Enhancing Scenario-based Testing for Automated Driving Systems: An Ontology-Based Scenario Modeling Framework

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Abstract: Scenario-based Testing (SbT) emerges as a pivotal approach for validating the safe behaviors of Automated Driving (AD) and Advanced Driver-Assistance Systems (ADAS). Using virtual simulation, SbT allows for generating and running massive testing cases. This approach gathers typical driving situations and critical edge cases. Properly modeling representative scenarios is a primary challenge. A scenario model needs to account for complex components, such as roads, infrastructure, road users, and their behaviors and interactions. Ontology-based frameworks are proposed to model scenarios in a detailed manner. However, some limitations exist, such as (i) expressing dynamic behaviors, (ii) the capacity in complex scenario modeling to achieve more realistic simulation; and (iii) ensuring comprehensive ontology coverage and plausibility. This paper proposes an ontology framework addressing these shortcomings. A comparative evaluation is conducted using the developed quantitative metrics to assess the ontology framework against two other industrial ontologies.

1 INTRODUCTION

Automated Driving (AD) and Advanced Driver-Assistance Systems (ADAS) present an important evolution in automotive technologies, aiming to enhance road safety and reduce human error. The complexity of real-world driving environments requires rigorous validation to ensure these technologies are safe. Scenario-based Testing (SbT) has the potential to accelerate safety validation. A scenario describes a specific environment that an AD/ADAS-equipped vehicle could encounter in the real world.

Properly modeling representative driving scenarios is a primary challenge for SbT in both real-world and simulated environments. Diverse and complex scenarios can assess the safety of AD/ADAS in virtual simulation without risks and costs currently associated with real-world testing. Building a scenario model requires an in-depth knowledge and understanding of traffic and environments.

Modeling scenarios using ontologies provides a suitable framework for validation and testing of Automated Driving (Armand et al., 2014). Ontology-based modeling offers a flexible formalism for managing complex knowledge, which serves as the foundation for defining, generating, or identifying scenarios.

However, current ontology-based scenario modeling frameworks are facing challenges in covering various elements, expressing dynamism of driving behaviors, and effectively modeling complex scenarios.

In the present paper, the challenges of existing ontologies are presented in Section 2. In the subsequent Section 3, a new ontology framework for scenario modeling is proposed to capture the complexity of real driving environments more effectively. A preliminary ontology evaluation method using a comparative approach is conducted in Section 4, applied on the existing latest industrial ontology frameworks. Section 5 concludes the contribution of the presented framework.

2 RELATED WORKS AND CHALLENGES

Current scenario modeling ontologies are built, from a structural and organizational perspective, using hierarchical layered models (Bagschik et al., 2018;

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Scholtes et al., 2021; Schuldt et al., 2013), block-based categorical structures (de Gelder et al., 2022; Erz et al., 2022; Li et al., 2020), or their fusions (Armand et al., 2014; ASAM, 2022; Chen & Kloul, 2018; Westhofen et al., 2022). Previous research works have accounted for a wide range of knowledge within the driving domain, and diverse elements have been integrated into these ontologies. While existing models have made notable progress, there are still limitations leading to the need for new improvements to overcome these challenges.

2.1 Expressing Dynamics in Scenario Modeling

The symbolic nature of ontologies limits the expressiveness of dynamism in driving scenarios. In previous research, dynamic descriptions are commonly defined and encapsulated in the layer or module named *Dynamic Objects, Dynamic Entities*, *Dynamic Elements*, or *Traffic Participant* (ASAM, 2022; Bagschik et al., 2018; Erz et al., 2022; Scholtes et al., 2021; Schuldt et al., 2013). The layer incorporates behavioral descriptions, including (1) states: position, speed, acceleration; (2) actions: maneuvers and triggering events; (3) intentions & interactions: behaviors and activities.

These symbolic concepts lack the ability to express the spatial-temporal evolution of objects. Realistic dynamism relies on both temporal and spatial scales. While typically defined with discrete scenes, the relationships and dependencies between scenes are underrepresented in ontologies, failing to capture the continuous evolution of objects.

On the other hand, the spatial occupation of objects is often modeled through lane occupancy and relative positioning, such as when the EGO vehicle is driving on a lane and another vehicle is in its left rear. The gap between these high-level symbolic representations and the fine-grained occupancy grid (Elfes, 1989) highlights the need for an approach to bridge discrete symbols and continuous spatial data.

2.2 Complex Scenario Modeling

Traffic participants who do not directly influence the behavior of the EGO vehicle are often excluded from actual scenario modeling. While they may not directly impact the validation of AD/ADAS functions (Geyer et al., 2014), their presence is necessary to reflect realistic traffic environments.

In realistic driving environments, multiple traffic participants are present and interact. A considerable difficulty is to describe interactive driving behaviors of multiple road users with a generalized modelling framework.

The trigger-action mechanism is widely used to formalize scenarios and is sufficient to model less complex ones, such as those in the Car-to-Car Rear (CCR) series in the NCAP protocol concerning Automated Emergency Braking (AEB) function. However, this trigger-action practice is not well-suited for modeling scenarios involving multiple road participants because of simultaneous interactions or coordinated behaviors in real-world environments. Additionally, validating an AD/ADAS function requires a minimum test duration, such as 5 minutes for validating the lane-keeping capacity as required by the regulation (UNECE, 2021).

2.3 Coverage and Plausibility of Modeled Scenarios

Existing works have not addressed the issue of ontology coverage. The review (Zipfl et al., 2023) proposed a categorical coverage measure, using a checklist-based approach to determine whether an ontology covers certain categories of elements, such as lane marking properties of the road. While informative, this comparative review is insufficient for comprehensive coverage evaluation.

The problem is further related to the absence of a baseline ontology for scenario modeling. Under the Open-World Assumption, it is impossible to claim that an ontology covers sufficient elements or is complete when the baseline is missing.

Furthermore, the non-plausibility of scenario modeling was not discussed in the literature. The existing approaches bypass the necessary relationships and constraints that ensure scenarios remain valid. This can lead to modeling unrealistic scenarios, such as inappropriate or incompatible elements.

3 PROPOSED ONTOLOGY FRAMEWORK

An enhanced ontology-based scenario modeling framework is proposed and developed for AD/ADAS validation. The framework articulates refined ontology concepts in natural language and connects them through relations and constraints, addressing dependencies, mutual exclusions, and other factors relevant to validating AD/ADAS functions. Furthermore, this framework adapts spatial definitions to describe traffic participants within scenarios. The framework accounts for the complexity of real driving environments.

3.1 Refined Ontology Structure and Modules

In this paper, the proposed framework organizes four modules in ScenarioDomain to describe dynamic scenarios: Scenery, Dynamic Elements, Environmental Conditions, and Goals, as shown in Fig. 1. Scenery and Environmental Conditions provide static and environmental descriptions of scenarios. The Dynamic Elements module refines Maneuvers, Activities, and Behaviors for dynamic descriptions. The Goals module outlines validation objectives related to AD/ADAS requirements. The ontology elements, including concepts, properties, and axioms, are developed using Protégé Software (Noy et al., 2003).

Considering their use in automatic scenario generation, this framework organizes separately these descriptive elements with the layered containers. These containers serve as Components to form scenarios. A set of defined relationships contributes to associate elements, encapsulating concepts of Domain into containers of Components. This approach ensures the modularity and efficient composition of elements. For example, a Scenario occurs in a Zone, which consists of a RoadNetwork, including one or multiple Roads depending on the type of RoadNetwork, and so on. The four modules, organized as Domain, specify these container concepts. For example, each TrafficParticipant has its type and a set of Behaviors which involves Maneuvers, while the interactions of TrafficParticipants are formed and represented as Activities.

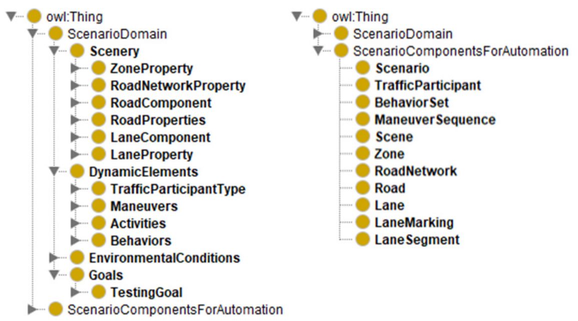


Figure 1: Concept hierarchy of the proposed ontology-based framework.

Besides, constraints are integrated in this ontology framework, to reduce non-plausible scenarios. For example, a pedestrian crossing road marking cannot exist on a highway, this mutual exclusion constraint between elements ensures semantic integrity. And other constraints improve the logical consistency and reduce modeling error, such as compatibility constraints, a speed limit of 110km/h is incompatible with a roundabout or a crossroad intersection. These restrictions ensure the validity of scenario modeling. The actual framework defined more than 200 constraints to improve the modeling quality for Scenario-based Testing.

The Maneuvers formalize driving actions, such as Accelerate, TurnRight (heading to right), Stop; and non-driving ones, like UseTurnIndicator, HonkHorn. The Activities module includes road user interactions, from the perspective of each road user.

An Activity is defined as a combination of maneuvers of multiple road users. A scenario contains one or multiple activities describing scenarios, for example, a vehicle CloseUp to another, then Overtake it.

The Behaviors enhance the dynamic description of both AD/ADAS-equipped vehicles and other road users within scenarios. Behaviors are associated with a series of maneuvers, for instance, the CarFollowing behavior involves a sequence of maneuvers Accelerate, Decelerate, ConstantSpeed, and Stop. This module incorporates the taxonomies from (NHTSA, 2018), which also include MaintainSpeed, LaneCentering, ObstacleAvoidance, among others. For example, MaintainSpeed refers to maintaining a safe speed set through longitudinal control with acceptable following distances.

Testing Goals in the Goals module, this module emphasizes the purpose of modeling traffic participants, specifically aligning with behaviors of AD/ADAS functions that should be achieved within a scenario. They are aligned with the behavioral competencies of AD/ADAS functions, using the taxonomies from (AVSC, 2021). A well-defined set of testing goals helps clearly identify the behaviors that need to be assessed in scenarios. For example, for an Adaptive Cruise Control (ACC) function, RespondingToOtherVehicles is a primary testing goal. To ensure safety, an ACC-equipped vehicle must demonstrate behaviors such as MaintainSpeed, CarFollowing, and ObstacleAvoidance within scenarios.

3.2 Spatial Segmentation and Layout

A surrounding location layout is proposed to describe objects' occupation and surrounding locations. The layout illustrates lanes as a grid-like pattern, where each cell corresponds to a specific area within the road network, defined by the lateral and longitudinal segmentation.

This layout divides a standard lane into three parts, as shown as Fig. 2: the Left Adjacent Area (L), the Central Area (C), and the Right Adjacent Area (R). The widths of L-C-R are proportional to the total lane width. For example, if a lane is 3.5 meters wide, the segments measure 1m-1.5m-1m.

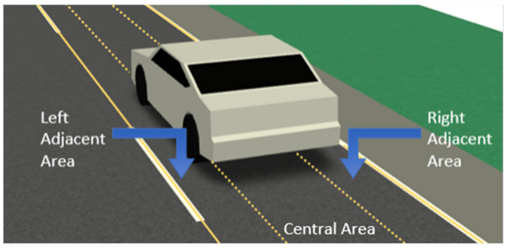


Figure 2: Illustration of the proposed lateral segmentation, screenshot of a scenario running on the esmini simulator.

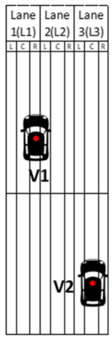
When the geometric center of a vehicle remains in the Central Area of a lane, it is driving in that lane. This proposed L-C-R lateral segmentation aims to describe between-lanes behaviors, such as a vehicle driving in the adjacent area of two neighboring lanes or a lane change. As shown in Fig. 3 (a), the V1 drives on the adjacent area between Lane 1 (L1) and L2, more precisely on the Right Adjacent Area of Lane 1 (L1-R).

The longitudinal length of each layout cell depends on the distance that the EGO vehicle drives per N seconds. For instance, when the EGO vehicle is driving 70 kilometers per hour, fixing N as 1 second, each cell would be 20 meters long. This segmentation improves the granularity of behavioral descriptions

This segmentation layout illustrates spatial surroundings, and cells are numbered following the same protocol in the standard ISO 34502 (ISO, 2022). As shown in Fig. 3 (b), a standard three-lane road is illustrated with respect to the proposed approach. The central cell represents an AD/ADAS-equipped EGO vehicle. Surrounding cells are numbered to indicate their relative positions, facilitating the description of spatial relations between the subject and other road users.

This segmentation approach facilitates describing the spatial occupation of road participants within a scene. The detailed lane segmentation layout is better suited for integration with behavioral concepts, compared to occupancy grids (Elfes, 1989), which are more aligned with concrete scenario presentations.

(a)



(b)

Lane 1			Lane 2			Lane 3		
L	C	R	L	C	R	L	C	R
72	61	57	53	49	51	55	59	63
73	42	33	29	25	27	31	35	64
74	43	20	13	9	11	15	36	65
75	44	21	6	1	3	16	37	66
76	45	22	7	EGO	4	17	38	67
77	46	23	8	2	5	18	39	68
78	47	24	14	10	12	19	40	69
79	48	34	30	26	28	32	41	70
80	62	58	54	50	52	56	60	71

Figure 3: (a) Illustration of two vehicles driving within the grid layout, with their geometric centers marked by red dots; (b) Numbered spatial layout of a standard three-lane road w.r.t. the grid numbering protocol of ISO 34502.

3.3 Temporal Sequence of the Spatial Layouts

The sequence of spatial occupation representations for traffic participants contributes to shaping a set of scenarios. Each sequence represents the spatial interaction of a vehicle from another vehicle's perspective and corresponds to an instance of traffic activity defined within the Activity module of the proposed ontology. Within a sequence, each spatial occupation offers a brief snapshot of the relative positioning and movement dynamics at a specific moment in the scenario, i.e., the Scene (Ulbrich et al., 2015). The following example illustrates the utility of the temporal sequence in conjunction with the segmentation layout.

As discussed in Section 3.1, ACC functions face considerable difficulty in scenarios modeled to evaluate their driving capability to RespondingToOtherVehicles. The behaviors involve maneuvers such as Accelerate, Decelerate, ConstantSpeed, and Stop. A common and challenging scenario is a cut-in, defined as an activity in the framework, where another vehicle merges in front of the ACC-equipped EGO vehicle.

The following Fig. 4 shows the sequence of layouts to describe this scenario. Initially, V1 drives parallel in the left lane of the EGO vehicle. V1 then initiates a lane change, and merges into the lane of the EGO vehicle. This sequence results from V1 performing the two combinations of Accelerate and TurnRight, transiting from Fig. 4 (a) to (b), and then to (c). This is followed by a single combination of ConstantSpeed and TurnRight, moving from Fig. 4 (c) to (d).

Following the numbering protocol shown in Fig. 3 (b), the trajectory of V1 during this cut-in activity follows the sequence of cases 45-21-13-9 in the grid.

This sequence is one of possible sequences that illustrate the cut-in activity. This representation of behavioral dynamics bridges abstract scenario descriptions with detailed scenario parameterization, further aligning with real-world collected trajectory data.

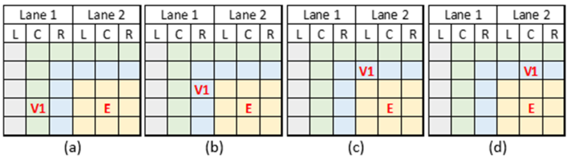


Figure 4: Sequence of grid layouts illustrating a vehicle (V1) performs a cut-in activity, where V1 changes lanes and merges into the same lane as the EGO vehicle (E).

Our ongoing work interests the needs of virtual validation for existing AD/ADAS functions. We are generating the occupation sequences to scale down the scenario space, before exploring the infinite situation-dependent concrete parameter generation. The generated sequences are transformed into filtering conditions, which are then applied to real world databases for extracting corresponding trajectories, such as the highD (Krajewski et al., 2018) dataset. These sequences serve as an intermediate layer, enabling the integration of behavioral concepts of the ontology framework with real-world data. By combining symbolic elements with time series data, the approach generates the necessary inputs needed to generate concrete scenarios in XOSC format (ASAM, 2019).

On the other hand, the AD/ADAS requirements are linked to behavioral descriptions through the logical chaining of concepts. In the ACC example, the Goal-Behavior-Maneuver chain narrows the scenario space for maneuvers of the EGO vehicle. And compatible interactions between EGO and non-EGO vehicles, defined as Activities in the ontology framework, are combined to complete the dynamic scenario description.

3.4 Potentials in Complex Scenario Modeling

The occupation sequences facilitate modelling dynamics with a more generalized manner. Unlike the current approach of defining trigger-action pairs in scenario generation, occupation sequences are more aligned with the real-world observation about driving behaviors.

Each sequence represents a driving activity, and the activity-based representations allow their concatenation to model complex scenarios. The cut-in activity, represented by the sequence of cases 45-21-13-9 in Fig. 4, can be superimposed onto a single layout representation, as shown in Fig. 5 (a). The spatial-temporal evolution of V1 is depicted in a single figure, with four red rectangles marking its location and three arrows representing its maneuvers in the scenario.

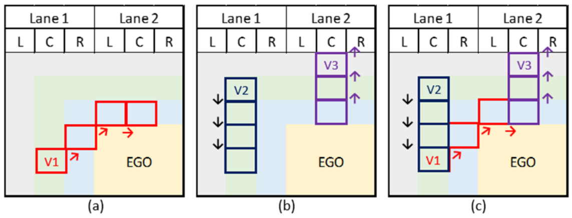


Figure 5: Illustration of overlaps of occupation layouts: (a) V1 vehicle's cut-in activity; (b) V2 vehicle's close-up activity and V3 vehicle's move-away activity; (c) the fusion of (a) and (b).

Combining activities can generate complex scenarios. A vehicle V1 performs a cut-in activity due to a slower leading vehicle V2 in Lane 1. This cut-in activity is compatible with the V2's close-up sequence. Similarly, these activities can be combined with vehicle V3's move-away activity, as shown in Fig. 5 (b). These three activities are logically compatible, and their fusion allows the creation of a complex scenario, illustrated in Fig. 5 (c).

Additionally, concatenating sequences also can produce complex scenarios. For instance, the vehicle V1 may execute a cut-in and then move away, increasing its distance from the EGO vehicle. In this case, the sequences of V1 and V3 could be concatenated to define a more complex scenario.

4 PRELIMINARY ONTOLOGY EVALUATION

A comparative approach is conducted to evaluate the enhanced ontology framework with other existing ones. Two scientific and industrial ontologies were compared: the Automotive Urban Traffic Ontology (A.U.T.O.) (Westhofen et al., 2022) and the ASAM OpenXOntology (ASAM, 2022). Both ontologies are accessible from Github and the ASAM website.

The A.U.T.O. ontology, a nested ontology which implements the 6-layer model (Scholtes et al., 2021), offers a series of ontology blocks to modularize distinct domain elements. Inter-module connections are established through the foundational ontologies, such as GeoSPARQL for geometry and W3C standards for temporal aspects.

The ASAM OpenXOntology, within the ASAM OpenX ecosystem, serves as a semantic foundation for knowledge representation in the AD/ADAS domain. It provides a comprehensive structure and terminology and is compatible with Scenario-based Testing tools. In contrast to A.U.T.O., this industrial ontology proposes an upper-level Core block to interconnect elements in different modules.

4.1 Initial Comparison

Three ontology frameworks, as illustrated in Fig. 6, share a similar structure of concept organization. Consequently, this structural review is insufficient for comparison. It resembles the checklist-based approach in (Zipfl et al., 2023), which limits the comparison to the categorical or modular level.

A.U.T.O.	OpenXOntology	Proposed Ontology
L1 Road Network and Traffic Guidance Objects	Road Topology and Traffic Infrastructure	Scenery
L2 Roadside Structures		
L3 Temporary Manipulation of L1 and L2		
L4 Dynamic Objects	Traffic Participant and Behavior	Dynamic Elements
L5 Environment Conditions	Environmental Condition	Environmental conditions
L6 Digital Information		
X	X	Goals

Figure 6: Comparison on the structure of ontologies.

4.2 Quantitative Comparison

A statistical analysis of the proposed ontology was conducted, along with the two ontologies. Following an exploratory analysis, the three ontologies are converted to graph-based representations to analyze their concept hierarchy and structural organization. Directed acyclic graphs were built to illustrate and analyze the overlapping elements among ontologies. This analysis used an automatic knowledge extraction tool that we developed with the RDFLib library in Python.

Four metrics are proposed and applied in these ontologies: the Connectivity Index, the Property Utility Ratio, the Redundancy Ratio, and the Branch Balance.

Connectivity Index (CI) measures the density of relationships and constraints per concept, calculated as the total number of relationships and restrictions divided by the number of concepts. A higher CI indicates stronger interconnections among concepts.

The Property Utility Ratio (PUR) assesses expressiveness by dividing the total number of relationships and constraints by the sum of object and data properties. A higher PUR implies a more densely expressed ontology.

The Redundancy Ratio (RR) measures the proportion of concepts having multiple parent concepts within the directed acyclic graph. It helps to identify the degree of overlap and assess unnecessary structural complexity. The RR is calculated as 1 minus the proportion of unique concepts relative to the total number of nodes in the ontology.

The Branch Balance (BB) reflects the distribution of nodes in different branches. It is calculated with the average entropy of all nodes in the graph, using the proportion of each node's subtree size relative to the total number of nodes. A higher BB score indicates a balanced structure, which enhances parsing and searching within the ontology, facilitating its automatic processing in applications. This metric may identify imbalances within the ontology, where branches are insufficiently developed or excessively complex.

Table 1 presents the statistical analysis of the ontology elements, the graph-based representations, and the evaluation of key metrics.

Table 1: Statistics and graph-based analysis.

		A.U.T.O.	OpenXOntology	Proposed Ontology
Statistics	Nb. Concepts	284	346	240
	Nb. Object Properties	118	96	37
	Nb. Data Properties	70	2	1
	Nb. Individuals	110	348	286
	Nb. Relationships	2682	3030	2283
	Nb. Restrictions	43	24	256
	Connectivity Index	9.59	8.83	10.58
	Property Utility Ratio	14.49	31.16	66.82
Graph-based	Nb. Nodes	595	2272	240
	Nb. Edges	582	2270	232
	Nb. Leaf Nodes	370	1645	191
	Nb. Levels of Nodes	11	13	7
	Redundancy Ratio	52.3%	84.8%	0%
	Branch Balance	0.86	1.46	1.76

The A.U.T.O. integrates more object and data properties compared to the others. However, the interconnections between concepts are limited, as indicated by the CI and PUR metrics.

OpenXOntology, while containing an impressive number of nodes in its directed acyclic graph, suffers from a high degree of concept overlap, as shown by the RR metric, which reduces its practicality for applications.

The proposed ontology framework introduces fewer concepts and properties, but integrates a substantial number of relations and restrictions, particularly reflected in the CI and PUR metrics. Its acyclic graph representation shows simplified and well-balanced branches, as highlighted by the RR and BB metrics, makes it suited for further applications, such as automated scenario generation.

4.3 Conceptual Consistency

Concerning the absence of a baseline for scenario modeling ontology, a preliminary approach was employed to validate the ontology concepts against international standards. The ISO 34504:2024 standard (ISO, 2024), an internationally recognized normative document for scenario annotation and categorization, offers a comprehensive set of concepts for scenario modeling.

Using ChatGPT[1], the terminology and taxonomy of the ISO 34504 were extracted. This process generated a taxonomy with 495 distinct concepts, which was then verified by two human reviewers.

Next, each of these 495 concepts and the concepts in the three ontologies were transformed into a 3072-dimensional word vector using ChatGPT's pre-trained text-embedding-3-large model. This transformation enabled us to capture the semantic nuances and contextual relationships inherent in the concepts. Cosine similarity between concepts was calculated. This similarity metric provided a quantitative measure of the alignment between the standard and the ontology, offering insights into their conceptual consistency.

Table 2 presents the aligned concepts between each ontology and the ISO standard.

Table 2: Aligned concepts between ontologies and ISO 34504 standard (the threshold Cosine similarity > 0.85).

	A.U.T.O.	OpenXOntology	Proposed Ontology
Nb. Concepts aligned with ISO 34504:2024	10	51	39

[1] https://chatgpt.com/share/66ea2eb1-46e4-800b-9653-744e1a321ed8

4.4 Discussion

Ontology evaluation poses significant challenges for real-world applications, particularly in complex domains such as AD/ADAS validation. In this work, we have explored and addressed the quantitative aspects of ontology evaluation, with a focus on structural and terminological aspects. These evaluations highlight the importance of building an ontology that is concise enough for effective scenario modeling while still being comprehensive enough to capture a wide range of scenarios.

A key challenge remains in evaluating semantic relations. The quantity and quality of relationships and restrictions directly impacts the realism and plausibility of scenarios. Poorly modeled relations can lead to oversimplified or non-plausible scenarios, which reduces the reliability of Scenario-based Testing for AD/ADAS validation. Our ongoing work focuses on evaluating the semantic relations between concepts and their relationships across different ontologies, using word embedding models. We aim to capture the nuanced similarities and differences in how knowledge is represented and interconnected for scenario modeling.

This evaluation work did not systematically investigate the well-known modeling issues in semantic relations, such as those identified by (Poveda-Villalón et al., 2014). However, during an initial investigation, a few modeling errors were identified when comparing ontologies. For example, in the A.U.T.O. ontology, there is a relation "Cloud is_part_of exactly 1 Sky," representing a subset composition between Cloud and Sky concepts. While a constraint "Cloud disjoint_with Moon, Sun, Air, Ground, Air_Particle, Sky, Wind" declares a disjoint relation between Cloud and Sky. Here, a subset relation cannot be compatible with a disjoint constraint.

5 CONCLUSION

This paper identifies critical gaps in existing ontology-based scenario modeling frameworks that limit the effectiveness of modeling scenarios for validating AD/ADAS functions. These challenges include the issues with ontology coverage and the plausibility of modeled scenarios, the limitations in expressing dynamic scenarios, and the capacity to model complex scenarios that are aligned with the operating conditions and requirements of AD/ADAS validation.

To address these gaps, this paper makes several contributions. Firstly, the behavioral descriptions of dynamic objects within scenarios are refined. This refinement allows a more nuanced representation of dynamic objects' actions and interactions. Second, the ontology framework develops relations and constraints associated with the Goals, Behaviors, Maneuvers, and Activities are developed in this ontology framework. These relationships and restrictions are particularly useful in determining the relevance of scenarios for AD/ADAS validation. Third, lane segmentation and grid layout are introduced to enhance the modeling capability of real-world traffic environments. Fourth, activity-based combinations for scenario modeling have been introduced. By combining the activities of dynamic objects, the proposed model allows for a detailed description of the spatial-temporal changes in a scenario. Moreover, multiple activities can be combined in sequence, enabling the concatenation of scenarios. These contributions enhance the quality of the ontology framework for valid, detailed, and complex scenario modeling. This work lays a foundation for more effective scenario generation for AD/ADAS validation.

This paper also contributes to quantitative evaluation of ontologies, offering a systematic approach to assess the structural and terminological aspects. This evaluation highlights key strengths and areas for improvement, supporting the development of more robust and practical ontology-based scenario modeling framework for AD/ADAS validation.

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