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HiDaM: A Unified Data Model for High-definition (HD) Map Data

Yunfan Kang
Dept. of Computer Science and Engineering
Center for Geospatial Sciences
University of California, Riverside
Riverside, California
Email: ykang040@ucr.edu

Amr Magdy
Dept. of Computer Science and Engineering
Center for Geospatial Sciences
University of California, Riverside
Riverside, California
Email: amr@cs.ucr.edu

***Abstract*—Smart cities are emerging and under development worldwide. As one of the core components for achieving the goal of smart transportation, autonomous vehicles are undoubtedly on the blueprint for smart cities. The development of autonomous driving cars leads to the demand for highly accurate and detailed machine-readable maps. To meet this demand, the high-definition (HD) maps are being developed. The HD maps are extended three-dimensional maps that tend to contain enough detailed information in the driving environment to be consumed by machines. Both commercial companies and research communities got a recent interest in building and are exploring research problems on this kind of mapping data. Several companies have already defined their commercial HD map formats, but there are arguments that the existing HD map formats are not research-friendly enough. In this paper, we propose to define a research-friendly HD map data model by extending the popular node-edge model that is widely used by researchers. Our model considers both on-road and off-road data to be extensible for future use cases and information that will be available on various three-dimensional objects in the outdoor space. This is partially motivated by several use cases that will benefit from HD mapping data other than the self-driving technology. We give a brief discussion for such potential use cases and how our model will fit their requirements. We also discuss that our model can be still used for human-machine interactions for compatibility with existing techniques and applications.**

I. Introduction

Autonomous vehicles are recognized as one of the key factors that pave the way for smart cities. Existing mapping platforms, e.g., Google Maps, are designed, built, and deployed for human-to-machine interaction, where the major implicit assumption is that a human user is consuming the mapping data from a computing device, e.g., a smartphone. Over the past few years, the rise of self-driving cars technology has triggered an urgent need for a new type of mapping data that is designed, built, and deployed for machine-to-machine interactions as the human driver is being replaced with an automated machine driver. This is the main motivation behind the research wave of "high-definition" maps or "lane-level" maps, that includes several research efforts [1]–[7] to enrich existing maps with much more detailed information that are needed to be consumed by machine users.

High-definition map (HD map) provides accurate and detailed centimeter-level three-dimensional (3D) information and it plays an essential role in several important applications for self-driving cars and data driven smart cities. The detailed 3D localization objects included by HD maps enable the self-driving cars to have a more precise and comprehensive knowledge of its environment and help the vehicles to better determine their position and orientation, which enables the autonomous vehicles to perform controlled maneuvers beyond the sensing range [8]. Potential risks and obstacles ahead that are out of the range for the sensors can also be predicted and avoid with the rich information [9]. HD maps are also able to store prior information that is of great help when the self-driving cars need to perform computations for applications such as traffic light recognition and speed sign recognition [10]. In addition to the application and techniques required by self-driving cars, HD maps are also deployed to help with the development of the advanced driver assistant systems (ADAS) [11], [12] and push the existing navigation applications to provide more detailed lane-level instructions [13].

The huge potential of HD map has attracted plenty of efforts on map data collection, automated map modeling and algorithm design for related applications. However, there are arguments that the existing HD map data formats are not research-friendly. The existing commercial HD map models are confidential, and some require a commercial membership to be accessed. The commercial models, taking the Navigation Data Standard (NDS) as an example, are complained to be not suitable for researches due to their complexity and the features supported [14]. Researchers with such complains tend to define their own data model. The different data models used in different research works may downgrade the reusability of the data and hinder the experiments that need to be performed on different data sources. Thus, we propose to design a standard research-friendly data representation for HD map data.

The proposed data model builds on the popular node-edge model that is widely used by researchers to model the road network. By keeping this popular model as the foundation of our model, we target three goals, the first two of which are complementary. The first goal is to design a research-friendly standard for HD map data that enables researchers to explore various problems in this rich space. This overcomes the current limitation of having different definitions for HD map data by

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different providers [8]. In addition, the leading data format for HD maps, the NDS format, is identified to be not research-friendly enough due to its complicated data structure and the features supported [14]. The second goal is to maintain the widely used node-edge model for compatibility with existing techniques and applications. This way, the existing information and applications associated with the traditional maps can be safely imported to our model. A third goal, that is orthogonal from the other two goals, is having an extensible model that is able to adapt information about all objects in the outdoor space, even the ones that we have limited information about at the moment. This includes buildings, parking lots, parks, etc. Mapping such detailed information will allow various applications that are currently limited by traditional maps.

With these goals in mind, we define our data model that consists of two major parts: road network and landmarks. We enrich the information for road network by extending the node-edge model using LaneBundles, which are sets of lanes associated with various landmarks and attributes, while maintaining the compatibility for existing maps representing a road segment with an Edge entity and an intersection between two or more road segments with an Intersection entity. However, the detailed definition of each entity is enriched to absorb the new detailed information. In addition, we associate with the road network data entities for landmarks, both on-road and outdoor landmarks. The landmarks are identified to record the 3D objects in the driving environment to facilitate the vital applications for autonomous driving cars such as localization and advanced routing features.

The remainder of this paper is structured as follows: Section II reviews the HD map models. Our data model design is described in Section III. We provide a discussion in Section IV and we conclude with a perspective and future work in Section V.

II. Related Work

Geographic Information System (GIS) is playing an important role in the development of smart cities and there have been discussions about building 3D-GIS maps for smart management and decision making [15]–[17]. In this paper, we focus on the HD map for autonomous vehicle applications. HD map for commercial purpose was first launched in 2015 by Tomtom [18]. Since then, several map providers have defined their own HD map standard. Navigation Data Standard (NDS) is the leading data format in the industry [14]. The NDS format classifies all data into different building blocks, such as routing building block, lane building block and 3D objects building block [19]. Building blocks are used to address different functional aspects of NDS. The TomTom HD Map with RoadDNA model is also claimed to be a highly accurate representation of the road. It provides numerous features, including lane models, traffic signs, road furniture, and lane geometry, with high accuracy [18].

Although being supported by major industry, there are some potential drawbacks for existing commercial data models for HD maps. One main concern is being confidential and not open for research purpose. It is hard to obtain the data as well as the data format specification. From a research perspective, there are scattered data that is valuable for constructing partial HD maps, such as the OpenStreetMap data and other crowdsourced data sources. However, the lack of an open standard data format adds difficulty for using such data and also downgrades the reusability of them. Secondly, the features supported by the data models tend to be demand-driven. The features included are for achieving certain functions or benefits. This may be helpful for supporting different applications, but it also makes the features to be discrete and set obstacles for introducing new features for researchers, especially those similar to or closely related to the existing features in the data model. Last but not least, commercial data formats are usually divided into discrete building blocks or layers and this design choice should be closely related to the objectives of modularity, compatibility, and interoperability. However, applications that make use of the HD map may require specific types of data. As a result, the data models tend to have detailed divisions that are on the same level and become too complicated for research purpose.

For all the above reasons, we observe that researchers tend to start from a relatively simple model and focus on certain features when studying HD maps. Jiao pointed out that the four elements an HD map usually contains are the reflective map of the road surface, the 3D shape of the surface of the driving environment, lane/road model and the static elements in the driving environment [2]. Some researchers from HERE, a major map provider worldwide, construct a road model containing only lane boundary, occupancy grid and the road sign [14]. Takeuchi et. al. make use of Point Cloud Map and Vector maps for blind traffic prediction [9]. The researches on HD map creation also focus on determining the details of the lanes [1]–[6] and modeling the driving environment [5], [7]. Hence, we may draw a conclusion that the basic components of HD map data models for research should be the road, which is extended to the level of lanes and the peripheral driving environment.

III. Data model

In this section, we give descriptions for our HD map data model. Our model builds on the popular node-edge model that has been used for long in academic research environments. The node-edge model represents the road network as a set of nodes and edges. Edges represent road segments and nodes represent intersections between roads. Special semantics are added to handle special cases, such as dead ends and different types of intersections, e.g., 2-way. 3-way, or 4-way intersections. This model is intended to be simple, of low storage, and isolates road network data from all other data objects in the outdoor space due to lack of applications that comprehensively use all these data items together.

The standing point of our model is to extend the node-edge structure to model the new rich information added to HD maps. The new information includes the lane system and various types of landmarks. This modeling effort tries to provide a

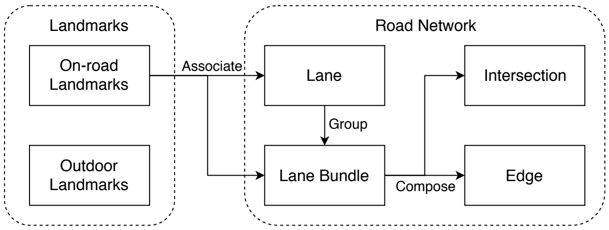


Fig. 1. Overview of the data model

research-friendly model for HD map data, compared to the existing various models [8] and the NDS standard that is argued not to be research-friendly enough due to its complicated data structure, the features supported, and openness [14] as discussed in Section II. In addition to regular road network information, HD maps also include landmarks data that is essential for several applications, such as localization as well as obstacle avoidance for self-driving cars.

Figure 1 depicts an overview of the data model. The model schema is divided into two parts, the road network, and the landmarks. The road network still consists of two main entities, Intersection and Edge, that correspond to node and edge in the traditional model and represent intersections and road segments, respectively. In addition, both entities are composed of LaneBundle entities that represent the lane-level information of the road network. Each LaneBundle consists of a group of Lane entities. Both Lane and LaneBundle entities can be associated with on-road landmarks that are represented by On-road Landmarks. Examples of on-road landmarks are road signs and traffic lights. In addition, landmarks could also include information about off-road landmarks, represented by Outdoor Landmarks in the figure. Details of both road network and landmarks are described in the rest of this section.

A. Road network

The roads in traditional maps can be viewed as intersecting polylines. The two central elements of the road network data model are Edge and Intersection, which correspond to the edge and node in the popular node-edge model. Our model extends these two elements with lanes and lane bundles. We will first describe the definition of the lane and lane bundle and then show how we extend the Edge and Intersection to model the HD map.

A lane, corresponding to the regular driving lane, is a sectional slice of the road segment. It is modeled as a 3D surface with a boundary that records the information including the basic shape of the driving lane and the elevation. Each lane starts and ends with a cross-sectional boundary, which is a three-dimensional line in the space, usually perpendicular to the lane driving direction, starts and ends with a node that is a three-dimensional point in the space and represents the farthest corner point in the lane. A lane reference is associated with each lane to help to show the orientation of the lane and locate the point attributes and range attributes. Example of point attributes is the vehicle checkpoints where polices may stop the vehicles to conduct the roadside detention with a legitimate reason. Example of range attributes is the lane maximum speed that might have different values over different distance ranges in the lane, e.g., the lane has a maximum speed of 30 MPH before a certain point and 40 MPH after that. Parallel lanes in the same road segment are grouped into lane bundles. A lane bundle reference is used to record the attributes of the lane bundle and the attributes would apply to all the lanes within the current lane bundle. The lane bundle starts and ends with a cross-sectional boundary, represented as a polyline, that is the union of all cross-sectional boundary lines of all lanes within the lane bundle.

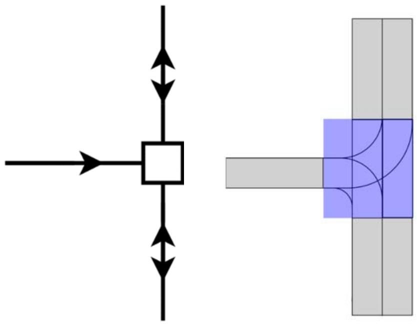
With the definition of lane and lane bundle, we then extend the node-edge model in the traditional map models. In the traditional maps, a road segment is represented by an edge that is a simple polyline. We extend the Edge into a sequence of one or more connected lane bundles. The connection between two lane bundles is represented with sharing the same cross-sectional boundary polyline. Thus, two lane bundles B1 and B2 are connected if and only if the starting boundary of B2 is the ending boundary of B1 or vice versa. Furthermore, the nodes in the traditional map represent the intersections among road segments, i.e. Edges. In our model, an intersection, represented by the entity Intersection, is a group of overlapping lane bundles in different directions based on the type of intersection, e.g., 4-way, 3-way, or 2-way intersections. Each lane bundle in the intersection connects two lane bundles that belong to two different road segments, either in the same direction or in angular directions, e.g., perpendicular directions. Figure 2 gives an example of the Intersection-Edge representation and the lane bundle representation of the same T intersection of a one-way street and a two-way street. Lane bundles boundaries are represented by the solid lines in the right figure. The area bounded by the blue rectangle corresponds to the Intersection and the gray lane bundles correspond to the Edges.

The Intersection-Edge model is extended using the lane bundles so that the HD map can carry more detailed information for emerging applications while maintaining the practicality. The simplicity and the potential for feature extensions enable the data model to be more research-friendly.

B. Landmarks

Landmarks are intended to include the objects in the driving environment. We classify the landmarks into two subclasses: on-road landmarks and outdoor landmarks.

On-road landmarks represent landmarks that are associated with either the road segments or intersections and are part of the driving roads, such as lane marks, traffic lights, road signs, and guardrails. The on-road landmarks carry certain attributes or will lead to the changes of attributes of lanes or lane bundles on certain directions. For example, lane marks will determine whether a vehicle can pass certain lane boundaries to turn or overtake another vehicle and speed sign marks change of the speed limit attribute for lanes or lane bundles at a certain point.



(a) Edge-Intersection (b) Lane Bundle

Fig. 2. T intersection of a one-way street and a two-way street

Outdoor landmarks represent other real objects that exist in the outdoor space but not part of the road network, such as buildings, trees, parking lots, lights, and parks. These objects are diverse and of different nature and could have different usages for HD map consumer. For example, trees and lights could be used for self-localization algorithms while parking lots and parks could be used as routing destinations.

Both on-road and outdoor landmarks are represented by Landmark entity that has generic attributes such as type and photo. The generic representation of a landmark comes with the reality of limited data available on this type of entities for now, so generality allows more flexible accommodation for new information later.

C. Detailed Schema Description

The previous subsections give a high-level overview of different components of our proposed model. This subsection gives a detailed data scheme along with a more detailed description of different entities and relationships among them. Figure 3 shows the data schema. We start from the Intersection and Edge model and extend them with the LaneBundle to accommodate lane-level information. The LaneBundle is defined to be a group of parallel Lanes. To register and locate the attributes on Lanes and LaneBundles, a reference geometry is associated with each of those entities. The reference geometry represents the underlying physical spatial coordinates, represented with points, lines, and polylines of latitude and longitude coordinates. Points are modeled with entity Node, lines and polylines are modeled with the entity LineSegment, and more complex geometries are represented with the entity LaneLevelGeometry. Each LaneReferenceGeometry or LaneBundleReferenceGeometry has an orientation that represents the orientation of the Lane or the LaneBundle. An attribute is registered using the relative distance from the start of the reference geometry. An attribute could be a point attribute, such as a U-turn point or a vehicle checkpoint, or a range attribute, such as a range on the road for the speed limit. Each Lane is bounded by a Boundary. The Boundary is associated with the attributes that depict its characteristics, such as whether it is a boundary that connects two Lanes from different LaneBundles or two parallel lanes in the same LaneBundle, whether it allows vehicles to pass through it to perform maneuvers. The Boundary, LaneReferenceGeometry, and LaneBundleReferenceGeometry are defined as subclasses for LaneLevelGeomerty. The LaneLevelGeometry is a sub-entity of the LineSegment entity that connects a sequence of Nodes. A Node represents a point in the three-dimensional space, and its attributes include its latitude, longitude, and altitude and it is the fundamental entity of the data model.

A landmark is located by a single Node and the Node serves as the center point for the landmark. A landmark is bounded by its Boundary. The boundary sketches the shape of the vertical view of the landmark and it could be an arbitrary polygon. We propose to make photo as one of the attributes of the Landmark. In cooperation with the cameras and sensors on autonomous vehicles, photos taken beforehand can play an important role in applications such as vehicle self-localization, traffic sign recognition, and traffic light recognition. The On-roadLandmarks are associated with the Lanes and LaneBundles. Example of On-roadLandmarks is the speed sign. A speed sign is represented by a 3D point cloud that depicts the shape and the size of the object in the real world. High-resolution photos of the sign are stored to facilitate the recognition process of the sensors to save computation power and increase safety. The absolute location of the sign is represented by a Node and its Boundary. The sign is associated with the LaneBundle and the range attribute that it has an effect on. The Outdoor Landmarks are not associated with Lanes or LaneBundles because they have no impact on the attributes. One of the examples could be a tree. The Node and the Boundary for the tree are located away from the LaneBundle representing the road. The more detailed information, such as the profile of the tree and the 3D point cloud representing the shape of the tree can be registered. Although the Outdoor Landmarks are not directly associated with the road network, the information about the position and the shape of these landmarks can be used for localization and incident avoidance.

IV. DISCUSSION

This section provides further discussion on three main points: (1) compatibility of the proposed data model with existing data and applications, (2) potential simplification for the proposed data model, and (3) potential applications for HD maps other than self-driving technology.

Model compatibility. As the existing applications need to be supported along with the emerging applications, such as autonomous driving, our data model is compatible to serve all existing applications. Due to economic and infrastructural reasons, human drivers are expected to share the roads for at least a decade after a large number of fully autonomous cars are on roads. For example, autonomous cars are not expected to be affordable for many people at the beginning, and it will be neither affordable nor indispensable for cities to build new roads for autonomous cars isolating them from other cars. This is regardless of the fact that having a reasonable number of fully autonomous cars is not even the reality yet. Therefore,

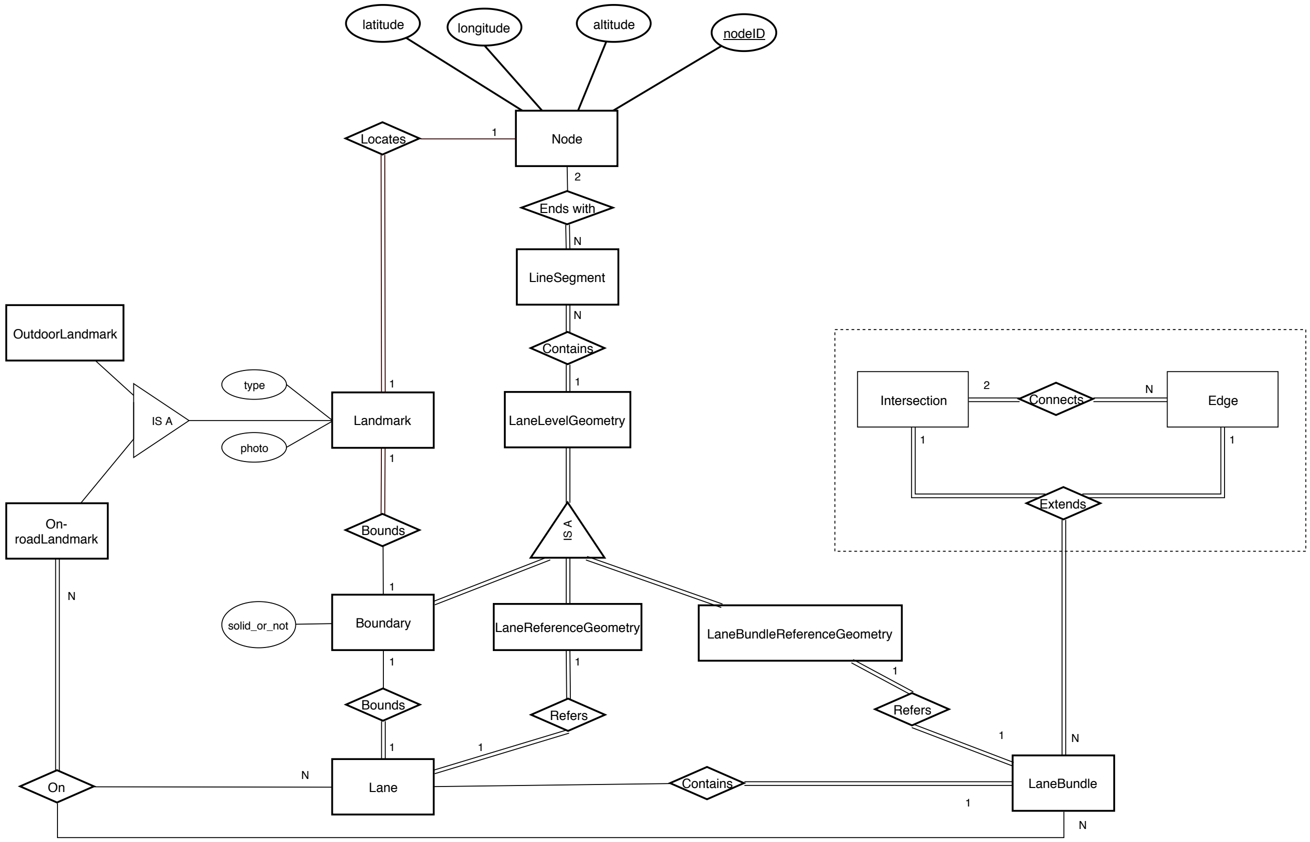


Fig. 3. Data model

there is still a demand for human-machine interactions and the existing map applications are also essential for a long time ahead.

Our model maintains compatibility with the traditional applications through using the same core entities, Edge and Intersection, so any attribute or processing on the old edge and node entities can be performed on their corresponding entities. For Intersection entities, a center point of the intersection can be used to represent the whole intersection and treat it as the original node if needed. For Edge entities, a polyline that spans the different connected lane bundles can be used to represent the edge in the traditional format. Both the center point of an intersection and road segment polyline can be easily derived from the stored attributes in our model. This serves the existing applications with even improved potential features. For example, out of the most popular applications nowadays are navigation and route planning. Turn-by-turn navigation directions can be easily provided using our model treating edges and nodes as highlighted. Furthermore, the introduction of the lane level enables the navigation and routing applications to give more detailed instructions, which help to further improve the user experience for human drivers. Google Maps has started to use lane-level data to provide more detailed driving instructions to its users.

Model simplification. In Section III, we described how we extend the existing Intersection-Edge format to model the HD map data. Reflecting on this extension while assuming we do not have the constraint of compatibility with the traditional node-edge model might lead to a potential simplification for the proposed model that worth further explorations. This simplification makes use of the observation that Edge and Intersection entities, which are marked with the dashed rectangle in Figure 3, are mere containers for a set of lane bundles. In fact, the definition of both entities has totally replaced with a set of lane bundles that have different spatial relationships. In the Edge, the set of lane bundles form a connected sequence, where a lane bundle starts wherever the previous one ends. In the Intersection, the set of lane bundles are geographically overlapping and connects different Edge instances. In all cases, each lane bundle encapsulates its own geometry that defines its geographical location and orientation. The entities Edge and Intersection are mere logical grouping that do not hold any attributes in the proposed model. Some popular applications, such as routing, might not need this logical grouping and can sufficiently use the lane bundles to provide the functionality. In this case, we can remove the abstraction of Edge and Intersection entities and use sets of LaneBundles as replacements for them. It worth exploration if this is applicable for the vast majority of applications, or there is still a significant need to keep the Edge and Intersection entities.

Before discussing the implications of the suggested simplification on other entities in the data model, it is essential to highlight merits and potential drawbacks of such simplification. One of the obvious drawbacks is the lack of compatibility with existing map models and applications. In other words, this simplification will convert the model into a model that purely serve HD map application and will make integration with traditional mapping application harder. In specific, it will be a necessity to map traditional edges to multiple lane bundles, that are not currently grouped at the logical level, and the same for traditional intersections. So, using this in applications need to be conditioned with an awareness of such limitation. On the other hand, the simplification will make the model simpler and will ensure more integrity for the underlying data due to removing one layer of redundancy.

Removing the Edge and Intersection logical grouping will have minimal effect on the rest of the modeled entities. First, it will not cause the model to collapse. The Intersection and Edges record the fundamental topology of the road networks. Since the Intersections and Edges are composed of lane bundles, the topology information is maintained by the relative position of different lane bundles. Second, it is worth considering how to accommodate the attributes associated with the Edges and Intersections. It is straightforward to map the Edge oriented attributes on to the LaneBundleReferenceGeometry. Since the Edge is decomposed into a sequence of LaneBundles that are not intersected, the attributes are also distributed into segments. The attributes associated with the intersections will be mapped to the specific lanes or lane bundles. For example, the Intersection traversal information will be reflected by whether there are turning lanes for the corresponding direction. The traffic lights will be associated with the boundary of the corresponding lanes to put a condition about when the vehicles can pass a certain boundary to proceed. Overall, all attributes that can be associated with both Edge and Intersection entities can be also associated with one of the other entities.

Potential applications on HD maps. Although high-definition maps are mainly motivated by self-driving cars, this kind of data can be used in endless applications that could make use of such fine-granularity information in other contexts. For example, an on-going research in forestry makes use of Google street images to identify types of trees that suffer from certain problems in Vancouver, Canada, and researchers are willing to expand their techniques to other geographical areas in North America and Europe. Another example is a tree atlas for Southern California that is being developed based on Google Earth images data that document forests and trees in the region. A third potential example is studying the development of urban areas and human migrations through analyzing data from different time snapshots. In nutshell, the on-going efforts to build high-definition maps will help researchers from different disciplines to study different problems with a relatively cheap source of data compared to existing methods.

We are also aware that one of the major features of the HD maps is the enormous map data size due to the details added. Currently, there are also room for improvement for efficient data management [8] and format compactness and efficiency [19]. These shortcomings may prevent the HD map from replacing the existing digital maps, but we have a positive prospect about with the development of communication technology and data access technology.

V. Conclusions

To cater to the requirement for highly detailed and accurate maps by self-driving cars, HD map has been widely discussed and there are several commercial HD map data models from different map providers. However, there are arguments that the existing HD map data models are not research-friendly. In this paper, we propose a standard research-friendly HD map data schema by extending the existing node-edge structure in the tradition map data models. The data model includes two major parts, road network, and landmarks. The paper also discussed the compatibility of the model with existing applications, potential simplifications to the model, and further applications for HD maps beyond self-driving cars. The data model serves as a generic framework for a more detailed design. Meanwhile, the management [20] and the efficient update of such a data model are also examples for future research directions.

References

[1] F. Ghallabi, F. Nashashibi, G. El-Haj-Shhade, and M.-A. Mittet, "Lidar-based lane marking detection for vehicle positioning in an hd map," in *2018 21st International Conference on Intelligent Transportation Systems (ITSC)*. IEEE, 2018, pp. 2209–2214.

[2] J. Jiao, "Machine learning assisted high-definition map creation," in *2018 IEEE 42nd Annual Computer Software and Applications Conference (COMPSAC)*, vol. 1. IEEE, 2018, pp. 367–373.

[3] P. Fischer, S. M. Azimi, R. Roschlaub, and T. Krauß, "Towards hd maps from aerial imagery: Robust lane marking segmentation using country-scale imagery," *ISPRS International Journal of Geo-Information*, vol. 7, no. 12, p. 458, 2018.

[4] W. Jang, J. An, S. Lee, M. Cho, M. Sun, and E. Kim, "Road lane semantic segmentation for high definition map," in *2018 IEEE Intelligent Vehicles Symposium (IV)*. IEEE, 2018, pp. 1001–1006.

[5] K. Massow, B. Kwella, N. Pfeifer, F. Häusler, J. Pontow, I. Radusch, J. Hipp, F. Dölitzscher, and M. Haueis, "Deriving hd maps for highly automated driving from vehicular probe data," in *2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC)*. IEEE, 2016, pp. 1745–1752.

[6] G. Máttyus, S. Wang, S. Fidler, and R. Urtasun, "Hd maps: Fine-grained road segmentation by parsing ground and aerial images," in *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, 2016, pp. 3611–3619.

[7] M. Javanmardi, E. Javanmardi, Y. Gu, and S. Kamijo, "Towards high-definition 3d urban mapping: Road feature-based registration of mobile mapping systems and aerial imagery," *Remote Sensing*, vol. 9, no. 10, p. 975, 2017.

[8] A. Zang, X. Chen, and G. Trajcevski, "High definition maps in urban context," *SIGSPATIAL Special*, vol. 10, pp. 15–20, 06 2018.

[9] E. Takeuchi, Y. Yoshihara, and N. Yoshiki, "Blind area traffic prediction using high definition maps and lidar for safe driving assist," in *2015 IEEE 18th International Conference on Intelligent Transportation Systems*. IEEE, 2015, pp. 2311–2316.

[10] M. Hirabayashi, A. Sujiwo, A. Monrroy, S. Kato, and M. Edahiro, "Traffic light recognition using high-definition map features," *Robotics and Autonomous Systems*, vol. 111, pp. 62–72, 2019.

[11] F. Li, P. Bonnifait, and J. Ibañez-Guzmán, "Estimating localization uncertainty using multi-hypothesis map-matching on high-definition road maps," in *2017 IEEE 20th International Conference on Intelligent Transportation Systems (ITSC)*. IEEE, 2017, pp. 1–6.

[12] S. Zheng and J. Wang, "High definition map-based vehicle localization for highly automated driving: Geometric analysis," in *2017 International Conference on Localization and GNSS (ICL-GNSS)*. IEEE, 2017, pp. 1–8.

[13] S. Bauer, Y. Alkhorshid, and G. Wanielik, "Using high-definition maps for precise urban vehicle localization," in *2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC)*. IEEE, 2016, pp. 492–497.

[14] A. Zang, Z. Li, D. Doria, and G. Trajcevski, "Accurate vehicle self-localization in high definition map dataset," in *Proceedings of the 1st ACM SIGSPATIAL Workshop on High-Precision Maps and Intelligent Applications for Autonomous Vehicles*. ACM, 2017, p. 2.

[15] W. Tao, "Interdisciplinary urban gis for smart cities: advancements and opportunities," *Geo-spatial Information Science*, vol. 16, no. 1, pp. 25–34, 2013.

[16] “GIS for Smart Cities,” https://www.esri.in/∼/media/esri-india/files/pdfs/news/arcindianews/Vol9/gis-for-smart-cities.pdf, 2015.
[17] “A Gateway to Smart City Using 3D GIS Maps of Cities - LiDAR News Magazine,” http://www.lidarmag.com/PDF/LiDARNewsMagazine_Gupta-SmartGISand3D_Vol5No4.pdf, 2015.
[18] “HD Map with RoadDNA info sheet,” http://download.tomtom.com/open/banners/HD_Map_with_Road_DNA_Product_Info_Sheet.pdf, 2018.
[19] “NDS Open Lane Model,” http://www.openlanemodel.org, 2019.
[20] A. Zang, S. Luo, X. Chen, and G. Trajcevski, “Real-time applications using high resolution 3d objects in high definition maps,” in *Proceedings of the 27th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems*. ACM, 2019.