
Ontology-Based Representation of Urban Mobility

Autonomous, Connected and On-Demand Shuttles

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RÉSUMÉ.

Dans le domaine des systèmes de transport à la demande, il devient essentiel de gérer les itinéraires de manière dynamique, optimisée et adaptative. Cet article propose une modélisation ontologique formelle, combinant deux modèles et visant à structurer et exploiter les informations relatives au transport autonome à la demande. Le premier modèle représente divers éléments d'infrastructure, tels que les rues, les quartiers et les zones urbaines, formant une carte numérique qui décrit le monde physique et facilite l'intégration transparente de sources de données hétérogènes, tout en assurant une gestion efficace des informations spatiales. Le second modèle inclut des éléments liés au transport public, basé sur le standard GTFS, et fournit un cadre sémantique pour décrire les relations entre les entités géographiques et leur interaction avec les réseaux de transport. L'ontologie globale proposée a été enrichie par l'intégration des concepts représentant la demande des utilisateurs. Ce travail constitue une base pour développer des systèmes autonomes et une étape cruciale vers un routage dynamique optimisé et adaptatif.

MOTS-CLÉS : Modèle de données, représentation multi-échelle, infrastructure urbaine, AMoD, informations géospatiales

KEYWORDS: Ontology-based data model, multi-scale representation, urban infrastructure, AMoD, geospatial information

1. Introduction & Related Works

In the context of disruptive developments in automated driving systems, autonomous mobility on demand (AMoD) will play a crucial role in the public transport system. It offers adaptive solutions to meet user needs. Dynamic routing is one of the key technologies for optimizing routes while enabling autonomous shuttles to quickly adapt to unexpected events, traffic conditions, and user demands. For such routing to be effective, it is essential to rely on data models that can handle the complexity of urban infrastructures in a scalable and interoperable manner. However, traditional data models are often static and lack semantics. Faced with this limitation, researchers are increasingly exploring ontology-based approaches, which can handle the semantic aspect. For example, (Nandini, Shahi, 2019) developed an ontology for transportation systems, focused on travelers' needs and capable of answering general questions such as the closest bus stop to a given location. This ontology aims to help travelers plan their journeys. (Mnasser *et al.*, 2010) proposed an ontology to represent the knowledge required for trip planning, integrating user preferences. This approach uses the Jess engine to perform inferences and provide itineraries tailored to the defined constraints. (Li *et al.*, 2024) introduced the concept of Digital Twin, using ontology to represent physical infrastructures and their dynamic relationships. The proposed paradigm aims to overcome challenges in managing complex infrastructures and improve decision making in multi-scale environments. (Tkachenko, Tkachenko, 2023) proposed an ontology focused on railway infrastructures, relying on standards such as BIM (Building Information Modeling) and EULYNX (European railway technology alliance). Their approach aims to digitize and intellectualize processes related to the design, construction, and maintenance of transportation infrastructures.

Although innovative, previous studies present certain limitations. Some models focus on digitizing physical infrastructure without accounting for dynamic interactions or specific user needs. Others, centered on the traveler's perspective, are limited to simple queries and do not model urban infrastructure or on-demand transport. Lastly, some works remain focused on traditional public transport. Our model stands out by integrating a digital map of the physical world with GTFS specifications to represent the public transport system, while enriching the ontology with concepts related to user demand for on-demand transport. This unified approach is essential for efficient, interoperable management of urban mobility systems.

2. Methodology

To build our global ontology, we created two distinct models. First, we developed an urban infrastructure model that represents infrastructure at three

levels of granularity: micro, meso, and macro. We reused the GeoSPARQL ¹ ontology, which provides a standardized vocabulary for representing spatial information and geometric relationships. Next, we built a model based on GTFS ², a standard data format that provides public transport information. Finally, these models were merged to form a generic ontology (Figure 1) dedicated to on-demand transport, enabling the representation of all the concepts needed to manage users’ requests and their trips.

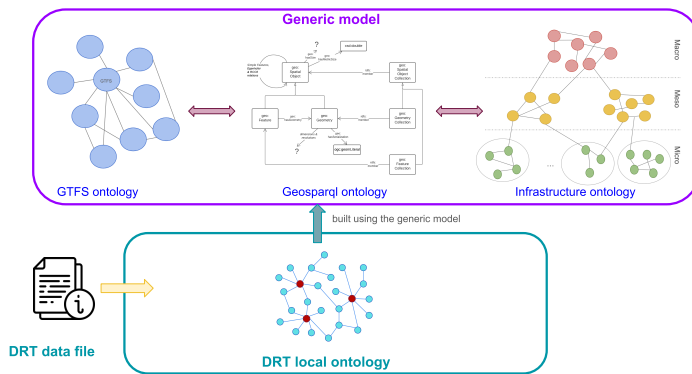


FIGURE 1 – Methodology

2.1. Graph Formalization

Our infrastructure model is organized into three levels of granularity: micro, meso, and macro as shown in (Figure 2). At the micro level, we model the finest elements of the road network, such as streets, road segments, traffic control devices, and road markings, etc., which are essential for the precise navigation of autonomous shuttles. To move on to the meso level, we consider that a concept representing a neighborhood groups together a set of streets. These neighborhoods are also connected to complementary concepts, such as points of interest and public spaces, etc. Finally, to move from the meso level to the macro level, which covers larger geographical areas, we consider that a municipality groups together several neighborhoods. All these infrastructures are essential for an autonomous shuttle to travel safely on the road. To form our multiscale infrastructure graph at three levels: *micro*, *meso*, and *macro*, we have been inspired by the approach proposed in (Oberoi *et al.*, 2017). The concepts from *Infrastructure ontology* are represented by the set of nodes:

$$X = X_{micro} \cup X_{meso} \cup X_{macro} = S \cup V \cup B \cup RM \cup O \cup R \cup I \cup N \cup M$$

1. URL: <https://www.ogc.org/standard/geosparql/fr/>, accessed October 2024

2. General Transit Feed Specification, URL: <https://gtfs.org/>, accessed September 2024

where: S : set of **streets**, V : set of **vehicles**, B : set of **buildings**, RM : set of **road markings**, O : set of **obstacles**, R : set of **road segments**, I : set of **intersections**, N : set of **neighborhood**, M : set of **municipalities**

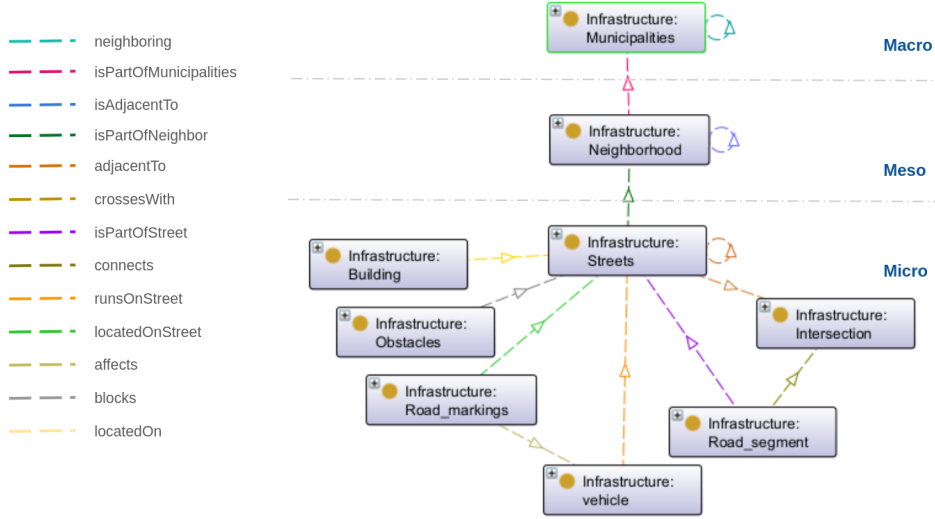


FIGURE 2 – multi-scale infrastructure root concepts

The *micro graph* $G_{micro} = (X_{micro}, E_{micro})$ describes the topological and functional relationships between various objects within a street. The set of edges E is defined as: $E = \{(x, y) \mid x\rho y\}, \rho \in \{TR, FR\}$ where $\{TR, FR\}$ represents the set of relation types in this graph: **TR : Topological relations**, **FR : Functional relations**. At the *meso level*, multiple streets are grouped to form a neighborhood. The meso graph $G_{meso} = (X_{meso}, E_{meso})$ captures relationships between streets and other objects within a neighborhood. At the *macro level*, neighborhoods are connected to form municipalities. The macro graph $G_{macro} = (X_{macro}, E_{macro})$ represents relationships between neighborhoods within municipalities. These relationships are summarized in table 1.

We have also built a GTFS model, which maps all concepts related to public transport systems, including trips, routes, stops, schedules, and other components. ensuring consistency and interoperability with geographic information systems (GIS) and mobility applications, guaranteeing their interactions with urban infrastructures and other transport systems, including on-demand transport.

Finally, we merged these models to build a global ontology dedicated to autonomous on-demand mobility. This model offers an integrated vision of on-demand mobility, proposing flexible solutions that combine elements of urban infrastructure and the public transport system, while ensuring effective interaction between them. The ontology was further enriched by the integration of

concepts and relationships related to user demand, enabling optimized management of passenger reservations and enhancing the overall efficiency of the system. In addition, we used La Rochelle’s on-demand transport data to verify our ontology’s ability to represent various transportation data sources. This step constituted an initial evaluation of our model.

TABLEAU 1 – Main concepts and object properties

Concept	Object Property	Related Concept
Macro:Municipalities	neighboring {TR} (SubPropertyOf : geo:sfTouches)	Macro:Municipalities
Meso:Neighborhood	isPartOfMunicipalities {TR} (SubPropertyOf : geo:sfTouches)	Macro:Municipalities
Meso:Neighborhood	isAdjacentTo {TR} (SubPropertyOf : geo:sfTouches)	Meso:Neighborhood
Micro:Streets	isPartOfNeighbor {TR} (SubPropertyOf : geo:sfWithin)	Meso:Neighborhood
Micro:Streets	isadjacentTo {TR} (SubPropertyOf : geo:sfTouches)	Micro:Streets
Micro:Streets	crossesWith {TR,FR} (SubPropertyOf : geo:sfCrosses)	Micro:Intersection
Micro:Road_segment	isPartOfStreet {TR} (SubPropertyOf : geo:sfWithin)	Micro:Streets
Micro:vehicle	runsOnStreet {FR}	Micro:Streets
Micro:Road_markings	locatedOnStreet {TR} (SubPropertyOf : geo:sfWithin)	Micro:Streets
Micro:Road_markings	affects {FR}	Micro:vehicle
Micro:Obstacles	blocks {FR}	Micro:Streets
Micro:Building	locatedOn {TR} (SubPropertyOf : geo:sfWithin)	Micro:Streets

3. Conclusion

In this paper, we presented an ontology-based data model for autonomous on-demand mobility in urban areas. By integrating urban infrastructure and public transport concepts, our model offers a flexible and adaptable solution to meet user needs. We tested it with La Rochelle transport data, showing its ability to work with different data sources and urban contexts. For future work, we will align our ontology with the Transmodel standard³ to reuse relevant concepts for autonomous on-demand shuttle systems and ensure interoperability within global transportation systems. Additionally, we plan to further validate our model and integrate a temporal ontology to manage dynamic transportation events. Finally, we aim to develop rules for autonomous shuttles to better represent their interactions with infrastructure and users, thus improving dynamic routing optimization.

3. <https://transmodel-cen.eu/>

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