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THE ROLE OF TOPOLOGY IN HIGH-DEFINITION MAPS FOR AUTONOMOUS DRIVING

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ABSTRACT:

Autonomous and highly automated driving has become one of the key research topics – even in mapping sciences. Today, it has been clearly proven that the desired autonomy can be reached solely by progressive development, where maps and requirements against environmental models shall be modified. The research of the past decades resulted in the specifications for building high-definition (HD) maps, which contain all necessary field objects with their relevant features in a sophistically designed database. Maps have also become indispensable tools in reliable automotive development processes as simulations request accurate and detailed environment descriptions. The most accepted simulator map format is ASAM's OpenDRIVE, having a complete ecosystem nowadays with ultra-fine resolution pavement surface model, traffic flow description, and essential modules to produce those components by mainly automatic data collection and processing. Simulations enable efficient analysis of vehicle behavior as well as testing workflow for (onboard) vehicular and infrastructure sensors. With respect to the requirements of HD maps, not only their geometric fidelity but also the correct topology is expected. The available technology already serves OpenDRIVE models for various scenarios, where the topologic correctness is hard to test. The current research puts the emphasis on the topology analysis: with parsing the existing models, topology descriptors are derived, then a test suit containing rules of acceptable cases is applied. The rule set is built of items for detecting errors and warnings considering topology parameter tolerances; the result is quality documentation after a comprehensive testing approach. The actual topology testing environment forms an excellent base for (semi)automatic error fixing platforms involving artificial intelligence.

1. INTRODUCTION

One of today's most effort- and resource-intensive research areas is transport automation. The development of driverless vehicles requires a number of technological solutions, which need software development, experiments, and field tests. Computer simulation is therefore increasingly being used to reduce the huge time and resource requirements. (Barsi et al., 2020; Burg, 2019; "CarMaker | IPG Automotive," n.d., "Simulation Technologies - avl.com," n.d., "SUMO - Simulation of Urban Mobility," n.d.; Horváth et al., 2019) High-definition (HD) maps, already useful in nowadays navigation but essential for the control of autonomous vehicles, are therefore of key importance. (HERE, 2018; Potó et al., 2017)

These maps require detailed, very accurate field surveys and the derivation of suitable (environmental) models. The maintenance of the resulting digital map database is a cardinal issue, and the vehicles carrying the sensors themselves are being deployed to address this issue.

The environmental models can therefore be used to effectively research and improve the sensing and then control mechanisms of vehicles.

In the simulation, the dynamic properties of vehicles can be investigated by driving the vehicles through the digital model. The geometry of the road elements and their interconnections are of crucial importance for the infrastructure. The latter is referred to in the literature as topology; it is the focus of much work.

2. THE ASAM OPENDRIVE MAP FORMAT

The OpenDRIVE map format was originally developed by Vires to provide a suitable format for describing reality for various vehicle simulations. The format has now become a standard. Currently, the standard is being further developed by an organization called ASAM. (ASAM e.V., 2022; Barsi et al., 2019)

OpenDRIVE aims at accurately describing objects relevant to roads, lanes, and infrastructure not only in planar but also in 3D spatial terms. The elements are specified in ASCII XML format by filling in the data fields of the corresponding hierarchical tags. The extension used for storing the format is XODR. Currently version 1.7 is the most recent, but in practice version 1.4 is used for most simulators.

In our research, we used the Mathworks product RoadRunner to create sample files in OpenDRIVE format. (MathWorks, n.d.)

The most important data sets in the format are the header with reference data, the roads with their geometry, lane, pavement type, speed limits, etc. Other important groups are junction and junction group, which are used to describe the intersections; controller for traffic signs and control, and station for railway stations.

The topological solutions of the standard are described in the next section.

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3. TOPOLOGY ELEMENTS AND RULES

Map topology has proved to be very important, especially in the study of road networks. It has led to the discovery of a number of laws, the development of a suitable notation system and solutions for describing topological elements, properties and laws.
The topology of roads can be decomposed into line (arc-node) and polygon (polygon-arc) topology, and then the line topology can be further decomposed into reference lines of roads and lanes (Fig.1).

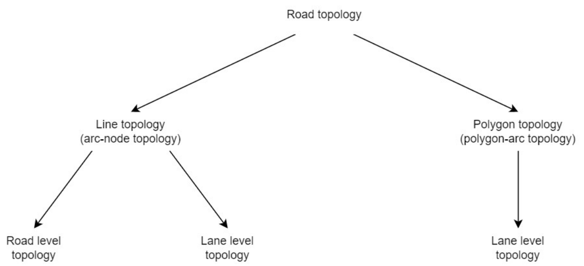


Figure 1. Groups of road topology

The most important elements are illustrated in the example in Fig.2.

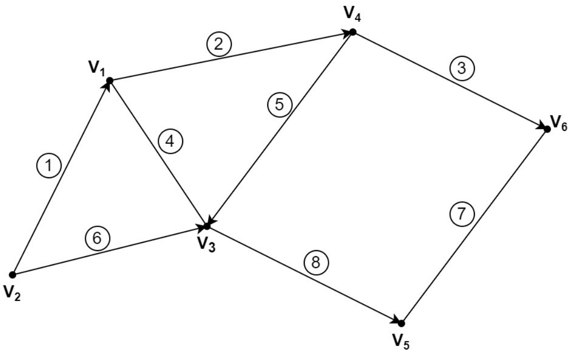


Figure 2. Sample to introduce topology elements

Vertices are V = {V_1, V_2, V_3, V_4, V_5, V_6}, and edges E = {①, ②, ③, ④, ⑤, ⑥, ⑦, ⑧}. The cardinality of vertices and edges are *n* and *m*, respectively. In the example n is 6, m is 8.
The above example shows a directed graph, with an official definition, being as the **Rule 1**:

$$E \subseteq \{(x,y)\} \mid (x,y) \in V^2 \; and \; x \neq y \qquad (1)$$

where *x* and *y* are vertices, more precisely *x* is a starting point and *y* is an endpoint. The edges and vertices can be used to define adjacency – point-to-point or vertex-to-vertex relation, stored in a square matrix. The formal definition is

$$A_{ij} = \begin{cases} 1 & if\ edge\ (V_i, V_j) \\ 0 & if\ no\ edge \end{cases} \qquad (2)$$

so an A_{ij} edge between vertices V_i and V_j is given by 1, otherwise by 0.
This matrix is more representative, if ones are replaced by the corresponding edge identifiers (unnecessary elements are left empty):

	V_1	V_2	V_3	V_4	V_5	V_6
V_1			④	②		
V_2	①		⑥			
V_3					⑧	
V_4			⑤			③
V_5						
V_6					⑦	

Table 1. Adjacency matrix for Fig.2

Similar feature is incidence, where a cross-relation between edges and vertices are expressed considering the starting points (SP) and endpoints (EP):

$$B_{ij} = \begin{cases} -1 & SP \\ 1 & EP \\ 0 & otherwise \end{cases} \qquad (3)$$

In relevant matrix form it seems like this table:

	V_1	V_2	V_3	V_4	V_5	V_6
①	EP	SP				
②	SP			EP		
③				SP		EP
④	SP		EP			
⑤			EP	SP		
⑥		SP	EP			
⑦					EP	SP
⑧			SP		EP	

Table 2. Incidence matrix for Fig.2

The third representation is the edge-edge relation, defined with predecessors (P) and successors (S) as following

$$C_{ij} = \begin{cases} -1 & P \\ 1 & S \\ 0 & otherwise \end{cases} \qquad (4)$$

It also has a matrix form, like this

	①	②	③	④	⑤	⑥	⑦	⑧
①		S		S				
②	P		S		S			
③		P					S	
④	P							S
⑤		P						S
⑥								S
⑦			P					
⑧				P	P	P		

Table 3. Edge-edge matrix for Fig.2

There is a mathematical way to derive adjacency-similar matrix directly from incidence matrix

$$\mathbf{A} = \mathbf{B}^{\mathbf{T}} \cdot \mathbf{B} \qquad (5)$$

and also edge-edge matrix-similar output

$$\mathbf{C} = \mathbf{B} \cdot \mathbf{B}^{\mathbf{T}} \qquad (6)$$

Now as we have seen the relation between the basic descriptions, we might define further rules. In the coming definitions, we suppose to have all derived matrices (adjacency, incidence and edge-edge matrix).

Rule 2 is formulating the number of edges:

$$\sum_i \sum_j A_{ij} = m \tag{7}$$

Rule 3 is a detection tool for points without any connections, called isolated points:

$$\sum_i A_{ij} + \sum_j A_{ij} > 0 \tag{8}$$

Rule 4 is specifying a single starting and endpoint for a road

$$\sum_j B_{ij} = 0 \tag{9}$$

Rule 5 deals with isolated point checks

$$\sum_i B_{ij} > 0 \tag{10}$$

Rule 6 is working with starting points

$$\sum_j B_{ij}^{SP} = \sum_j A_{jk} \tag{11}$$

Rule 7 is similarly with endpoints

$$\sum_j B_{ij}^{EP} = \sum_j A_{kj} \tag{12}$$

Rule 8 tests whether an edge has only two points

$$\sum_i \sum_j B_{ij} = 2m \tag{13}$$

Rule 9 is similarly with testing edge numbers

$$\sum_i \sum_j C_{ij} = 2m \tag{14}$$

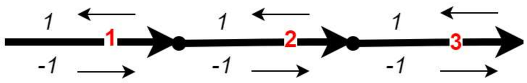
Lastly, **Rule 10** is a quasi-symmetry check with inverse edge-edge matrix elements

$$\sum_i C_{ij} = -\sum_j C_{ij} \tag{15}$$

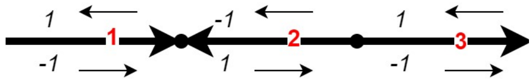
The presented rules are simple test measures, which can be implemented easily and identifies anomalies – mostly globally for the model, but sometimes specific error places can be discovered (like with Rule 10).

4. TOPOLOGY ANALYSES IN OPENDRIVE MAPS

For the OpenDRIVE model, topological correctness is also important. The topology is implemented by links; there are road level links and lane level links. In ambiguous cases (e.g., a lane branches in several directions) a junction is required.
In links, OpenDRIVE specification defines predecessor and successor elements - both at road and lane level. To understand them, let's have a look at the following two examples! For straight road sections, there are two types of junction layouts, as shown in Fig.3a and 3b.



a) continued connections



b) merging and branching connections
Figure 3. Connection cases of straight road segments

The following two tables provide a quick overview of the topology:

		Predecessor		Successor	
Road ID	Lane ID	Road ID	Lane ID	Road ID	Lane ID
1	1	2	1	–	–
1	-1	–	–	2	-1
2	1	3	1	1	1
2	-1	1	-1	3	-1
3	1	–	–	2	1
3	-1	2	-1	–	–

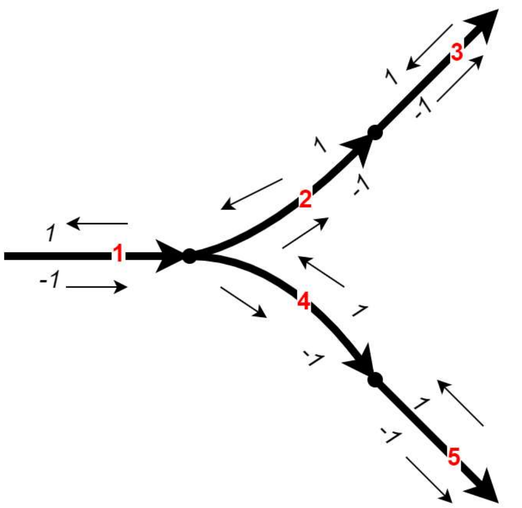
Table 4. Topology table for Fig.3a

as well as

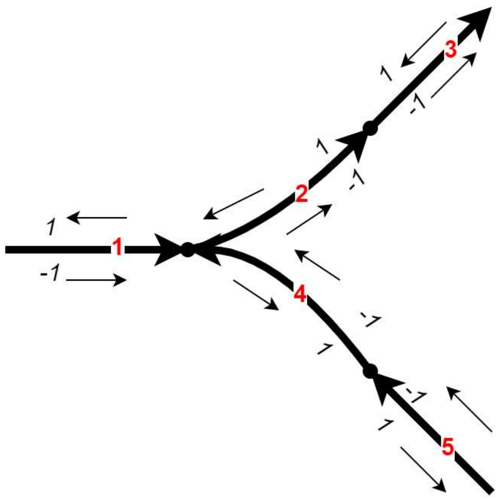
		Predecessor		Successor	
Road ID	Lane ID	Road ID	Lane ID	Road ID	Lane ID
1	1	2	-1	–	–
1	-1	–	–	2	1
2	1	1	-1	3	-1
2	-1	3	1	1	1
3	1	–	–	2	-1
3	-1	2	1	–	–

Table 5. Topology table for Fig. 3b

It is clear to see that with these simple connections, an unambiguous correspondence can be established between roads and lanes. The two tables above can also be understood as indicating that the possible regular connections can only be given by these cases.
Each lane of each road (in this case both lanes) occurs only once in the topological tables.
The cases of branching and merging are illustrated by the following examples (Fig. 4).



a) splitting road connections



b) merging (and splitting) connections
Figure 4. Splitting and merging connection cases

The corresponding topological tables for the two examples are:

		Predecessor		Successor	
Road ID	Lane ID	Road ID	Lane ID	Road ID	Lane ID
1	1	2	1	–	–
1	-1	–	–	2	-1
1	1	4	1	–	–
1	-1	–	–	4	-1
2	1	3	1	1	1
2	-1	1	-1	3	-1
3	1	–	–	2	1
3	-1	2	-1	–	–
4	1	5	1	1	1
4	-1	1	-1	5	-1
5	1	–	–	4	1
5	-1	4	-1	–	–

Table 6. Topology for Fig. 4a

and the second example

		Predecessor		Successor	
Road ID	Lane ID	Road ID	Lane ID	Road ID	Lane ID
1	1	2	1	–	–
1	-1	–	–	2	-1
1	1	4	-1	–	–
1	-1	–	–	4	1
2	1	3	1	1	1
2	-1	1	-1	3	-1
3	1	–	–	2	1
3	-1	2	-1	–	–
4	1	1	-1	5	1
4	-1	5	-1	1	1
5	1	4	1	–	–
5	-1	–	–	4	-1

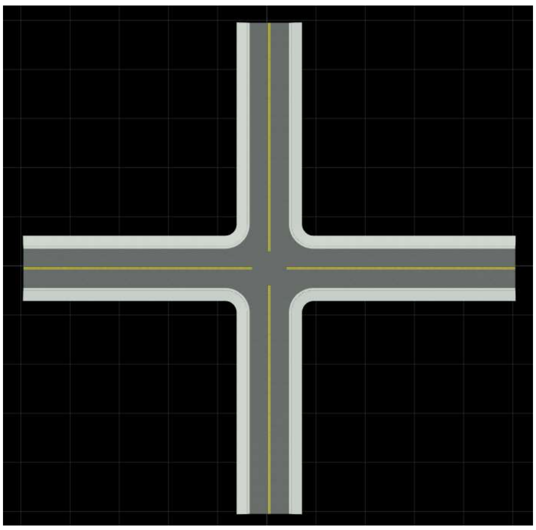
Table 7. Topology for Fig. 4b

By definition, the lanes of merging and splitting roads identify several connecting lanes (and thus roads) as adjacent elements. This is reflected in the tables by having several rows of the same road-lane pair. In the example above, the number of rows of road #1 has just doubled - this shows the fact of a split or merge. The standard therefore requires this road to be included in a junction and treated as its road.

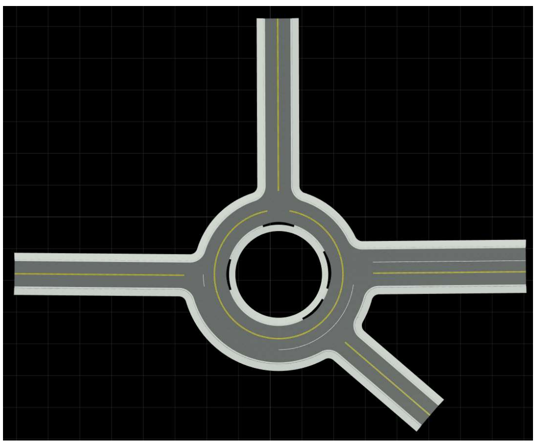
To investigate more complex configurations of similar branching and merging, we therefore manually created four sample cases using Mathworks' RoadRunner software. Sample cases cover one simple, one difficult and two intermediate variants respectively (Fig. 5).

For the sample cases, we have written an analysis procedure in MATLAB to generate and study the contents of the topological tables presented earlier. (MathWorks, n.d.)

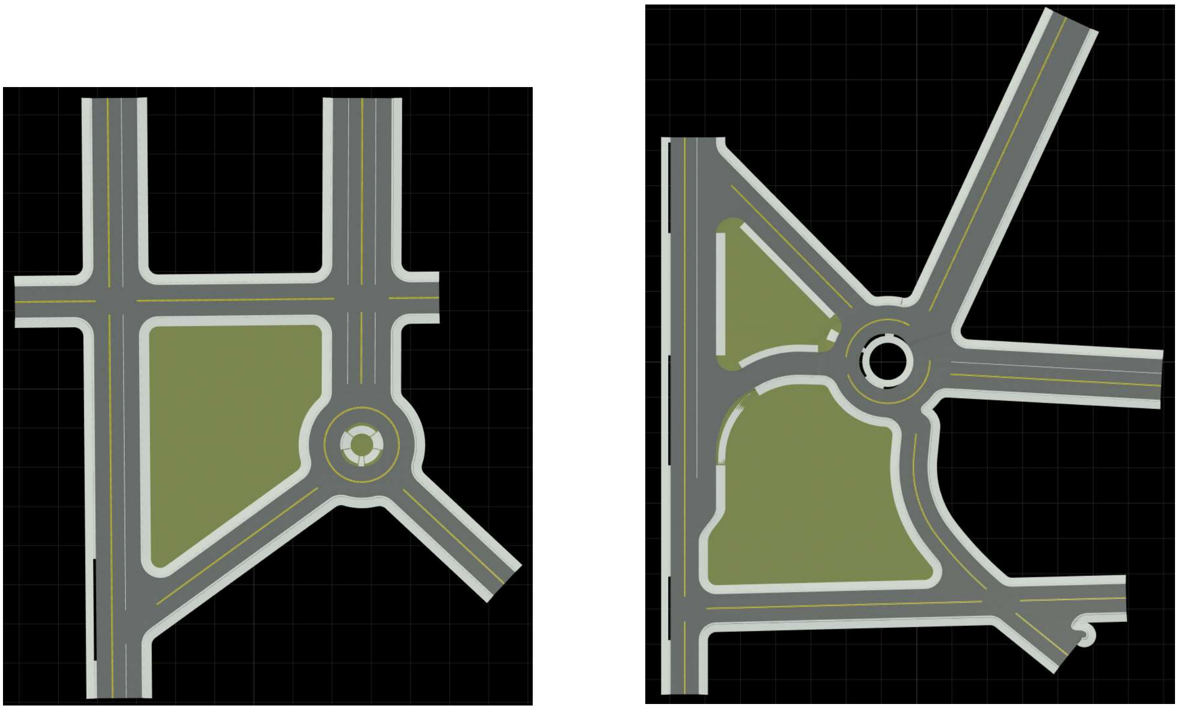
The main statistics obtained from the analysis are presented in Table 8.



a) Case 1



b) Case 2



c) Case 3 d) Case 4

Figure 5. Sample synthetic cases

	Case 1	Case 2	Case 3	Case 4
Number of roads	20	41	80	83
Number of lanes	56	131	243	258
Number of junctions	24	55	108	117
Required memory [kB]	168	428	831	1003
Number of lines	2015	4950	9899	11053
Topology status	OK	successor overlap error 1×	predecessor overlap error 2× successor overlap 1×	predecessor overlap error 1×

Table 8. Statistics for the samples
(Number of lines are counted in the XML model)

One of the quickest ways to interpret the tabular results obtained with the analysis routines is to visualize them. To this end, we have derived adjacency, incidence and edge-edge tables from the derivation of the road, lane and junction topology tables. The contents of the tables were populated by checking for topological inconsistencies by running the rules and flagging problematic locations. Fig. 6 shows the derived edge-edge table of the second intermediate example, which sheds light on two anomalies in the predecessors and one in the successors.
By identifying the anomalous cell in the derived table, the roads and lanes of the link affected by the fault can be identified.

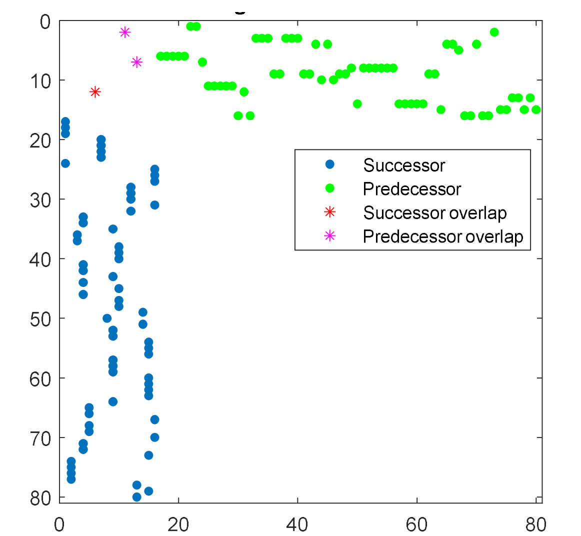


Figure 6. Edge-edge table visualization to detect predecessor and successor errors

5. CONCLUSION

The development of self-driving vehicles can be effectively supported by computer simulations. However, in order for the excellent simulations, the input data must be of the right quality. A common requirement in vehicle simulations is the need to provide map data. These maps can be purely synthetic or accurate realistic maps. A synthetic map is characterized by the description of the geometry designed for testing purposes, which includes roads, lanes with the appropriate pavement material and other additional features. Realistic maps, on the other hand, are the result of a survey and careful evaluation of the terrain. In both cases, various vehicles and other road users (e.g., pedestrians, cyclists, motorcyclists, wildlife, etc.) are added to the model and the behavior and accuracy of the vehicle's sensors, assistants, and control are studied.

As simulations have become more widespread, it has become clear that, in addition to geometric fidelity, the accuracy of the connections between elements, i.e., the quality of the links between road network elements, is essential. If a connection of successive road elements is incorrect, for example because the wrong element is referenced, the simulation will not run and may result incorrect outputs.

To avoid this problem, models should be subjected to checks. In our research, we have already considered the geometric properties to be adequate and verified, and focused on the topological relations.

Topology, according to recent experience in geoinformatics, consists of rules, a collection of rules. With this approach, we studied previous methods of network analysis and description, and then created rules in mathematical formulas. These rules open up the possibility of verifying the information about the topology by numerical algorithms and, where appropriate, identifying the error. It is essential to underline that in the simulations we treat not only roads but also their lanes. This implies a significant increase in the amount of data compared to traditional road network models, and an automated testing solution is needed. In our study we report the first results of this development. Naturally, as a continuation of this work, we intend to apply the method to real survey datasets and to develop a procedure for the identification and later automatic correction of specific topological inconsistencies.

The results are presented in OpenDRIVE models used in the simulation world. However, this can be extended to the huge amount of data currently available for all map formats, in particular for HD map formats. Topological relations in these formats are also important issues. Thus, in order to generalize the methodology, the storage model specificities need to be homogenized and addressed by developing a single interface that works in the same way. The content of any map database can then be examined.

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