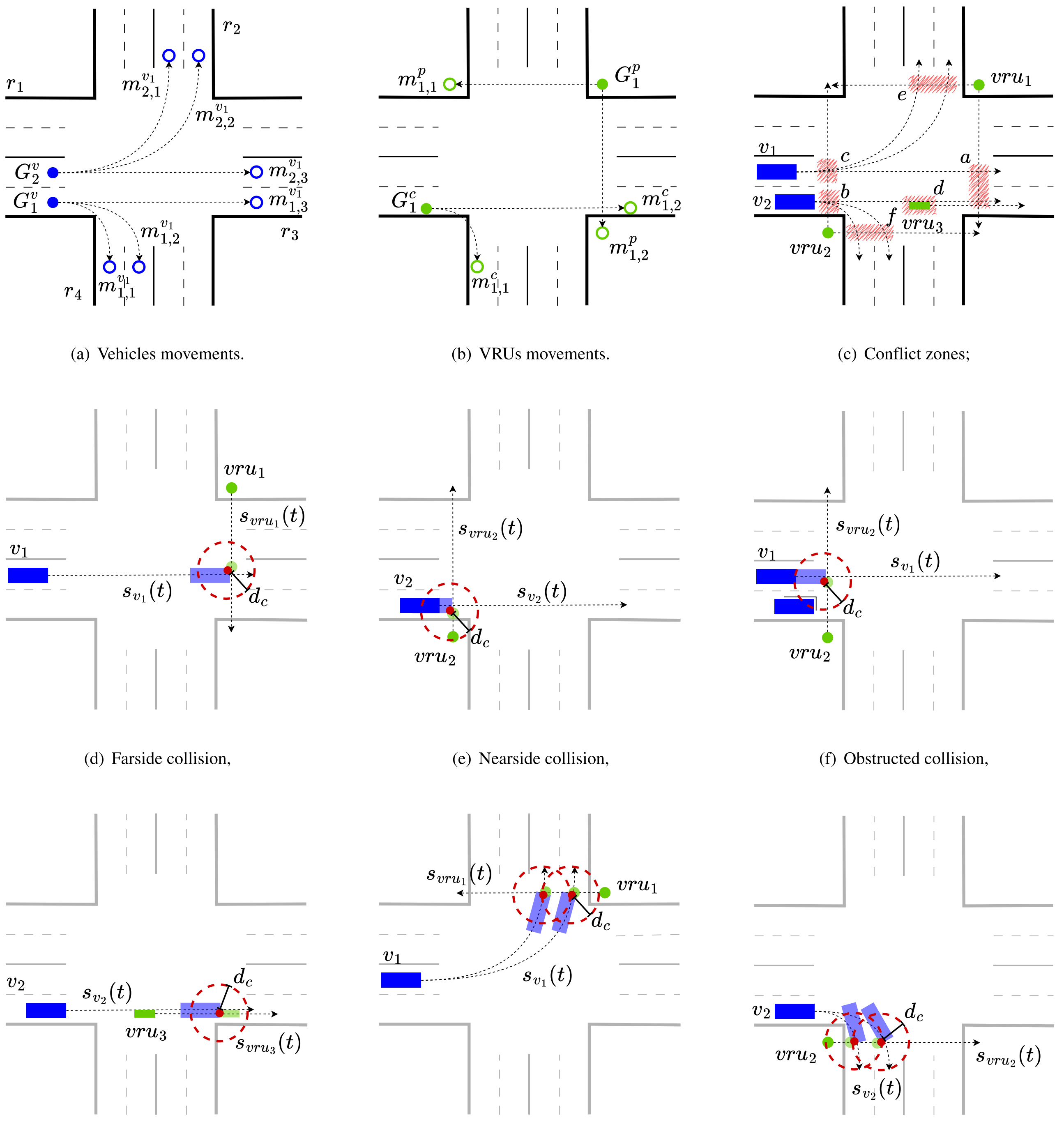
#### 2) PROGNOSIS FOR VRU COLLISIONS

Once the set of potential collision scenarios is identified, each collision point and the respective time-to-collision (TTC) [7] can also be determined. Based on the definition of movement groups, the DT-RI derives conflict zones, that is, spatial regions where the trajectories of different agents may intersect. These zones, illustrated in Fig. 6(c), results from the geometric and temporal overlap of permitted movements at the road intersection and serves as the primary locus for potential VRU-vehicle conflicts. Each conflict zone is semantically labeled according to its type (e.g., farside collision, nearside collision, longitudinal, and obstructed, as illustrated in Figs. 6(d)-6(i) and classified in Table 2. The identification of conflict zones is dynamic: as agents move, their current and future positions $s\,(t)$ are projected ahead.

For the sake of simplicity, consider the case for longitudinal collision in Fig. 6(g). Assume that a simple non-uniform rectilinear motion model in Eq. 1 can be defined for any agent $j$ in the intersection, where $(v, p, c) \in j$. Future positions along the path $S_j\,(t)$ are computed from the initial position $s_0$ of agent $j$ with velocity $v_0$ and acceleration $a_0$ at the intersection, determined by the first detection at time $t_0$ of the particular agent in the traffic intersection (awareness-radius) region.

$$s_j\,(t) = s_0 + v_0 t + \frac{1}{2} a_0 t^2. \tag{1}$$

Spatiotemporal overlaps can then be evaluated against the defined zones for longitudinal collision in Fig. 6(c). These conflicts may lead to collisions at a specific collision time $t_c$. In Fig. 3 the DT-based ITS model, in the Sematic Module, holds Application Programming Interface (APIs) to interact with the Applications Layer as well as with a communication technologies to interact with the Physical Layer. This will allow safety-oriented applications to make full use of DT's functionalities to intervene in order to reduce risky scenarios, prevent accidents, or at least minimize the harmful consequences of unavoidable events at road intersections. Note that to prevent collisions, there are not only agent's velocities and accelerations coefficients to be modulated, but also the possibility of switching movement groups. For instance, a vehicle can depart from $m^v_{1,1}$ toward $m^v_{1,3}$ in Fig. 6(a) to avoid a pedestrian within a given conflict zone as shown in Fig. 6(c). Evidently, the considered




(a) Vehicles movements. (b) VRUs movements. (c) Conflict zones;

(d) Farside collision, (e) Nearside collision, (f) Obstructed collision,

(g) Longitudinal collision, (h) Farside turning collision, (i) Nearside turning collision.

**FIGURE 6. Road intersection traffic modeling (Partial Description).**

strategies will be conditioned to a complex combination of ethical issues and technical aspects, such as TTC, room for maneuver, and other physical and safety constraints in Fig. 4. A straw-man approach to addressing technical aspects when linking predictions to preventive actions can be outlined as follows.

### 3) FROM PREDICTED SCENARIOS TO PREVENTIVE ACTIONS

The DT-RI may continuously perform forward simulations over a defined prediction horizon $[t_0, T_{max}]$, evaluating whether the projected trajectories of agents will intersect within any conflict zone, as shown in Fig. 6(c). It is worth mentioning that the more in the future the DT-RI advances by increasing $T_{max}$, the larger are the prediction uncertainties for the agent's states. In addition, capital/operation expenditure with high-performance computing (HPC) resources is also expected to increase steeply for this faster-than-real time simulation [47]. For this purpose, the HPC infrastructure in Fig. 2 needs to be reached via low-latency networks; thus, HPC may have to be sitting at edge-based platforms rather than being hosted by regional clouds.

Let $R(v, vru)$ represent the set of all conflict relations between the vehicles and VRUs at any time in the intersection. An illustrative relation for detecting potential collisions can be defined as $C_i$ at time $t_{ci}$, for the i-th interaction pair $(v, vru)$ with $(p, c) \in vru$, as follows:

$$C_i(t) = \begin{cases} 1, & \text{if } \|s_v(t) - s_{vru}(t)\| \leq d_c, t \in [t_0, T_{max}] \\ 0, & \text{otherwise,} \end{cases} \quad (2)$$

where $d_c$ defines the collision threshold distance to consider, for instance, model uncertainties and safeguard aspects. Therefore, when $\sum C_i(t) \geq 1; \forall i, t$, means that the DT-RI was able foresee critical events, happening at the set $t_{ci} \in \{t \mid C_i(t) = 1\}$, to be dealt with in the near future considering that $t_0 < t_{ci} \leq T_{max} \forall i$. The DT-RI then requires also fast outcomes from (possibly iterative calculations in) the decision-making algorithms. Therefore, it is likely that HPC at edge would be required. The traffic crash prediction outlined above follows a conventional approach, whereas deep-learning models are already being exploited [49]. Autonomous vehicles and forthcoming regulations may even require intricate ethical aspects to be taken into account as in [43]. The formulation and implementation of such algorithms are beyond the scope of our discussions.

For the actuation cycle, that is, the implementation of outcomes from those decision-making algorithms focused on collision-prevention purposes, however, we can return to Fig. 2 to spot diverse elements for interacting with humans. Thus, for VRUs, given the time sensitivity of such scenarios, wearable devices or mobile applications can provide timely warnings. Technological advances will soon make them more suitable for such time-critical applications. For vehicles, on the other hand, it is already possible to perform machine-to-machine communications for preventive switching of movement groups, adjustment of vehicle speed and acceleration, and the use of adaptive traffic lights (for unconnected vehicles) [17], dynamic variable-message signals (VMS), and onboard driver assistance systems such as advanced driver assistance systems (ADAS) and other technologies described elsewhere for DTs in ITS [2].

Despite the importance of traffic models and preventive actions for VRU safety, we must return to the basic elements in Fig. 1 and reaffirm that the purpose of this paper is to focus on the virtual representation of our ontology-driven DT computational model. Actually, this is the foundation where complex preventive actions discussed above will be built upon. Therefore, efforts should be now directed toward a practical demonstration of how the conceived semantic module can be implemented and instantiated, based on open-source platforms, as depicted in Fig. 7 and explained below.

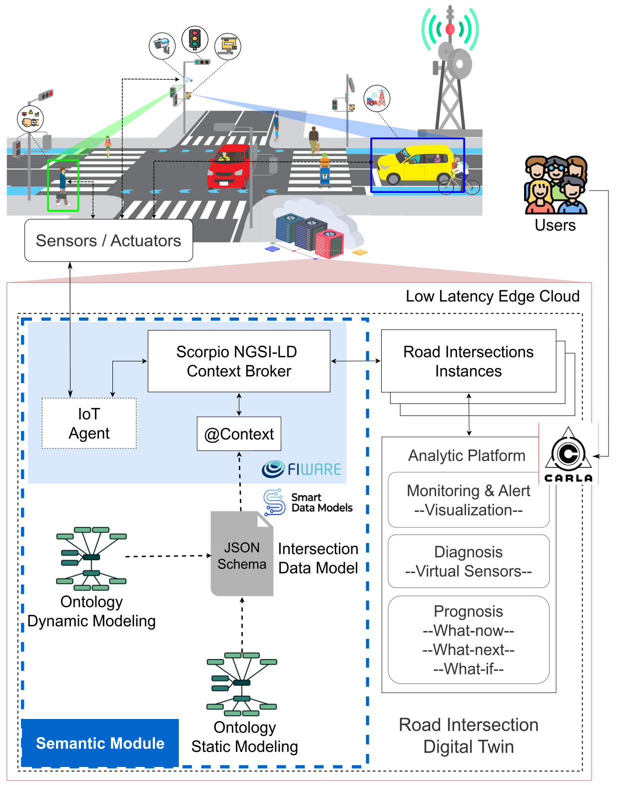
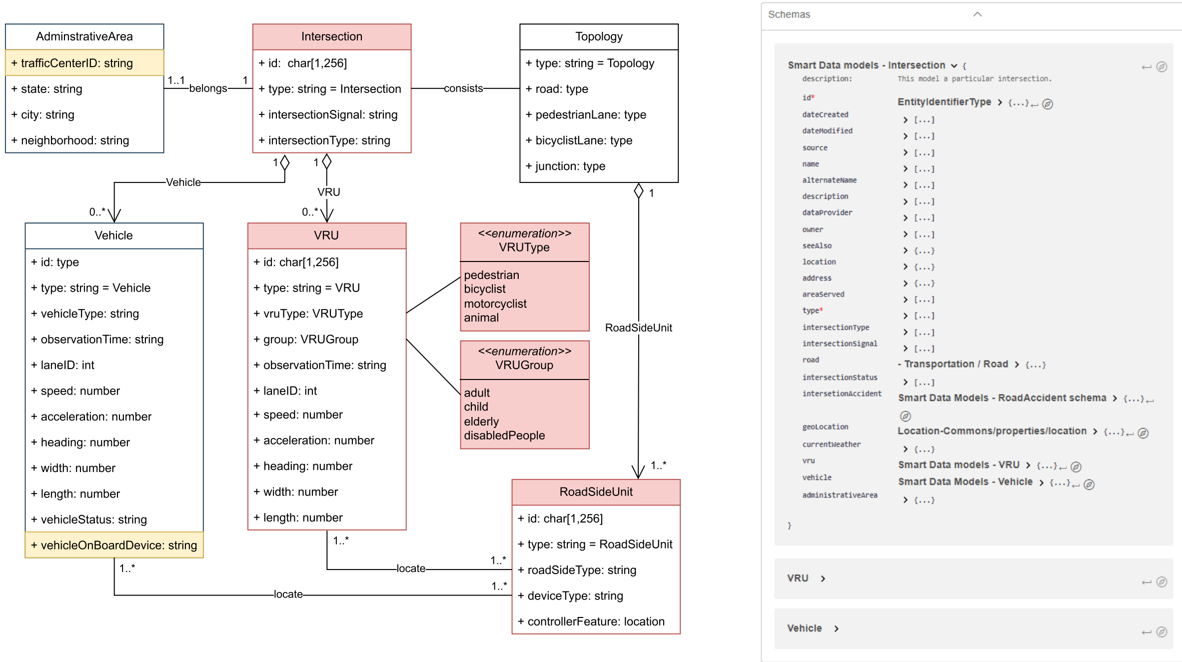



**FIGURE 7.** Semantic module implementation.

## IV. A FULLY OPEN-SOURCE-BASED INSTATIATION

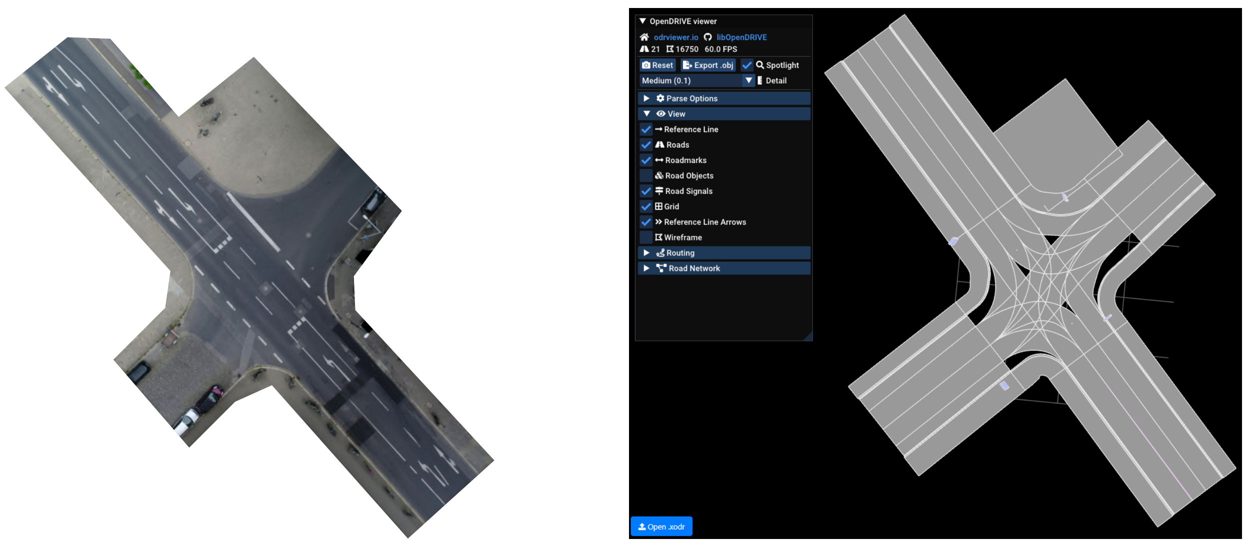
The purpose of ontology is to provide semantics to the data collected at road intersections. Thus, this section moves a further step toward building a corresponding virtual representation (i.e., computational models) of the physical assets and processes at road intersections. Moreover, such a computational model also requires well-defined methods for synchronization and interaction tasks with physical world assets through a communication channel, as illustrated in Fig. 1. Creating data models from scratch can be an inefficient approach for prototyping, considering that there are already solutions to provide support for creating and operating DTs, which are usually known as DT platforms. Lehner et al. [50] performed a comparative analysis on Amazon, the Eclipse ecosystem, and Microsoft Azure DT as platforms to support the development of prototypes.

Our objective here is to demonstrate a methodology for creating DT-RI prototypes using an ecosystem built on open-source tools and data repositories, enabling inexpensive and accessible prototyping of ontology-based semantic modules, as highlighted in Section III. This process involves platforms for creating and instantiating smart data models, as illustrated in Fig. 3. Furthermore, these computational instances must be populated with physical-world data.




(a) Road intersection data model UML diagram
(b) Road intersection data model schema.

**FIGURE 8.** **Road intersection data model.**




(a) Road intersection view
(b) Opendrive representation

**FIGURE 9.** **Road intersection static information modeling.**

Finally, a DT instantiation tool is required to allow users to interact effectively with the physical world.

## *A. SMART DATA MODEL AND APPLICATION PROGRAMMER INTERFACE*

To implement the DT-RI semantic module, we chose the FIWARE platform, as shown in Fig. 7, which provides all necessary tools for building DTs. FIWARE is containerized, highly scalable, and easy to implement and replicate [14]. Cloud-based network-slicing solutions [51] can be designed to meet the computational and communication network requirements of the elements shown in Fig. 7. Data originate from heterogeneous sources, utilize diverse protocols, and encompass various data attributes, types, and relationships. Consequently, it is essential not only to standardize communication among DT components but also to ensure that

```
{
    "id": "urn:ngsi-ld:Intersection:001",
    "type": "Intersection",
    "intersectionSignal": {
        "type": "Property",
        "value": "non-signalized"
    },
    "intersectionType": {
        "type": "Property",
        "value": "four-leg"
    },
    "geoLocation": {
        "type": "GeoProperty",
        "value": {
            "type": "Point",
            "coordinates": [50.78207, 6.0711
                6]
        },
    },
    "vru": {
        "type": "Relationship",
        "object": "urn:ngsi-ld:VRU:001"
    },
    .
    .
    .
    "vehicle": {
        "type": "Relationship",
        "object": "urn:ngsi-ld:Vehicle:001"
    },
    .
    .
    .
    "@context": [
        "https://mygithub/
            FIWARE_smart_intersection/
            datamodels.context-ngsi.jsonld"
    ]
}
```

**Listing 1.** Road intersection entity.

the data formats flowing through these components are standardized to guarantee interoperability. The IoT agents in Fig. 7 translate IoT-specific protocols from the sensing and acting system of the road intersection into NGSI-LD context-information protocols.

FIWARE offers data modeling and management mechanisms through its FIWARE RESTful API, enabling access to current information on physical systems and facilitating data updates. The main element in the NGSI-LD standard is the context entities that represent the physical or logical objects. Each context entity has a set of attributes, and attribute metadata represents real-life properties. Based on context entities, NGSI-LD provides a smart data model for context information, an interface for exchanging data, and an interface for exchanging information on how to obtain such data. NGSI-LD API interactions are made using HTTP/HTTPS requests. The Scorpio context broker in Fig. 7, is the core element that allows managing and requesting context information in NGSI-LD format.

```
{
    "id": "urn:ngsi-ld:VRU:001",
    "type": "VRU",
    "vruType": {
        "type": "Property",
        "value": "bicyclist"
    },
    "heading": {
        "type": "Property",
        "value": 130.52964
    },
    "Location": {
        "type": "Relationship",
        "object": "urn:ngsi-ld:RoadSideUnit:
            001"
        },
    },
    "speed": {
        "type": "Property",
        "value": 4.9064
    },
    "acceleration": {
        "type": "Property",
        "value": 0.8421
    },
    "@context": [
        "https://mygithub/
            FIWARE_smart_intersection/
            datamodels.context-ngsi.jsonld"
    ]
}
```

**Listing 2.** VRU entity.

We followed the recommendations in [13] to create our smart data model for the road intersection ontology proposed in Section III. We created a smart data model called *Intersection* as shown in the road intersection data model UML diagram in Fig. 8(a). The relationships between entities make up the road intersection. Based on the intersection smart data model, schemas for the entities are created, where the technical representation of the model defines the technical data types and structures in a written document for human readers. Figure 8(b) shows the main schema of the data model of the crossing together with schemas of the other main entities involved in the construction of the digital twin.

Our smart data model reuses different models from the FIWARE Smart Data Models catalog.[3] Smart Data Models offer data models for digital twins and data spaces, facilitating true data interoperability among diverse systems based on open-licensed data models. They are compatible with the FIWARE platform and export in several other formats, including JSON, JSON-LD, CSV, SQL, and DTDL. Specifically, we reused data models belonging to the transportation domain to create at smart intersection data model. Other critical elements for developing VRU safety applications were modeled from scratch. The *VRU* and *RoadSideUnit* models were created specifically for use in our

[3]https://smartdatamodels.org/

```
{
    "id": "urn:ngsi-ld:Vehicle:001",
    "type": "Vehicle",
    "vehicleType": {
        "type": "Property",
        "value": "car"
    },
    "heading": {
        "type": "Property",
        "value": 130.43668
    },
    "width": {
        "type": "Property",
        "value": 1.93507
    },
    "length": {
        "type": "Property",
        "value": 4.94025
    },
    "Location": {
        "type": "Relationship",
        "object": "urn:ngsi-ld:RoadSideUnit:
            001"
        },
    },
    "speed": {
        "type": "Property",
        "value": 9.6565
    },
    "acceleration": {
        "type": "Property",
        "value": 2.0056
    },
    "vehicleStatus": {
        "type": "Property",
        "value": "moving"
    },
    "@context": [
        "https://mygithub/
            FIWARE_smart_intersection/
            datamodels.context-ngsi.jsonld"
    ]
}
```


**Listing 3.** Vehicle entity.

road intersection model. The VRU models specify features of interest for safety applications, such as age, location, travel speed, and direction, which road intersection sensing mechanisms could provide. In addition, specific attributes of the intersection were created, such as *intersectionType*, *intersectionStatus*, *intersectionSignal*, among others related to the transportation system. The new models we created are highlighted in red, while the new properties of existing models are highlighted in yellow in Fig. 8(a).

Furthermore, context is necessary when using these smart data models under a linked data paradigm. Therefore, every implementation requires a *context.jsonld* reference file (seen interacting with JSON Schema Fig. 7) used by the context broker to instantiate the road intersection digital twin. The FIWARE community offers the necessary mechanisms using Swagger tool[4] to generate the NGSI-LD context file from the road intersection smart data model.

### B. POPULATING THE SMART DATA MODEL

Custom agents, created by sensing system developers for FIWARE IoT, can also be easily integrated to interact with the context broker. The communication mechanisms and protocols used in the data acquisition phase are outside the scope of this work, so we assume that the IoT agents in Fig. 7 provide reliable and secure data for creating DT-RI instances.

Third parties responsible for the operation and management of road intersections must develop their IoT agents[5] or reuse already available IoT agents.[6] For prototyping purposes, we populated our smart data model with the inD dataset, which is a collection of traffic recordings from four distinct locations captured via drones, detailing each road user's movement and type [52]. Given the detailed level of user information provide by the dataset, for this proof of concept, we assume that the dataset is equivalent to the information that IoT agents should provide by sensing the road intersection scenario.

We chose the ASAM OpenDRIVE standard [53] for implementation, an open-source format organized in a hierarchical structure and compiled in an Extensible Markup Language (XML). OpenDRIVE allows the modeling of the static information of the road intersection and provides a standardized format for road descriptions, reducing the cost of creating and converting these files for development and testing purposes. The implementation is complex, because roads are generated from a sequence of segments.

To construct the OpenDRIVE file, we used tools designed to create and edit OpenDRIVE structures, some of which can be derived from widely recognized map formats. To simplify the development of virtual maps using OpenDRIVE, the HLRS is developing the software ODDLOT.[7] The ODDLOT tool provides a graphical interface for loading maps and designing roads using different prototypes specified by the number of lanes, width, and road markings. Junctions can be created automatically by defining the intersection area or manually by using a specialized editor.

For a straightforward approach toward the instantiation of a road intersection virtual representation, we can also take advantage of the fact that the inD dataset provides both OpenDRIVE files and images of the road intersection, as shown in Figs. 9(b) and 9(a), respectively [52]. The static information of our smart data model for road intersection can be properly visualized using the OpenDRIVE Online Viewer tool.[8]

The context broker in Fig. 7 provides the most up-to-date context information for the entities described. Other components subscribe to updates for the entities of interest.

[4] https://swagger.io/
[5] https://iotagent-node-lib.readthedocs.io
[6] https://www.FIWARE.org/catalogue
[7] https://www.hlrs.de
[8] https://odrviewer.io/

**FIGURE 10.** DT-RI Visualization and Simulation using CARLA: 6 vehicles, and 2 cyclists (frame 0 of recording 7 from inD database).

Dynamic information, such as data related to vehicles, vulnerable road users (VRUs), and weather conditions, was processed by the context broker. These data are obtained through IoT agents, ensuring seamless integration and real-time update. To represent the dynamic elements of the scenario, we selected recording number 7 from the inD database, and within it, we chose the initial frame. At that time, eight traffic agents were present at the road intersection, six vehicles (five parked), and two cyclists [52].

The instantiated road intersection entity is shown in Listing 1 using the normalized NGSI-LD format. The relationships between the dynamic elements, vehicle entities, and VRU entities are declared within the road intersection entity. Owing to space constraints, we have only represented the entity of the first VRU and the first vehicle in the selected frame, in Listing 2 and Listing 3 respectively, also using the normalized NGSi-LD format. The properties specified with values in each entity result from the data provided in the InD dataset, which are similar to the data provided by the sensors in the roadside units at the intersection illustrated in Fig. 2.

### C. VIRTUAL ROAD INTERSECTION VISUALIZATION: SCENARIOS AND SIMULATIONS

As shown in Fig. 1, DTs have a Virtual Representation with computational models to provide a unified platform for simulation, learning, prediction, and visualization. This Analytic Platform is detailed in Fig. 7, interacting with the instantiated FIWARE DT's Semantic Module (via the Scorpio NGSI-LD Context Broker). Such interaction with the smart data model discussed above is needed not only for performing basic Monitoring and Alert Visualization as in regular Traffic Control Centers but also for advancing toward areas such as simulations for diagnosis (e.g., use of Virtual Sensors) and prognosis studies (i.e., What-now, What-next, What-if scenarios) in future ITS using DT-RI.

Note that realistic and flexible visualization is a basic feature required for dealing with current state observations and possible future scenarios in simulated cases. CARLA[9] is an open-source driving simulator grounded on Unreal Engine,[10] which implements a scalable client-server architecture.

In its simplest simulation mode, the CARLA platform allows the creation of the layout of the road intersection using the OpenDRIVE specification and representing all agents in the traffic scenario. For this purpose, CARLA clients were developed to serve as an interface between the Scorpio context broker (see in Fig. 7) and the CARLA server, where simulations and their visualization were executed.

CARLA clients collect information corresponding to each entity instantiated by the broker using the NGSI-LD API and insert the information into the simulator through the CARLA Python API to represent vehicles and VRUs on the previously generated map. Unlike previous uses that integrate the CARLA simulator as a virtualization element in creating the DT [54], our proposal focuses on a FIWARE-centric approach. In our case, the CARLA simulator illustrates only one of the many applications that can consume the context data from the Scorpio broker. Thus, other DT enablers native to FIWARE can be implemented to store historical data for training machine learning algorithms and to interact with the simulations executed in CARLA.

The reference intersection of the inD database that we used to instantiate the FIWARE entities of the DT-RI has also been created as a world in the CARLA simulator from the OPENDRIVE file available in the database. Building on the methodology used to instantiate FIWARE entities, a simulation was conducted in CARLA, replicating recording 7 of the inD database. At that time, recording 7 depicted an urban intersection with eight traffic agents: two

[9]https://carla.org/
[10]https://www.unrealengine.com/

moving vehicles, four parked vehicles, and two cyclists [52]. Despite the low number of moving agents, this scenario is relevant for studying VRU-vehicle interactions in a controlled and computationally efficient environment. CARLA's clear visualization supported visual validation and analysis, laying a solid foundation for future, more complex scenarios. This scenario, along with the agents, was retrieved by CARLA using Scorpio, as defined in Listing 2 and Listing 3.

Figure 10 shows a textured visualization of the scene using CARLA. Thus, the simulation at the beginning, corresponding to frame 0 of recording 7, was used to create the FIWARE entities in Subsection IV-B. This simulation can be visualized remotely (but without texture) in a web browser using the CarlaViz[11] tool to provide simulation as a service to remote DT-RI users, as shown in Fig. 7.

## V. CONCLUSION

This paper proposed a practical response to the pressing issue of VRU safety at road intersections by proposing and building semantic models to equip virtual space of a DT-ITS with the necessary properties for an accurate and reliable description of the physical world. It pushed forward a clear data classification, a systematic DT development framework, and a practical approach to the modeling of RI data. For the first time, a hands-on approach was proposed for designing an ontology-based information modeling method for RIs, leveraging open-source and market-driven platforms to support DT applications aimed at VRU safety.

A DT-RI prototype was developed using an ecosystem of open-source tools and data repositories, enabling accessible prototyping of ontology-based semantic modules. Furthermore, the ontology-driven nature of our DT-RI enables sophisticated simulation and risk analysis, where causal relationships among agents and infrastructure are clearly defined and machine-interpretable. By embedding semantic understanding within the DT-RI, the system gains contextual awareness of the environment, allowing it to reason over data and adapt its behavior based on specific conditions. The key feature is that it captures both static elements (infrastructure, sensors, road components) and dynamic elements (traffic agents, behaviors, environmental conditions), along with their relationships with traffic models and safety-oriented applications. The ability of the framework to continuously learn and evolve based on new data ensures the ongoing refinement of safety strategies, making it resilient and adaptable to emerging traffic patterns and behaviors.

However, improving both the computational and communication network capabilities of the system components is yet to be achieved. To address scalability across various ITS elements, the infrastructure must align with FIWARE's highly scalable features to coordinate intersection-wide policies to optimize, for instance, traffic signal phases or dynamically prioritize the VRU. Therefore, a suitable cloud-based network slicing solution must be explored, particularly to ensure security and privacy throughout the operational lifecycle of the system. Furthermore, the implementation of the data-format standardization block depicted in Fig. 7 will be pursued. This block enables the translation of IoT-specific protocols from the sensing and actuation systems at the intersection into the NGSI-LD context information protocol. Besides, the CARLA simulator in this study was successfully employed to test the proposed framework and provided valuable insights into the dynamic interactions within road intersections. Nevertheless, future efforts will try to improve the realism and diversity of simulated scenarios.

Future work will exploit such capabilities to support real-time decision-making, enhance the situational awareness of autonomous vehicles, and facilitate safer automated navigation. The system's ability to continuously learn and evolve based on new data ensures the ongoing refinement of safety strategies, making it resilient and adaptable to emerging traffic patterns and behaviors using machine learning-based approaches.

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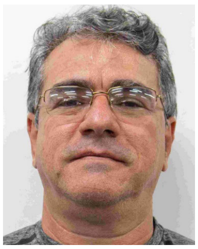

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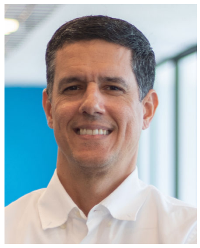

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