Model-based Database Generation for Traffic Management Systems

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***Abstract*— Traffic Management Systems (TMSs) are essential for optimal utilization and safety of highway infrastructure. They consist of a network of Matrix Signal Indicators (MSIs) that inform road users about adjusted traffic situations. To control this MSI network, a TMS consults a database describing its layout. The database requires an update every time this layout changes. To improve the adaptability of the database, this paper investigates how to obtain a database from highway topology data. In the proposed method, the database is represented by two models, related to the highway topology and the MSI network. A method to derive these models from highway topology data is presented and elaborated as a proof-of-concept tool. Two practical case studies with Rijkswaterstaat (RWS) demonstrate the method's maturity and its utility in testing TMS control for future highway topologies.**

I. Introduction

The application of Traffic Management Systems (TMSs) is shown in [1] to be essential for the optimal utilization and safety of highways. This is supported by various analyses. For example, a study in [2] on the I-66 highway in Virginia, USA, shows that TMSs contribute to a reduction in travel time of up to 15% and a 31% reduction in the number of accidents. Similarly, an investigation in [3] concludes that the general application of TMSs in the Netherlands has led to 15% to 20% less congestion and a reduction in the number of accidents by more than 25%. A safety review in [4] on the M42 highway in the UK even reports that TMS application halved the average number of accidents per month.

The TMSs considered in these studies use an on-site network of illuminated electronic displays called Matrix Signal Indicators (MSIs). As shown in Fig. 1, MSIs show legends to road users, such as speed legends, arrow legends, and cross legends. These legends inform road users of an exceptional traffic situation, such as highway maintenance or an accident, enabling them to respond in a safe manner.

An algorithm in the TMS controls legend patterns based on predetermined rules. To avoid unsafe guiding of road users, the algorithm must be informed of the highway topology. For example, an arrow legend must never guide road users off the asphalt. Highway topology information is required to determine when an arrow is pointing away from the asphalt.

In addition, legends must convey a consistent message. For example, an arrow legend must never point towards a lane where a cross legend is displayed; indeed, this combination of legends provides contradictory information that confuses the road user. The algorithm therefore also requires information on the relations between MSIs in the network.

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Fig. 1. A British highway equipped with 4 MSIs, where the left lane is closed and a temporary speed limit of 50 miles per hour is indicated on the other lanes. Image source: [5].

Thus, to safely control legend patterns, the algorithm consults a database containing highway topology information and MSI network properties. This also means that this database needs to be constantly updated whenever the highway topology or the MSI network changes. This constant maintenance of a TMS database is a challenge in adaptability and knowledge management, presenting an opportunity for model-based methods to be applied.

This paper investigates how to obtain the database of an MSI-based TMS from highway topology data. The proposed method uses two models to represent the database: one for the highway topology and another for the MSI network. The MSI network model is adapted to the TMS used by Rijkswaterstaat (RWS), the executive agency of the Dutch Ministry of Infrastructure and Water Management. A method to derive both models from highway topology data is presented and elaborated as a proof-of-concept tool. To test the method in practice, two case studies are conducted with RWS. One case study demonstrates the maturity of the method, the other its utility in testing TMS control for future highway topologies.

This paper is structured as follows. A general description of TMSs and previous work in modeling TMS components is given in Section II. A model of highway topologies is presented in Section III. A model of MSI networks and its relation to the highway model is presented in Section IV. A proof-of-concept tool is briefly described in Section V. Two practical case studies are described in Sections VI and VII. Finally, concluding remarks are given in Section VIII.

II. System description

In [6], TMSs are categorized as infrastructure-based or infrastructure-free. This paper considers infrastructure-based TMSs, consisting of an on-site network of sensors and actuators. An overview of such a TMS is shown in Fig. 2.

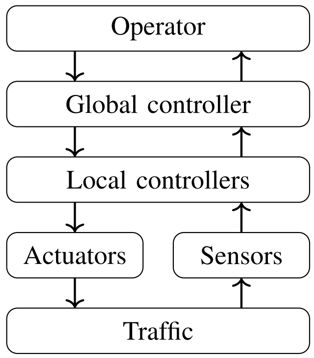

Fig. 2. Overview of an infrastructure-based TMS.

A. Local control

The goal of a TMS is to increase highway utilization and traffic safety. To this end, it interacts with traffic using sensors and actuators. The TMS's sensors are detector loops in the asphalt that measure the speed of vehicles. Its actuators are MSIs. These communicate adjusted traffic situations with the road user by displaying various legends. For example, lane closures are indicated with arrow and cross legends.

Local controllers interact with these sensors and actuators. Sensor values are used to calculate the speed and density of traffic. When the traffic density is high or the traffic speed is low, variable speed limits are activated: nearby MSIs are instructed to display speed legends, lowering the local speed limit.

B. Global control

A global controller receives the current state of the local controllers: the sensor values and legends that are currently shown on the MSIs. This is visualized for the system operator. In the event of an accident, the operator intervenes by making a legend request. The global controller then generates a legend pattern that safely introduces the requested legends. This process makes use of an algorithm and a database.

The algorithm processes a legend request in a few steps. Generally, it iteratively adds cross and arrow legends upstream of the closure so that traffic is safely guided away from the closed lanes. Then, it adds speed legends on adjacent lanes and end-of-restriction legends downstream of the last restricting legend.

To achieve clear communication with road users, legend patterns must adhere to a set of predetermined rules. A database is consulted to determine the applicable rules. This database stores various attributes of the highway, such as the number of lanes and the presence of a hard shoulder or variable access lane. The database also contains MSI relations that describe how each MSI is positioned with respect to another. MSI relations are used to prevent adjacent or consecutive legends from contradicting each other.

The generated legend pattern is shown to the operator for review. Once approved, the pattern is sent to the local controllers. As a safety feature, the local controllers check whether the pattern does not violate any rules locally. When this check passes, the legends are displayed on the MSIs, and traffic responds to the adjusted situation.

C. Models of a TMS

In recent years, formal models of RWS's TMS have been developed with the aim of standardization. In [7] and [8], the components of local controllers are modeled and a configurator is developed. In [9], formal descriptions of legend placement rules are introduced, turning the algorithm of the global controller into an optimization problem: legend pattern calculation. These formal descriptions are concise, clearly interpretable, and easy to adjust. This is an improvement over the original hard-coded algorithm.

This paper covers the database of the global controller. It is represented by two models: a highway model and an MSI network model. A method is presented to derive these models from highway topology data. The resulting models are compared with the existing TMS database, and they are used for legend pattern calculation as described in [9].

III. Highway model

This section discusses a formal model of highways. This model is constructed in such a way that it contains all highway topology data required for the MSI network model. To illustrate the models, a representative example topology of a highway equipped with MSIs is shown in Fig. 3.

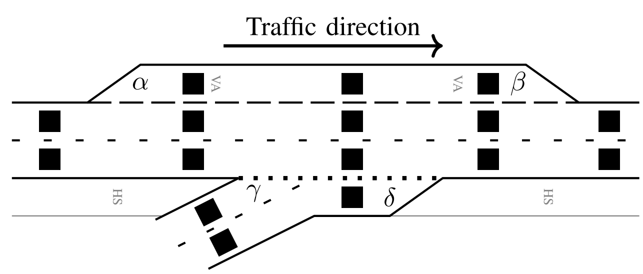

Fig. 3. A fictional example highway topology with MSIs (the black boxes).

A. Highway structure

Highways consist of asphalt surfaces divided into lanes. Each lane is designed to accommodate a single line of motor vehicles. The lanes converge and diverge, forming a network of straight sections and junctions. A convergence is depicted near γ in Fig. 3.

Adjacent lanes that share the same destination or origin are grouped into carriageways. As a result, there are often two carriageways before a divergence or after a convergence. In Fig. 3, the carriageways are separated by dotted lane markings. Carriageways are added to the highway model because they affect the placement of speed legends.

Along the length of the highway, new lanes can start or end. Lane broadening occurs when a lane is added on the left or right side, such as at α in Fig. 3. Lane merging occurs when traffic on a lane has to merge into an adjacent lane. If one of the middle lanes merges, this is called a taper. Fig. 3 features lane merging at β and δ and a taper at γ.

To complete the description, two lane types are described that have a special interaction with MSIs. The first is the variable access lane (VA lane), which is the leftmost lane in Fig. 3 (between α and β). This type of lane is made accessible by MSIs, mainly during rush hour. The second is the hard shoulder (HS), which appears on the right side of the highway in Fig. 3. Hard shoulders are the extra widths of asphalt on either side of the highway, used primarily for emergencies. In case of highway maintenance, it is possible that traffic is guided onto the hard shoulder by MSIs.

B. Directed graphs

In the literature, highway topologies are commonly modeled using directed graphs. The directed graph in [10], for example, uses nodes to model junctions and edges to model straight sections. However, this graph model leaves out most of the lane information that is necessary to derive MSI control. Thus, a more detailed graph model is required.

Three abstraction levels for highway graph models are distinguished in [11]: the planning level, the instruction level, and the driving level. The directed graph in [10] is an example of the planning level, which is most suitable for route planning. The instruction level provides more detail on the structure of junctions, making it suitable for providing driving instructions.

The driving level preserves the most detail and is the most suitable for the purpose of this paper. Its edges follow the shape of the highway in the direction of travel. Each edge represents a single lane configuration: a description of adjacent lanes that are constant on that edge. Transitions in lane configurations are represented by nodes. These connect the edges, forming a graph model. This model structure is capable of capturing the highway topology data that is necessary to derive the MSI network model.

C. Model attributes

The highway topology of Fig. 3 is described using nodes and edges in Fig. 4. The lane numbers are provided for reference, arranged from left to right from the driver's perspective. At each transition in the lane composition, indicated with a vertical dashed line, a node is placed that separates the edge before and after the transition. The highway model edges store the following attributes:

- The *number of lanes*, excluding any hard shoulder, indicated by a single number.
- *Carriageways*, indicated by the number of lanes per carriageway, from left to right.
- *Broadening* or *merging* of lanes, indicated by the lane number and the direction of merging or broadening (left or right). In the example, edges d, f, and h each have a distinct type of lane merging. The different types are distinguished in Section IV.
- *VA lanes*, indicated by their lane number. In the example, lane 1 of edges b to h is a VA lane.
- The position of *hard shoulders*, indicated by a direction: left, right, both, or neither. The example only features a hard shoulder on the right side.

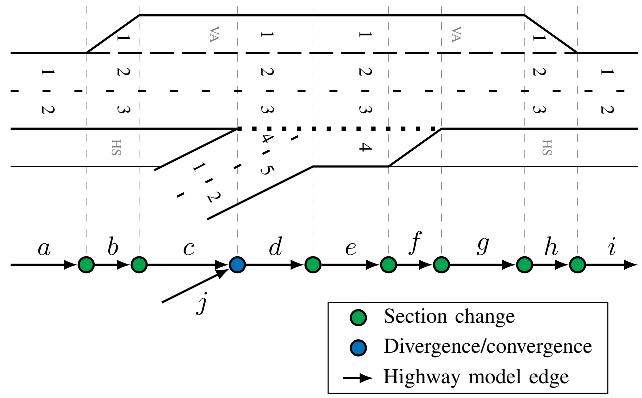

Fig. 4. The highway in Fig. 3, split up and represented by a directed graph.

TABLE I
EDGE DATA OF THE HIGHWAY MODEL EXAMPLE IN FIG. 4.

Edge letter	a	b	c	d	e	f	g	h	i	j
# Lanes	2	3	3	5	4	4	3	3	2	2
Carriageways	-	-	-	3/2	3/1	3/1	-	-	-	-
Broadening	-	1L	-	-	-	-	-	-	-	-
Merging	-	-	-	4L	-	4L	-	1R	-	-
VA lanes	-	1	1	1	1	1	1	1	-	-
Hard shoulder	R	R	R	-	-	R	R	R	R	-

Table I shows the data for each edge of the graph model displayed in Fig. 4. Additional attributes, such as maximum speed, are also relevant for MSI control. They are stored in a similar way. For brevity, these attributes are left out of the examples in this paper.

IV. MSI NETWORK MODEL

The algorithm of the global controller consults a database to determine legend patterns. The MSI network model is meant to provide the MSI data for this database. It contains properties of MSIs and MSI relations. Both are derived directly from the highway model.

A. MSI nodes

MSIs are usually placed in rows, where each MSI corresponds to one lane. An example of this is shown in Fig. 1. In the MSI network model, a row of adjacent MSIs is captured as a single MSI node. This is similar to how adjacent highway lanes are captured with a single edge. Each MSI node inherits all properties from its respective highway model edge. The MSI nodes therefore store the number of lanes, carriageway division, etc. This data is used to derive properties of individual MSIs, such as which carriageway they are part of or whether they are next to a hard shoulder.

In Fig. 5, the six MSI rows are represented by one node each (A to F). Each node is positioned on an edge of the highway model. From every MSI node, all upstream and downstream MSI nodes are found by traversing the highway model in both directions. At a divergence or convergence, all edges in the same direction are explored further. In the example in Fig. 5, MSI node C has two upstream MSI nodes (B and F) and one downstream MSI node (D).

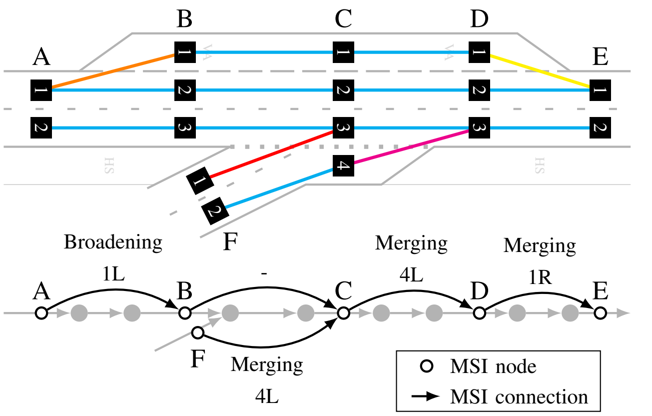

Fig. 5. MSI network model and MSI relations of the highway in Fig. 3.

B. MSI relations

To prepare for the case studies with Rijkswaterstaat (RWS) in Sections VI and VII, this section adopts RWS's implementation of MSI relations. Their configuration management documentation, given in [12], defines five types of MSI relations: primary, secondary, broadening, narrowing, and tapering relations. Each relation type has a distinct influence on legend placement. Table II briefly describes each relation type. Each type appears at least once in the example in Fig. 5.

TABLE II
MSI RELATION TYPES AND GENERAL PLACEMENT CONDITIONS.

Relation type	**Placement conditions**
Primary	An uninterrupted lane.
Secondary	Situation where road users likely change carriageway, or where an MSI has no other upstream relation.
Broadening	Broadening on an outer lane (same carriageway).
Narrowing	Merging on an outer lane (same carriageway).
Tapering	Merging on a middle lane (different carriageways).

To determine which MSI relations apply between two MSI nodes, the edges of the highway model that connect the two MSI nodes are considered. For example, between MSI nodes A and B, a lane broadening occurs on lane 1 (1L of edge *b*). For easier reference, this is also indicated in Fig. 5. Following the placement conditions in Table II, a broadening relation is added between the MSIs before and after the broadening. Primary relations are placed between MSIs connected by an uninterrupted lane. This does not mean that the relation is always placed between the same lane numbers: here, MSI A1 has a primary relation with MSI B2, because the lane numbering changes between MSI nodes A and B.

The three instances of merging require different relation types. First, between MSI nodes F and C there is a merging on one of the middle lanes, between different carriageways. As a result, a tapering relation is placed between the MSI before and after the taper. Second, the merging between MSI nodes C and D occurs on the outer lane, between two carriageways. Because it is likely that the road user will change between carriageways, a secondary relation is placed here. Last, between MSI nodes D and E there is a merging on the leftmost lane, within the same carriageway. This matches the placement condition for a narrowing relation.

The example in Fig. 5 shows the most prevalent scenarios in which each type of MSI relation is placed; exceptional cases are left out. The full scope of the placement conditions for various highway topologies is given in [12] and [13].

V. Tool

The method is elaborated as a proof-of-concept tool.[1] Its development and validation are described in [13].

A. Data source

The highway model is easily integrated with OpenStreetMap's highway topology data, which are found in [14]. This global source is managed by the public and is freely available under the Open Database License. The OpenStreetMap data structure converts well to the highway model data structure presented in Table I.

The tool takes MSI position data from the Dutch source "WEGGEG", documented in [15]. Although similar sources exist in other countries, it is straightforward to manually mark MSI node locations using software such as QGIS [16].

B. Format conversion

Based on a user-defined area selection, a portion of the highway topology data is imported into the tool. The highway model and the MSI network model are derived in seconds. In addition, the tool generates three output files:

- A file containing all MSI relations in a plain format: `[name] [relation type] [name]`. This allows for automated comparison with the TMS database, from which it is possible to obtain the same plain format.
- A file containing MSI network properties, serving as input for the legend pattern calculation from [9].
- A visualization file of the selected highway, see Fig. 6. MSIs are displayed on the side for better readability.

C. Validation

Part of RWS's TMS database is made available for tool validation. It includes three Dutch junctions: *Goirle*, *Vught*, and *Bavel*. For these junctions, all MSI relations in the TMS database are correctly derived. At *Bavel*, three additional MSI relations are derived that turned out to be missing from the TMS database. RWS has since added these MSI relations.

[1]The proof-of-concept tool is available at `https://github.com/Marijn3/Road-Model-code`.

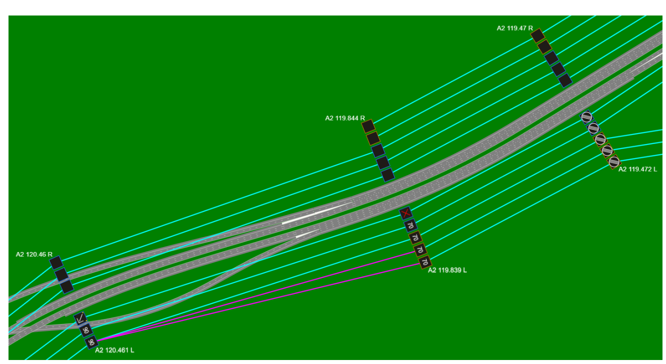

Fig. 6. A legend pattern on display in the generated visualization.

VI. Case study 1: A2 highway

The purpose of the first case study is to show the applicability of the method to a large real-world highway topology. The chosen topology is a section of the Dutch A2 highway that spans 18 kilometers. A lane will be added to this section, as described in [17]. This makes it relevant for RWS to be able to obtain a TMS database for this area.

A. Topology data import

The initial import of the highway topology data in this area reveals an inconsistency in the source: one edge occurs twice, with different data. The tool correctly indicates the inconsistency, but is unable to resolve it. Generally, inconsistent data can be detected, but not automatically resolved.

After manually resolving the inconsistency using QGIS, all data are fully automatically imported and processed in under 6 seconds, including the generation of the three output files. The highway model consists of 179 edges. The derived MSI network model consists of 232 MSIs and 225 MSI relations.

B. MSI relation comparison

An automated comparison between the derived MSI relations and the 226 MSI relations in the operationally used TMS database identifies 224 matches. Non-matching MSI relations are found in two instances. These two instances are further inspected.

In the first instance, the relation itself is correctly derived; however, the TMS database deviates from the naming convention for one of the MSIs. The MSI is named after a diverging road instead of the main highway. As a result, it is impossible to compare its relations automatically. This naming difference seems to present itself sometimes when an MSI is positioned very close to a divergence. Because the relation itself is derived correctly, no changes are required in the method.

In the second instance, a secondary relation in the TMS database is not automatically derived. The relation seems to be placed due to a transition from an on-ramp to a VA lane, as shown in Fig. 7 between MSI A2 and MSI B3.

This situation is not covered by the placement conditions for secondary MSI relations as given in Table II, perhaps indicating that the conditions need to be adapted. However, even after consulting with the RWS TMS operators, no justification is found for this secondary relation. In fact, the relation is considered obsolete and will be removed from the TMS database in a future update. Therefore, no changes are required to the placement conditions for MSI relations.

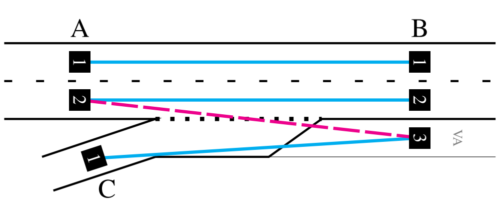

Fig. 7. The situation with a secondary relation in the TMS database.

C. Takeaways

The case study for the A2VK area has shown the maturity of the method: MSI relations have been correctly derived for a large real-world highway topology. The non-matching MSI relations are found to be the result of minor inconsistencies in the operational TMS.

In addition, an inconsistency is revealed in the highway topology data. This highlights the potential of the method for source comparison. The ability to cross-compare one source with another improves the quality of both sources.

Of course, this case study is not representative of all highway topologies around the world. More broad and diverse case studies are required to determine the global applicability of the method.

VII. Case study 2: Amstel junction

The purpose of the second case study is to investigate the utility of the method as part of the development of TMSs for future highway topologies. The chosen topology is the "Amstel" junction between the A2 and A10 highways, located south of Amsterdam. As described in [18], RWS is preparing to adjust the highway topology at this location to improve traffic flow. As a result, the MSI network will also change. In this case study, the difficulty and time investment in creating a future topology will be weighed against the potential insights provided by the analysis of the future TMS.

A. Data creation

To start, a project expert has to manually create data describing the future highway topology. In this process, it is found that the strictness of the data structure poses a challenge. For example, it is easy to forget to propagate changes that affect multiple edges, resulting in inconsistencies. However, with the help of feedback provided by the tool, inconsistencies are located and resolved.

After about eight hours of work, the manually created data for the future highway topology are usable for constructing a highway model. The MSI network model is automatically derived and manually checked for correctness. Combining this result with the work in [9], it is then possible to calculate legend patterns for the future highway topology.

B. Analysis of a critical situation

The Amstel project team has identified a potentially critical situation in the future MSI network. One of the lanes on the junction, connecting one highway with another, might become completely closed off when a lane closure is requested somewhere downstream. The situation is shown in Fig. 8, where the critical lane portion is highlighted. Specifically, their concern is that requesting a cross legend on MSI F1 also causes a cross legend on MSI B4. That would block the flow of traffic from A to G, which is undesirable. The team considers installing an additional MSI between rows E and F to prevent this situation from occurring.

However, the legend pattern calculated for this request shows that this situation is not critical. As visualized in Fig. 8, an arrow legend is placed on MSI B4—instead of

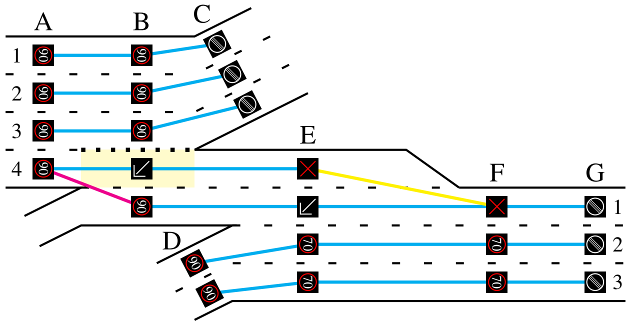

Fig. 8. A portion of a future highway topology at the Amstel junction, with a legend pattern that has been calculated for it.

a cross legend—which is considered acceptable. In other words, the upstream effects of the red cross request at MSI F1 are less severe than expected. These results enabled the team to decide that the additional MSI is unnecessary.

C. Takeaways

The strictness of data structures poses a challenge during manual data creation. This is a human factor that cannot be fully prevented. Therefore, effective feedback on data inconsistencies is necessary for the manual creation of highway topology data.

Approximately eight hours are required to set up the data. This is relatively little on the scale of highway renewal projects. Even so, the expectation is that the time investment can be reduced by employing a more streamlined process.

The model-based analysis of TMSs for future highway topologies has been beneficial for RWS: the time cost for data creation is minor compared to the resulting monetary savings. In addition, the method has proven to be useful in supporting discussions with system experts.

VIII. Conclusions

In this paper, a method is proposed to obtain a TMS database from highway topology data. First, the database is represented by a highway model and an MSI network model. Next, these models are derived from highway topology data using a proof-of-concept tool. The models are then compared with the operational TMS database and used for legend pattern calculation. Finally, the method is successfully applied in two practical case studies that show the method's utility in real industry scenarios. The models, method, and tools presented in this paper contribute to further advances in the adaptability and control of TMSs.

The general applicability of the method naturally depends on the similarity of highways and TMSs to the models presented in this paper. For highways, efforts have been made to ensure general applicability. This shows in its compatibility with OpenStreetMap, which is a global source. In contrast, the MSI relations in the MSI network model are specifically adapted to the TMS used by RWS, as mentioned in Section IV. The structure of both the highway model and the MSI network model is expected to be flexible enough to allow any required adaptations to suit other TMSs.

RWS is considering adopting the method for future highway renovation projects. An example is the A9 highway near Amsterdam, where a reversible lane will be introduced in the future. This lane uses MSIs to indicate a change in traffic direction, accommodating traffic intensity patterns. The applicability of the highway model to a topology with reversible lanes is a subject of further research.

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