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An information model for highway operational risk management based on the IFC-Brick schema

Bencheng Zhu [a], Fujin Hou [b], Tao Feng [c,d], Tao Li [b], Cancan Song [e,*]

[a] The Key Laboratory of Road and Traffic Engineering of the Ministry of Education, Tongji University, Shanghai 201804, China
[b] Shandong Hi-Speed Construction Management Group Co., Ltd., Jinan 250014, Shandong, China
[c] Urban and Data Science Lab, Graduate School of Advanced Science and Engineering, Hiroshima University, 7390046 Higashi-Hiroshima, Japan
[d] Department of the Built Environment, Eindhoven University of Technology, Eindhoven 5600 MB, the Netherlands
[e] School of Civil Engineering, Shanghai Normal University, No.100, Haisi Road, Shanghai 201418, China

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ABSTRACT

With the development of highways, new technologies should be continuously introduced to improve highway traffic safety. Digital twin (DT) has been an emerging field of research in recent years. To develop a digital twin management system, a data model is essential. In the field of highway operational risk management (HORM), however, the development of data models is still in its infancy. Motivated by the concept of linked data, in this paper, we attempt to propose an information model for HORM. The main achievements of this paper include data architecture, identification and classification code methods, data interaction method, and the developed system. Based on data needs analysis, the highway information model architecture for risk management is defined as five layers: basic highway products, traffic sensors and equipment, traffic rules, traffic flow, and weather. Furthermore, according to the concepts of semantic data, these five layers can be classified into three categories: highway product data, topology data, and sensor data. Although the Industry Foundation Classes (IFC) standard and Brick schema were first proposed and applied in the building domain, some of their entities and relationships can also be applied to highways. To this end, we defined some new classes, a specific ontology, and an integrated framework for HORM. Finally, a case study was carried out. Applying such information model to highways has broad potential. It changes the file-based exchange method to the data-based one, which can promote highway data exchange and applications. The proposed information model could be of great significance for HORM.

1. Introduction

There are still many people injured and killed in traffic accidents nowadays, which is a long way from the "Vision Zero" (Kristianssen et al., 2018). For the highway traffic safety, operational risk management plays a very important role. It's better to identify and control these risks in advance to prevent traffic accidents. With the development of highways, new technologies should be continuously introduced to implement highway operational risk management. In this way, the "Vision Zero"

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* Corresponding author at: Cancan Song, 201804 Shanghai, China.
E-mail address: songcancan@tongji.edu.cn (C. Song).

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will no longer be far away. Digital twin as an emerging research field brings at least two main interesting possibilities: one is capturing in-use information to feed back into the creation phase and the other is the idea of "front-running" simulation in real-time (Grieves and Vickers, 2017). Digital twin technology has been used in multidisciplinary research, e.g., product design (Tao et al., 2019), healthcare (Elayan et al., 2021), energy management (Francisco et al., 2020), buildings (Khajavi et al., 2019). Based on the concept of DT, research and applications have been also carried out in the field of highways. For instance, a method based on DT and multiple time series stacking were proposed to predict the performance of highway pavement (Yu et al., 2020). However, the data used was a historical dataset rather than real-time data. In addition, DT was also used to evaluate the condition and performance of highway bridges (Ye et al., 2020) and tunnels (Yin et al., 2020). Compared to the work of performance evaluation, applications become increasingly prevalent in recent years in planning and construction stages, such as urban road planning (Jiang et al., 2022), highway construction process schedule, and cost management (Bradley et al., 2016).

Overall, in the field of highways, DT is still in its infancy. Existing research and applications are mainly concentrated on the stages of highway design, construction, and maintenance, but less on the operation stage. Therefore, investigating the application of DT in highway operational risk management (hereinafter referred to as HORM) is needed. Furthermore, the data model is the premise and key part of any management system (McHugh et al., 1997). For HORM, it still lacks a data model, especially considering the fact that data models in other domains are not directly applicable to the highway. Wang et al. (2021) recently created an intelligent transportation system based on road-side sensors and a 3D model using an animation software, Blender. However, the data format used in the software is not generic. The most popular software actually used in highway design, construction and maintenance is BIM software, such Revit, Civil 3D, InfraWorks, and so on. To solve the problem of difference in data format between different software, the IFC standard has been adopted internationally (Lichun et al., 2015). Regarding the highway model in HORM stage, the IFC standard is superior in terms of its portability and scope of use. Meanwhile, the consistency in model format also benefits other stages in design, construction, and maintenance. However, considering that the IFC format stores only 3D static highway data, it remains an issue of how to combine it with the dynamic highway data. In this regard, the method for linking static and dynamic data applied and validated in BIM (Mavrokapnidis et al., 2021) may provide some inferences and additional insight.

Based on the above analysis, it is of great practical significance to establish a data model that connects the static highway model in IFC format and the dynamic data in the HORM stage. Firstly, this can promote the widely use of highway models in IFC format constructed in the design and construction stages. Thereby the modeling workload of static highway products in the operational risk management stage can be reduced. Secondly, based on the static and dynamic data interaction framework and method proposed in this study, an intelligent management system for highway traffic operational risk can be further constructed. This will not only facilitate the digital application in the entire life cycle of highways but also improve the highway operational safety and efficiency further.

This study aims to propose an information model for the HORM stage. The second part of this paper will analyze the device and data demand for HORM. Then the data architecture of highway regions will be identified. The lane-level management unit and coding method will be further proposed. As for the third part, based on existing standard IFC and Brick ontology, some new classes and attribute sets will be defined firstly. Then the integration implementation method of highway static and dynamic data will be proposed. The fourth part is a case study. To verify the validity of the proposed data model, a real highway information model will be constructed based on the actual design data. A HORM system will be developed. Then the interaction connection between static and dynamic data will be tested by writing query code. In the fifth part, the paper will be concluded with the elaboration of future works.

2. Data demand analysis

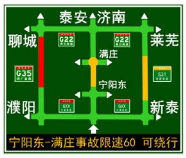
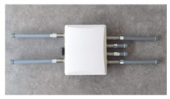
2.1. Sensors and equipment on highways

Besides the basic highway infrastructure, another necessary component is various sensors and equipment on highways. Many years of construction experience and specifications have resulted in relatively fixed elements of the basic highway infrastructure. However, sensors and equipment used on highways are constantly evolving nowadays. Therefore, it is significant to further sort out the sensors and equipment involved in the HORM stage. Based on extensive field investigation, it is concluded that the sensors and equipment on highways are mainly divided into the following four categories, as shown in Table 1.

2.2. The proposed highway region data architecture

As pointed out that a BIM model or digital twin is not meant to be complete, it is meant to hold the information and data that is needed for particular uses (Costin and Pauwels, 2022). In the HORM stage, there are many application possibilities for digital twins. A possible case is when a traffic incident occurs, its precise location can be quickly known for rescue. In addition, when severe weather or traffic congestion occurs, traffic simulations can be performed to determine the control measures such as dynamic speed limits and diversion.

Table 1
The main sensors and equipment on highways for operational risk management.

Number	Type of sensors and equipment	Main function	Example photos
1	Traffic operational data collection sensors: LiDAR, vision camera, etc.	Collecting traffic operational data such as speed, density, traffic volume, and headway	 
2	Meteorological data collection sensors: rain, fog, ice, snow and wind monitor, etc.	Collecting meteorological environment data and highway pavement surface condition parameters	 
3	Management information dissemination equipment: variable message signs, dynamic speed limit signs, etc.	Publishing the management and control measures and the service information to highway users	 
4	Data transmission equipment: roadside units (RSU), roadside computer, etc.	Transferring data between various devices in the highway system	 

According to the definition of systems engineering (Yu and Xiong, 2006), when the system is in a static state that has not been running or has stopped running, the physical combination that constitutes the system is the system's physical structure. This paper proposes that the physical structure of highways includes two layers: the basic highway layer and the traffic sensors and equipment layer. The physical structure can also be considered as the highway product data, which is static data. The third layer is the traffic rules layer, including the connectivity of the highway segments, lane changing parameters, speed limit value, and other traffic rules parameters. This layer can be considered as the topology data. As for the dynamic data, both traffic flow and weather need to be taken into account. The dynamic data of the two layers are collected and released by highway sensors and equipment. In summary, the above five layers of data can be classified into three categories: highway product data, topology data, and sensor data.

Based on the analysis of sensors and equipment on highways, as well as the comprehensive demand of HORM specifically, a five-layers data architecture of highway region information for HORM is proposed, as shown in Fig. 1.

2.3. Lane-level management unit

Through extensive investigation of the development status of worldwide highways, it is concluded that the modern highway presents some new features such as bigger density, more lanes, faster driving speed, and larger traffic volume (Lv et al., 2021). It also has advanced software and hardware for data collection, transmission, calculation, and release. As analyzed in the first part, it is necessary to break through the previous information expression, monitoring, and management methods for the risk management of highway operation. In other words, lane-level management, precise control, and early blocking of the traffic operational risk are expected to achieve by combining modern information technology. Therefore, from the perspective of risk management, it is essential to distinguish lanes with different functions and nodes that can split traffic flow on the highway to "block" the traffic operational risk. As a result, the lane-level operational risk management unit is defined as the carrier component for information exchange in this paper. For the management unit codes, which are significant to develop a system, there should be both identification code and classification code. The identification code is unique and do not duplicate. While the classification code represents the type of the object and may be duplicated (Liu and Wu, 2021a).

2.3.1. The identification code of lane-level management unit

Considering the order in which the operational risk management measures take effect and the arrival of vehicles, to "block" the oncoming traffic of a certain road section, it should be at a node before this road section to divert the upstream oncoming traffic or take other management measures. That is to say, the diversion of a node or other control strategies is for the oncoming traffic of the upstream adjacent road section. Therefore, this paper regards the "node and a neighboring road segment upstream" as a segment management unit, represented by a code of the specific highway node. Based on the standard "Cataloguing and coding rules for the highway database" (Liu et al., 2014), this paper further considers the upward and downward directions (1 represents the upward direction, 2 represents the downward direction). Then interchange (I), toll

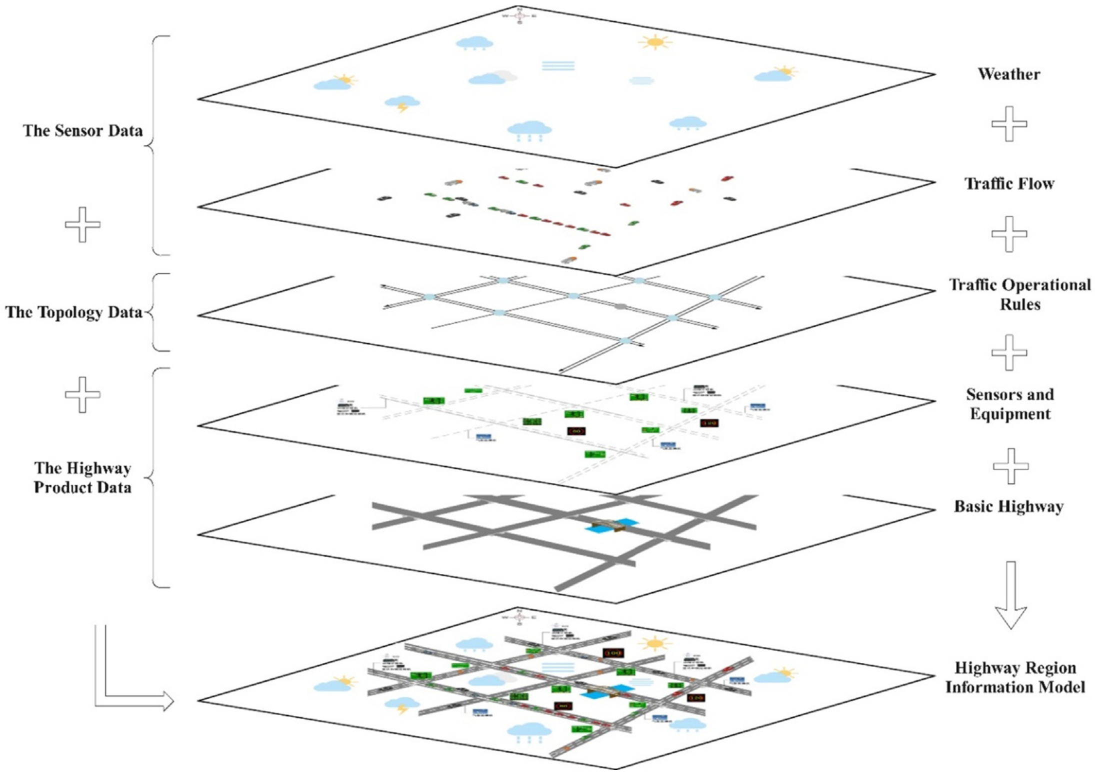


Fig. 1. The proposed highway region data architecture.

station (TS), service area (S), median opening (M), bridge (B) and tunnel (T) are determined as the six types of highway nodes. The identification code structure of highway nodes is defined as Fig. 2.

For the lane-level management unit, this paper proposes a method based on the code of highway nodes. The lanes in each direction are numbered from inside to outside as 1, 2, 3, 4, 5, et al., as shown in Fig. 3. Furtherly, a lane-level management unit can be represented in the form of "the highway node code adding the lane number". For instance, the identification code of the first lane on the inner side of upward direction in Fig. 3 can be expressed as " G3 370881T001 1 1″.

2.3.2. The classification code of lane-level management unit

For the classification code of lane-level management unit, there are no definitive rules yet. The ISO Standard "Building construction-organization of information about construction works Part 2: framework for classification (ISO 12006-2:2015)" determined information as results, processes, resources and attributes. From this perspective, the lane category information belongs to attributes. In addition, the table code of characteristic attributes in the Chinese Standard (Liu and Wu, 2021b) is 46. Therefore, this paper adopted the hierarchical code mode of "46-XX.XX.XX.XX" in the existing standards. The characteristic attribute classification table was extended by the self-defined classification codes of eight categories of lane. They could also be extended with the need of new unit types later, as shown in Table 2.

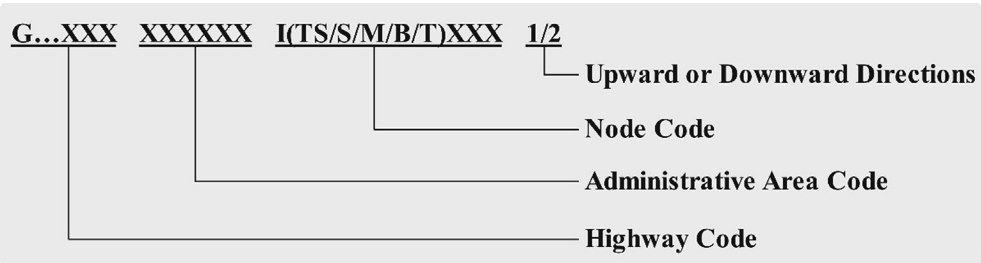


Fig. 2. The proposed identification coding method for highway node.

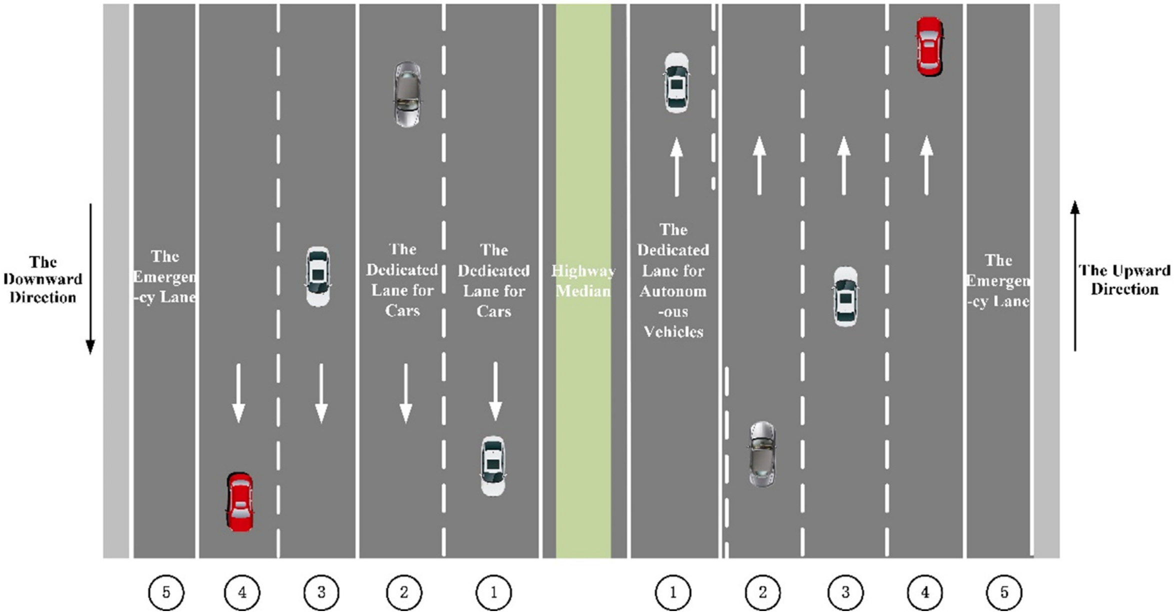


Fig. 3. The proposed coding method of lane divided and identification (highway segment).

Table 2
The proposed coding method of lane classification.

Serial No.	Lane type	Classification code
1	The conventional lane	46-08.07.01.00
2	The emergency lane	46-08.07.02.00
3	The entry ramp	46-08.07.03.00
4	The exit ramp	46-08.07.04.00
5	The dedicated lane for autonomous vehicles	46-08.07.05.00
6	The dedicated lane for cars	46-08.07.06.00
7	The dedicated lane for passenger vehicles	46-08.07.07.00
8	The dedicated lane for trucks	46-08.07.08.00

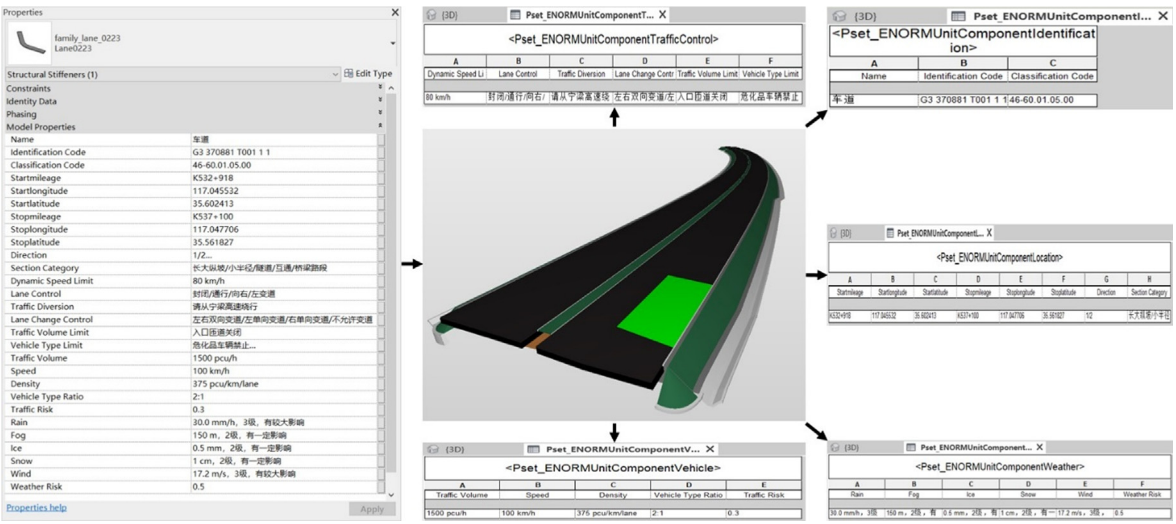


Fig. 4. Highway information model based on IFC.

3. Data storage and integration methods

3.1. Highway components based on the IFC standard

Industry Foundation Classes (IFC) is a standardized, digital description of the built environment, including buildings and civil infrastructure. It is an open, the most widely used, international standard (ISO 16739-1:2018). Although the IFC standard defines a limited number of entity types, it can be extended to other domain entities and attributes as needed. Considering the urgent needs of highway information integration in the current HORM stage, this paper adopts the combination method of instantiating general entities and extending attribute sets to express the highway physical and attribute information based on the existing IFC standard. These highway components are generated by instantiating the existing general entity, IfcBuildingElementProxy, while adding some sets of self-defined attributes. The PredefinedType attributes for these extended entities are set as USERDEFINED. The self-defined attributes information include Pset_ENORMUnitComponentIdentification, Pset_ENORMUnitComponentLocation, Pset_ENORMUnitComponentTrafficControl, Pset_ENORMUnitComponentVehicle, and Pset_ENORMUnitComponentWeather. Fig. 4 shows the highway information model based on IFC.

IFC is very powerful in representing geometric data, element classification and product property data. However, it is insufficient in the representation of dynamic data, such as real-time data streams, time series data and geographic information system data (Pauwels et al., 2022). In other words, the IFC format file stores the highway static product data mentioned in Fig. 1.

As for the highway operational dynamic data collected by road-side LiDAR, visual-camera, weather sensors and other equipment, they are more appropriate to be stored in a relational database, such as MySQL, SQL Server, etc.

3.2. Highway ontology based on the brick schema

As indicated by Pauwels et al. (2017a, 2017b), linking different data resources through semantic web technology has been accepted by more and more researchers. This transforms the previous file-based information exchange method into the data-based one, which can facilitate highway data integration and application. In computer engineering, an ontology is an explicit specification that refers to the objects, concepts, and other entities that are presumed to exist in some area of interest and the relationships that hold among them (Gruber, 1993). In order to combine the dynamic and static highway data, a highway ontology is required. The Resource Description Framework (RDF) is a widely used semantic web standard in the world. RDFS (RDF Schema) and OWL (Web Ontology Language) are two kinds of lightweight ontologies used to help users build application domain related ontologies. Brick ontology is developed and applied in building operation management (Balaji et al., 2018). Meanwhile, the IFC standard has also been converted to the semantic ontology ifcOWL format, which has been updated to the IFC4.1 version. These existing and successfully applied ontologies provide strong support for building highway ontology.

According to the introduction on its official website, Brick is an open-source effort to standardize semantic descriptions of the physical, logical and virtual assets in buildings and the relationships between them. The typical Brick ontology and its relationships are shown in Fig. 5.

The existing Brick ontology alone cannot meet the needs of HORM. Some new classes for highways need to be defined. Therefore, the new class “brick: Highway” is defined as one subclass of the existing class “brick: Location” by RDF predicate “rdfs: subClassOf”. In the same way, the new classes “brick: Segment” and “brick: Lane” are defined as subclasses of the existing class “brick: Storey”. Finally, these classes and relationships available for highway modeling are shown in

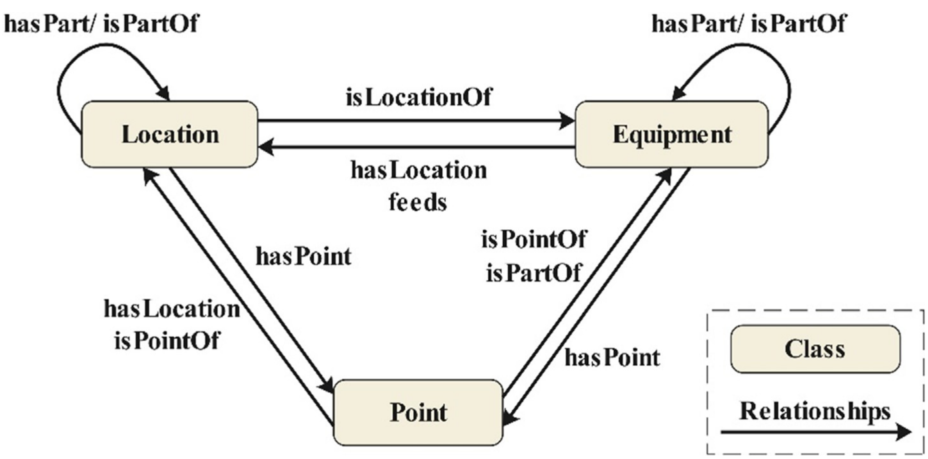


Fig. 5. The typical Brick ontology and their relationship (image according to Balaji, 2018).

Tables 3 and 4. Based on the above self-defined classes and the existing Brick, together with ifcOWL and OWL ontology, these ontologies are combined to form an available highway ontology that can be used for HORM.

3.3. The data integration method and implement steps

Based on the above IFC-Brick schema and consistent with Fig. 1, this paper proposes an integration method for highway static and dynamic data in the HORM stage, as shown in Fig. 6.

Table 3
The self-defined and existing classes available for highway modeling.

Category	Highway Elements	Brick Classes	Remarks
Static data	Highway	brick: Highway	Self-defined
	Segment	brick: Segment	Self-defined
	Lane	brick: Lane	Self-defined
Sensors and equipment data	Traffic sensors	brick: Occupancy_Sensor, brick: Speed_Sensor, brick: Position_Sensor, brick: Camera, etc.	Quoted from Brick
	Meteorological environment sensor	brick: Humidity_Sensor, brick: Fire_Sensor, brick: Luminance_Sensor, brick: Rain_Sensor, brick: Temperature_Sensor, brick: Weather_Station, etc.	Quoted from Brick
	Information release equipment	brick: Safety_Equipment, brick: Security_Equipment	Quoted from Brick
	Data transmission equipment	brick: Electrical_Equipment	Quoted from Brick

Table 4
Relationships available for highway modeling and their definitions.

Brick Tag	Definition	Remarks
brick: hasPart	The subject is composed in part of the entity given by the object	Containment relationship
brick: isPartOf	Inverse hasPart	
brick: hasLocation	Subject is physically located in the location given by the object	Location relationship
brick: isLocationOf	Inverse hasLocation	
brick: hasPoint	The subject has a source of telemetry identified by the object. In some systems the source of telemetry may be represented as a digital/analog input/output point	The point entity
brick: isPointOf	Inverse hasPoint	
brick: feeds	The subject is upstream of the object in the context of some sequential process; some media is passed between them	Data flow order
brick: isFeedBy	Inverse feeds	
brick: hasTag	The subject has the given tag	Tags
brick: isTagOf	Inverse hasTag	
brick: hasTimeserieIeld	The unique identifier (primary key) for this TimeseriesReference in some database	Time series data
brick: storedAt	A reference to where the data for this TimeseriesReference is stored	Database

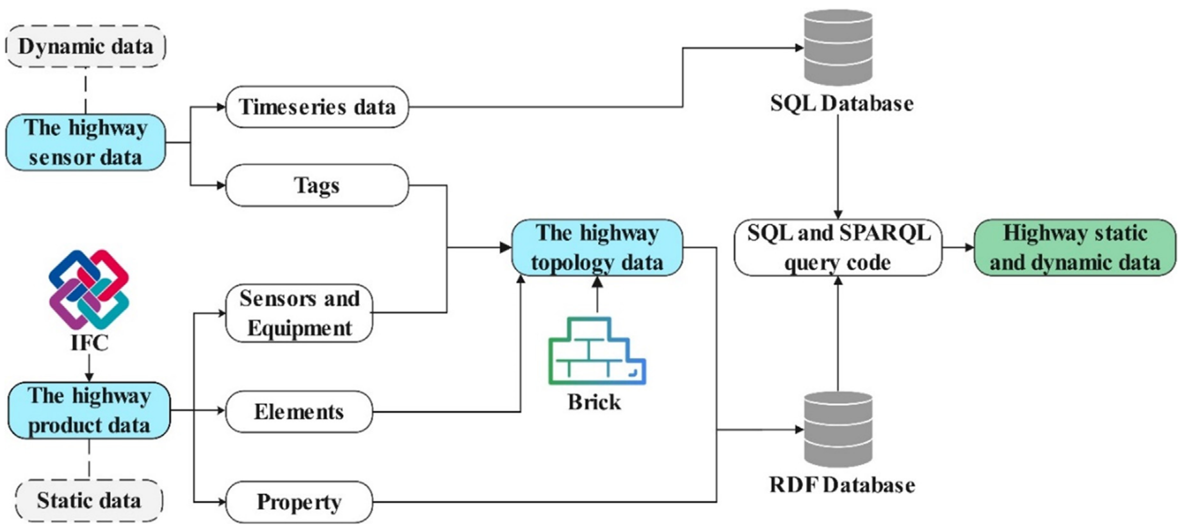


Fig. 6. The proposed data integration method for highways.

In this framework, the highway product data created in IFC format is converted to RDF format and stored at RDF database. The highway topology is modeled using the methods in 3.1 and 3.2 Sections, and also stored at RDF database. By combining two query languages, SPARQL and SQL, the integration of highway static and dynamic data can be achieved.

To achieve the goal that integrating highway dynamic and static data, the following steps are proposed.

Step 1: Create a highway model in IFC format based on the BIM modeling software (e.g., Revit, Civil 3D, InfraWorks). Convert the highway model file into a Turtle file.
Step 2: Create a specific highway ontology based on the existing ifcOWL, OWL, Brick schema and the new self-defined classes.
Step 3: Link the highway model in RDF format and specific highway ontology to form a merged model file, and store them in a RDF database.
Step 4: Query the concerned parameters of HORM. Dynamic data is stored in a SQL database. Various devices are represented by the same tags and associated with the highway topology model.
Step 5: Display the concerned data. One way is to visualize the space based on the static model. Another way is to directly display dynamic data as graphs, tables and other forms.

In this method, the main used tools and implementation process are illustrated in Fig. 7. So far, the interaction of highway static and dynamic data based on the IFC-Brick can be realized.

4. Case study

4.1. Highway modeling and data collection

To verify the effectiveness of the method proposed in this paper, a highway in Shandong Province, China, is used as a case for testing. The highway components mentioned in 3.1 were first built based on Revit, the most popular BIM modeling software. Then the G3 highway model (from Manzhuang to Ningyang East) was constructed. Consistent with Fig. 3, there are four common lanes and an emergency lane in the upward direction of this case segment. The innermost of these is a dedicated lane for autonomous vehicles. After modeling the case highway in IFC format, it was converted to the corresponding format and stored according to the method proposed in Section 3. Its location and product models are shown in Fig. 8.

Fig. 9 shows the semantic model of case highway based on Brick classes and the self-defined classes. In this highway case, take the upward direction as an example, highway_segment1. The highway_segment1 contains five lanes. The five lanes share the same set of traffic data and meteorological data collection equipment, the LiDAR, vision_camera, and weather_meter. In addition, this case highway_segment1 is also provided with a data transmission device, RSU, and an information

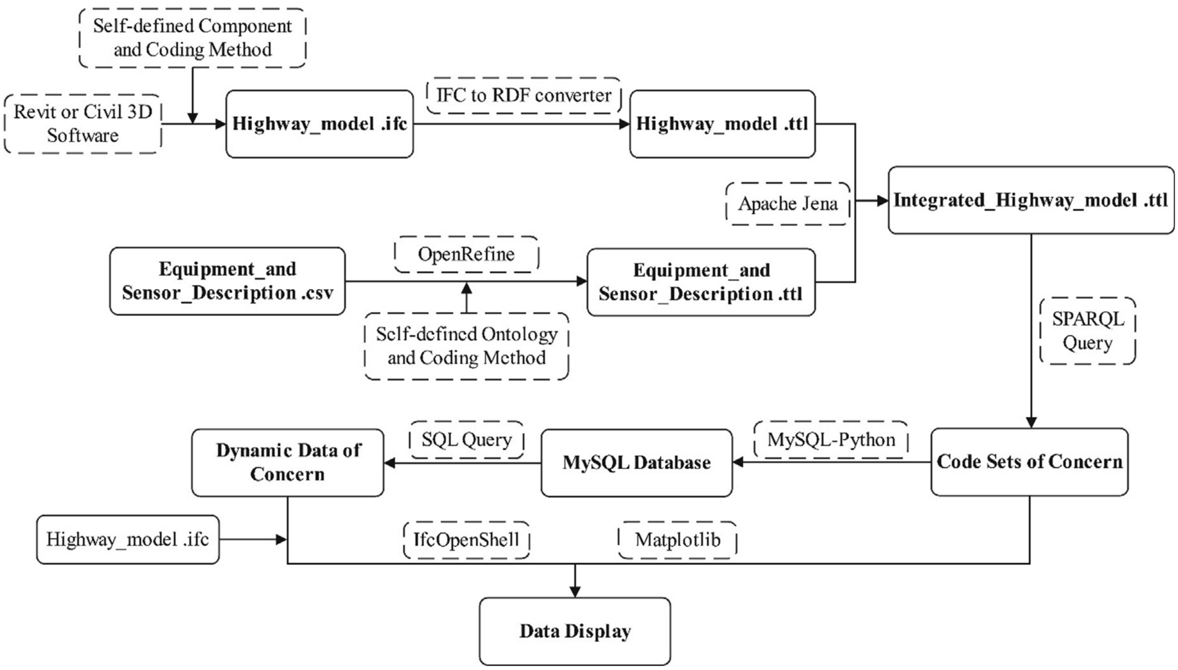


Fig. 7. The main used tools and implementation process.

Fig. 8. Static product model of the case highway.

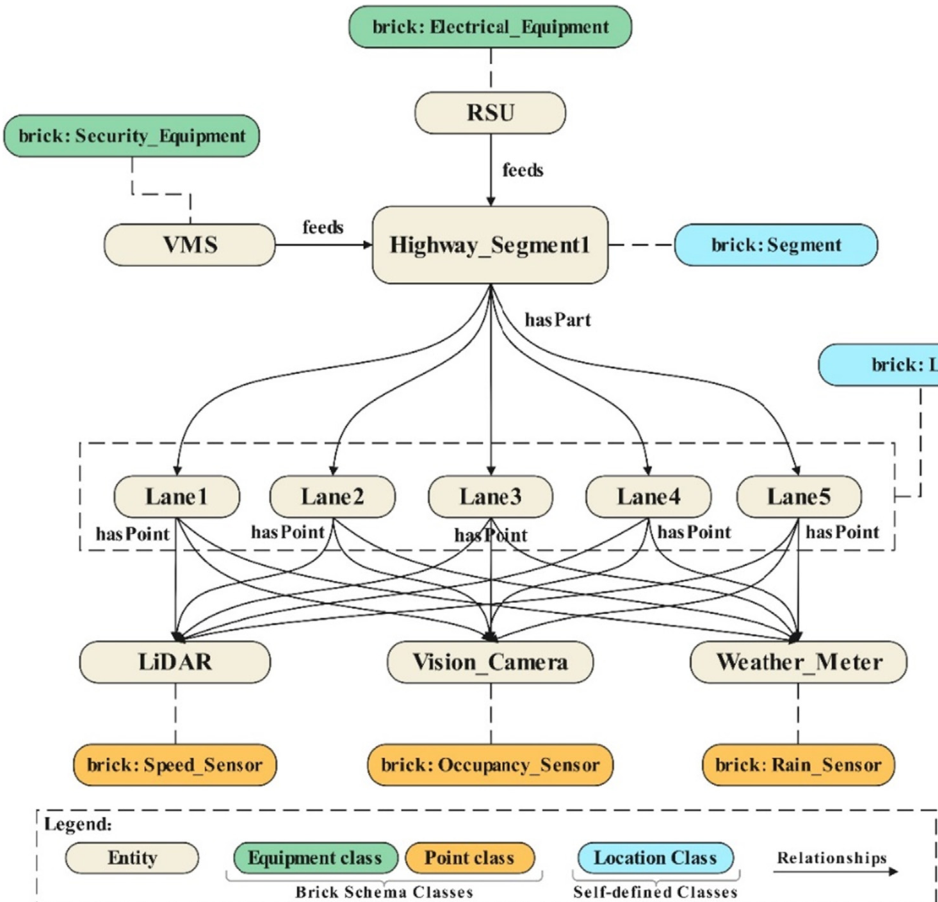


Fig. 9. Semantic model of the case highway.

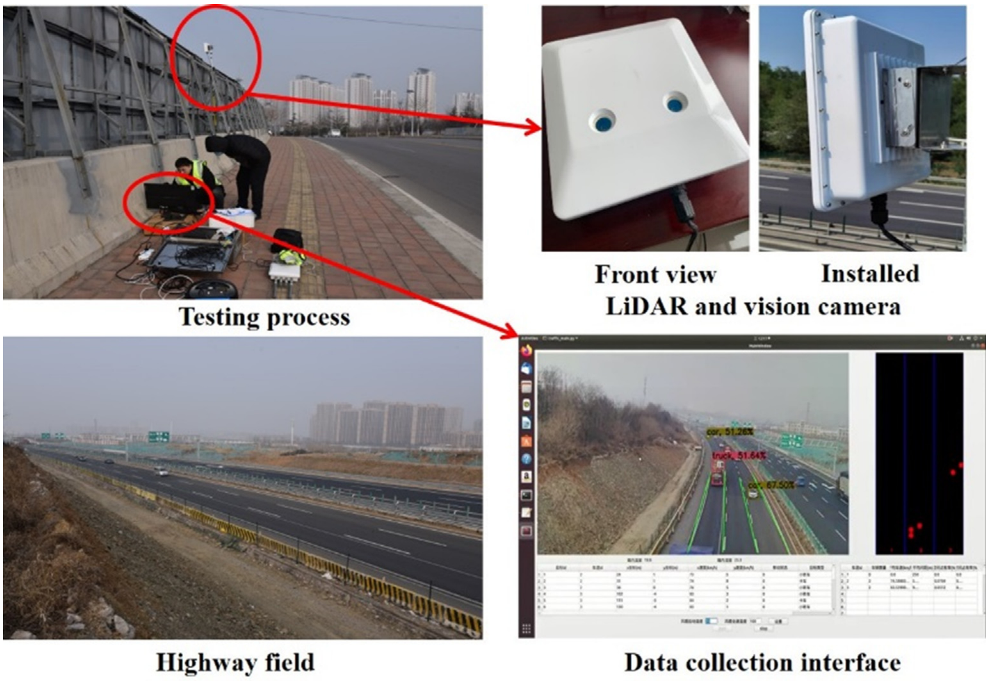


Fig. 10. The field dynamic data collection process.

release device, VMS. Among them, RSU is the abbreviation for road-side units, VMS is the abbreviation for variable message signs. Besides, the classes and relationships between these entities are marked in the graph.

To obtain real time dynamic data, we installed these sensors on the roadside. The time series data was stored in the MySQL database in real time. Take the LiDAR and vision camera as an example, the field data collection process is shown in Fig. 10.

4.2. The system development and data interaction

Furthermore, based on the data model proposed in this paper, a HORM system was developed. As parts of the system, the home page and data display page are shown as Figs. 11 and 12.

Fig. 11. The highway operational risk management system (the home page).

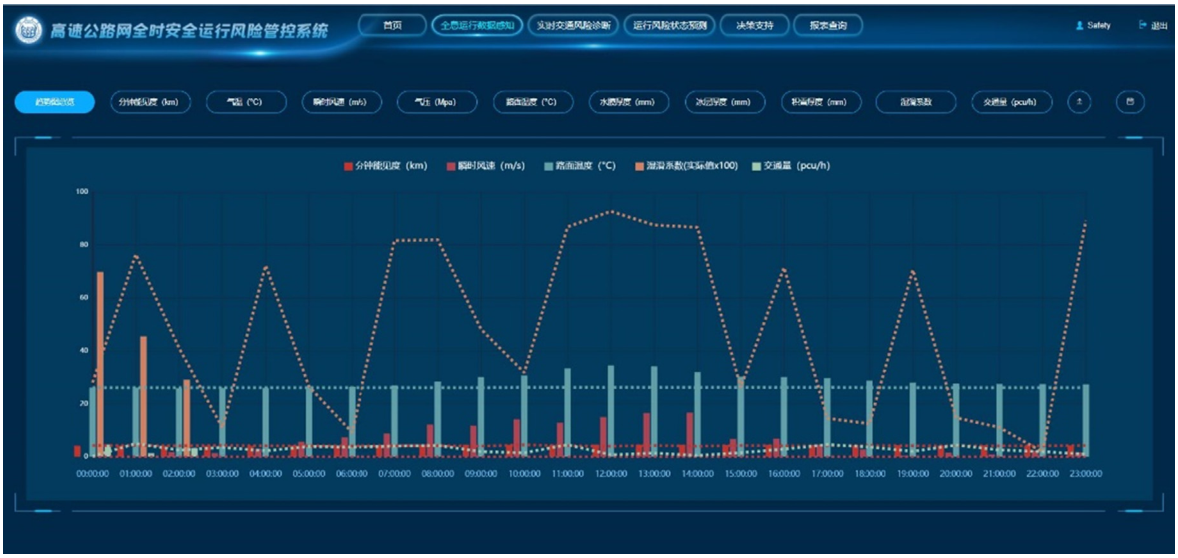


Fig. 12. The highway operational risk management system (the data display page).

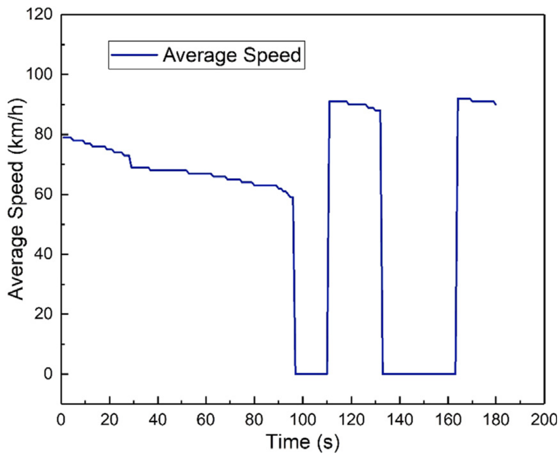


Fig. 13. The average speed query results in 3 minutes.

The developed HORM system has six main functions, including holographic operational data collection and processing, real-time traffic risk status diagnosis and assessment, traffic risk status prediction, decision support, data query, and refined display.

Take the average speed as an example, the retrieved result is shown in Fig. 13. The speed here refers to the average value of all vehicles passing through the section. This parameter is collected by the LiDAR and vision camera, which is stored in the MySQL database. It can be seen that the speed of the test point changes within 3 minutes of the test time. A speed of 0 in the figure means that no vehicle is passing by.

5. Conclusions

This study was carried out to promote the application of digital twin technology in the stage of highway operation, improving the efficiency of highway management and decision-making support. We analyzed the information requirements of highway operational risk management, proposed an information model for the HORM, and conducted practical tests. The main conclusions are as follows:

- The highway information model architecture for operational risk management is mainly defined as 5 layers: the basic highway layer, the traffic sensors and equipment layer, the traffic rules layer, the traffic flow layer, and the weather layer. Furthermore, according to the concepts of semantic data and linked data, the five layers can be classified into three cat-

egories: highway product data, topology data, and sensor data. The identification and classification code of lane-level management unit are defined like " G3 370881T001 1 1″ and ″46-08.07.01.00″ respectively.
- Although IFC and Brick schema was first proposed and applied in the building domain, known widely as BIM, some of their entities and relationships can also be used for highways. Besides, the new classes brick: Highway, brick: Segment and brick: Lane were defined. The proposed integration framework and information model for HORM based on the IFC-Brick schema is proven to be effective. It enables developing the HORM system.
- Applying semantic and linked data technologies to highways has broad potential. It changes the file-based exchange method to the data-based one, which further promotes the interaction and application of multi-heterogeneous highway data. Finally, the efficiency of highway management and decision-making support can be improved greatly.

However, the highway ontology used in this paper is a preliminary extension of the existing ontologies, which is a temporary solution for HORM. In future research, it is better to develop the highway specific ontology to improve the accuracy and efficiency of data connection according to the needs of HORM. Furthermore, consideration should be also given to more application of the proposed model in highway operation management systems and further testing such that the model utility can be truly exerted.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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