Exploring traffic jams of the future highways

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***Abstract*—The traditional highway management misses the opportunity to act-before-you-see action technique due to insufficient data collection and exchange. The emergence of crowd-sourced data, along with robust data collection, exchange and fusion engines opens the door to investigate the traffic jams on the highways in a broader context. The traffic jams have a dual nature: caused by events or caused by driving behaviours. The introduction of traffic model-based software products improves traffic operators' understanding of predicted traffic conditions during event-based jams and the ITS based traffic management tools can be evaluated on network level as well. However, driving behaviour-based jams and their associated impact curves heavily rely on human drivers' characteristics, which are expected to be gradually replaced as autonomous driving technology advances. The paper presents the current best practice in Hungary but shows an outlook to the probable change in terms of ITS intervention techniques.**

Keywords—component; operational decisions, centralized traffic management; traffic disruption; crowd-sourced traffic and incident data; traffic forecasting; national road; traffic model; decision support; distributed IT system

I. Introduction

Intelligent Transport Systems (ITS) are essential tools to meet environmental and sustainability goals. The field of ITS has also undergone radical change since the turn of the millennium, with advances in technology and communications. One of the main drivers of change is the emergence of collaborative, connected and self-driving cars, which poses new challenges for road managers.[1] This has been accompanied by the emergence of experimental systems that enable communication between vehicles and infrastructure, and the growing role of digital infrastructure alongside the physical, which in effect means that static and dynamic information is available digitally to an autonomous vehicle.[2] Of course, there may be levels of this, for example, the infrastructure may be able to detect microscopic disturbances in a real-time digital twin by continuously tracking vehicles, and even intervene to ensure the smooth flow of traffic.[3]

The gradually expanding automated guidance on the side of the vehicles, based on the fusion of sensor data from driver assistance systems, will also only be able to flourish in cooperation with the infrastructure. The efficiency of traffic management optimised for a specific area or road section will be further enhanced by autonomous vehicles. Traffic management is based on a traffic model that realistically describes network processes. The model and the analyses based on it can analyses processes, predict critical traffic conditions in the short term and anticipate the impact of interventions based on real-time roadside and vehicle sensor data. In line with this, the final, third phase of the CROCODILE project focused on the development of a centralized traffic management concept, one of the main outputs of which were static and dynamic traffic models for the national core network.

II. Background

Hungary has made significant progress in the field of intelligent transport systems. It was one of the first in Europe to complete the first C-ITS vehicle-to-infrastructure communication pilot on the M1 motorway as part of the CROCODILE project. This was followed in 2019-2020 by the first phase of the C-ROADS project, the Győr city pilot. (At around the same time, a C-ITS pilot was also carried out in Budapest on the M1-M7 feeder section and at a junction on Hungária körút.) Preparations are also underway for the implementation of a test section of almost 1 km on the M1-M7 motorway in the Budaörs area, where ADAS systems, self-driving and vehicle-infrastructure (and central traffic control) interoperability can be tested.

Between 2013 and 2022, the three phases of the CROCODILE project were decisive in the development and renewal of domestic traffic management systems. The project, which is also of major importance at regional level, built on decades of regional cooperation, continuing the joint work started in the CONNECT and Easyway projects. CROCODILE (Cooperation of Road Operators for COnsistent and Dynamic Information Level) is one of several EU corridor projects that provide regional cooperation between countries along a major European transport corridor, with the aim of creating coordinated, continuous services along the corridors. The CROCODILE corridors (Figure 1) concern countries in Central and South-Eastern Europe and, although several countries dropped out of the project by the final phase, 7 of the member countries have persisted until Crocodile Phase 3.

Fig. 1. Crocodile Corridors [4]

The work programme of the CROCODILE project focuses on the exchange of data and information between countries, in addition to the improvements made locally, in order to establish coordinated cross-border traffic information services along European corridors, in line with Directive 2010/40/EU of the European Parliament and of the Council (on the framework for the deployment of Intelligent Transport Systems in the field of road transport and for interfaces with other transport modes).

During the first and second phases of CROCODILE (2013-2019), in addition to the deployment of standard monitoring and traffic management tools, new services were introduced and pilot facilities were expanded [4], with the following main objectives of the work programme:

- Cooperation and data exchange with neighbouring countries;
- Improving the quality and availability of traffic data, automatic data exchange (DATEX nodes and implementation of the National Data Access Point);
- Improving traffic safety, and in particular the safety of working areas (Cooperative-ITS pilot project);
- Modernisation/extension of services for road users: traffic information, intelligent truck parking (parking management system).

The third phase, which ended in 2022, focused on traffic management and deepening cross-border cooperation, rather than on the field equipment, and continued the implementation and development of DATEX data exchange nodes. The work programme paid special attention to the preparation of a new National Traffic Management Centre. Traffic management on the national road network is decentralized, with minimal coordination, although the conditions for centralized supervision are largely in place. This is supported by a number of national IT systems, such as the Signal Light Remote Monitoring System, the Traffic Information System (FIR) and the Dispatcher System (DIS), which collects and transmits recorded events. The long-term objective is to create a hierarchical structure at two levels (regional and national). These levels would also correspond to the severity of the incident, but in principle regional centres would be responsible for day-to-day routine and limited impact incidents [5]. The national centre would coordinate incidents with regional or cross-border impact. The main tasks of the national centre are:

- Supervision and coordination of regional centres - including cooperation with concession companies;
- Liaising with partner organisations and authorities;
- Implementation of incident management and network traffic management measures;
- Implement cross-border traffic management measures.

In addition to establishing a second level of coordination, an important objective is to integrate as many external data sources as possible (e.g. fleet data) and to move traffic management from the current reactive to proactive intervention. This requires the use of traffic forecasting models, which are already used in many countries around the world. In line with this, a national dynamic traffic simulation model has been developed as part of the preparation of the national centre. The dynamic model provides information in near real time on the current traffic situation and future traffic evolution (forecasted at least 30 minutes ahead), thus supporting the work of the Hungarian Road Traffic Management experts. The framework installed together with the model, in addition to the visual display of the current traffic conditions, allows the monitoring and detailed evaluation of changes in various traffic indicators. The dynamic traffic simulation model allows users to make short-term forecasts of the expected impact of traffic disruptions on the network or of different traffic interventions. The macroscopic traffic model and the dynamic traffic simulation model mainly consider the elements of the national core network (motorway network and trunk road network), with a special focus on the elements of the TEN-T road core network.

III. Traffic Management

The traffic management centre is an essential element of traffic management and the starting point. This is where the decision is taken on what response or intervention is needed to deal with a given incident or traffic disruption. In the control centre, predefined strategies/scenarios are developed for the section and the control system, and the control is carried out along these strategies/scenarios. [6] Scenarios are a sequence of predefined process steps and controls activated automatically by predefined inputs or by operator initiative. The main functions are the complex support of traffic management and information tasks based on a predefined set of rules. Scenarios allow the operator to choose from automatically offered scenarios that are best suited to the current situation (location + situation), with the possibility of modification in some cases, instead of having to make complex decisions based on elementary information and data. The scenarios thus basically contain actions, which may be notification tasks, traffic management interventions (such as activation of a VJT signal image, modification of a traffic light programme, activation of a C-ITS broadcast message or alternative route recommendation/deployment or activation of a Traffic Management Plan (TMP)). The same scenarios created for those events may vary depending on the location and time period. Of course, for a more complex, dynamic control system where several possible traffic management services are available, or for a more complex e.g. urban road network, the role of the traffic model becomes more important. The traffic management services defined in the Reference Handbook for harmonized ITS Core Service Deployment in Europe [8], which replaces the European Easyway deployment guideline, are:

- Dynamic Lane Management
- Variable Speed Limits
- Ramp metering
- Hard Shoulder Running
- HGV overtaking ban
- Incident Warning and Management
- Traffic Management for Corridors and Networks

The above services can be considered as complex strategies/scenarios for dynamic traffic management systems.

A. *Dynamic traffic information and management systems*

Traffic management systems are usually grouped according to their coverage. At the highest level are network control systems, below these are line and point control systems. [9]

Network control allows for the optimal distribution of traffic and thus the best possible use of available capacity on a given road network. The objectives of network control systems are:

- relieving congested road sections by designating an alternative route or mode of transport,
- reducing the number and impact of traffic congestion/disturbances,
- reducing time losses,
- better use of network capacity, more evenly distributing the load.

Line control concentrated on a specific road section helps traffic flow smoothly and increases traffic safety. It does this by intervening with variable message signs (VJTs) on the road section, providing information, signals and instructions at the right place and at the right time, according to the current traffic and environmental situation. Line systems can perform the following main tasks/functions:

- temporary/periodic traffic management (speed control, overtaking, dynamic lane use),
- warning of dangerous traffic situations (congestion, accidents, road works, official controls),
- warning of unexpected weather conditions (hazards) (fog, rain, snow, gusts of wind, slippery - wet, snowy, icy - road surfaces).

Point-based regulation is used to address some local anomaly or hazard. It usually works in an isolated way, not as part of an overall regulatory system. It can be used in accident hotspots, local microclimatic conditions where other measures are not possible or ineffective, such as strong crosswind warning systems on long bridges, congestion warning systems in bottleneck areas, or systems to reduce environmental pollution (noise and air pollution). Specific forms of point control are control systems in the vicinity of junctions, which can operate in the vicinity of the exit or the entry. The best known example of the latter is ramp metering.

B. *Traffic Management for Corridors and Networks*

Traffic management services include traffic management of transport corridors and networks. Traffic management of transport corridors and networks means the elaboration, implementation and quality control of "Traffic Management Plans" (TMPs) covering the European transport network and corridors, including cross-regional and cross-border aspects and multi-modal options. Cross-border traffic management plans are a set of predefined measures for a number of specific situations: to regulate traffic, to inform road users in real time and to ensure consistent and up-to-date information. The basic situations can be unforeseen (e.g. emergency, accident) or foreseeable (e.g. recurring or non-recurring events). Traffic management plans can be prepared for the following levels of coverage:

- Regional TMPs: for networks within areas or regions on the TENT-T that can be extended, under certain conditions, to link with neighbouring regions for cross-regional and cross-border levels.
- Cross-regional TMPs: for national networks and key corridors on the TENT-T, covering multiple regions
- Cross-border TMPs: for cross-border networks and key corridors on the TENT-T and

- TMPs for conurbations: conurbations and the urban/inter-urban expressways network with relevance to long-distance traffic.

Initially, Austria and Hungary prepared traffic management plans for the Austrian-Hungarian-Slovak triple border area, and later, at the initiative of the Slovenian motorway manager, road and motorway management companies from Italy, Austria, Croatia, Slovenia and Hungary met. The initially informal cooperation was formalised on 19 September 2014, when a Memorandum of Understanding was signed in Abbazia, Croatia. As a result of this cooperation, road experts from the five countries meet regularly to jointly develop methods to avoid and manage critical situations and to discuss past experiences and future plans. The main objective of the joint work is to coordinate traffic management on international road corridors with significant traffic flows in order to better manage critical cross-border situations. The winter period is a priority, as it is the period when disruptions and border closures are most frequent, but the summer period is also becoming increasingly important.

The exchange of information is a key element of the tasks. The partners inform each other by e-mail of events that have a significant impact on international traffic by filling in a standard form. This first-hand information helps to better serve the needs of the travelling public and to provide a better service overall, but in many cases it is the type of information that requires intervention, for example when heavy goods vehicles are not allowed to cross the border. For an intervention of this magnitude, it is very important that the information is received before the restriction comes into force, if possible.

IV. Introduction of the Optima system

Optima is a real-time traffic management software system developed by PTV [10]. Magyar Közút Zrt. has built this software system and the underlying model for the Hungarian main and express road network, so it primarily supports road traffic management, but Optima is also capable of multimodal and intermodal route forecasting.

PTV Optima collects and evaluates information from real-time data sources to help traffic control centres. Its main functions include:

- Collecting real-time data and events describing the traffic conditions on roads
- Combining different data sources into a single comprehensive view
- Create traffic simulations to provide information
    - Multimodal transport information for drivers
    - Sending up-to-date traffic information to variable message signs
    - More robust and flexible adaptive traffic light management

The Optima system uses a dynamic traffic model to estimate time-varying travel times, traffic flows and queue patterns. The model is able to take into account the impact of planned (e.g. road works) or unplanned events (e.g. accidents) and traffic management strategies (e.g. traffic lights or variable message signs). The system can simulate several scenarios in parallel. [11]

The offline traffic model was created in PTV Visum. From the offline model, the supply, i.e. network data, and the demand, i.e. historical calibrated where-to-go matrices, are derived for the online part. This is typically done for different day types, in this case weekends and summer non-summer weekdays.

The offline model uses the TRE Traffic Real-time Equilibrium (add-in config) dynamic load balancing procedure. The online model also uses TRE, but with different settings. For the offline part, TRE calculates how demand is distributed across the network for all 24 hours of the day. The results are called Base Path Choices and Base Traffic Estimation, which describe the node turning shares and traffic conditions as a function of time. These two results are the next level of the offline part for the online part.

The information from the offline part describing typical days is corrected by the online part with real-time traffic data. The present model uses data from the counting stations of the Hungarian Public Roads Ltd. and the Inrix vehicle fleet.

The Traffic State Harmonizer component completes the pre-processing of traffic data by harmonizing all measurement data (traffic, speed).

The real-time traffic data is taken into account by the TRE Traffic Real-time Equilibrium (real-time config) real-time simulation. This variant of TRE does not simulate 24 hours of an average day, but runs in rolling mode. In this mode, the simulation typically covers the next 60 minutes, its initial state is determined by the previous simulation, its initial time is continuously advanced in real time and takes into account traffic measures.

Another source of real-time information is capacity or speed limitation. These can be unplanned, such as accidents, or planned, such as construction or various traffic signal programs, this model considers expressways, so no traffic signal programs have been included. Events & effects, real-time signal plans, and strategies & effects modules are the effects on the TRE. The real-time module of the TRE can run multiple scenarios in parallel, each with a different situation defined in the strategies & effects module. In this case, PTV Optima becomes a decision support tool for real-time traffic management. The strategies must be prepared in advance, as in the base model, but can be combined in any combination in real time and simulated as additional scenarios in parallel with the base simulation.

The online TRE Real-time forecasts speed, traffic and queue length for all sections of the network in real-time, typically for time intervals up to 60 minutes. These, Real-time forecasts, can be used in a variety of ways, here we list only those relevant to this model:

- Real-Time KPIs (Key Performance Indicators), an aggregated view of results, such as average network speeds or total line lengths in a particular part of the country. KPIs can be tailored to each individual project. They are particularly useful for a quick comparison of different scenarios.

- The Detection and Control module allows you to set alarms based on real-time forecasts and/or basic traffic estimates. It is possible for the traffic controller to generate an alarm if the travel time on a particular route is higher than the average travel time.
- The Smart Display module can provide recommendations on the content of variable message signs (VMS).

The Traffic Supervisor (GUI) is Optima's user interface that allows analysis and system control.

V. THE MACRO-SIMULATION MODEL

The Optima system needs an offline base model. This model was created in PTV Visum software. It is a macro-simulation model including the road network and the static demand matrices.

A. Description of the network and area model

The territorial delimitation of the model is the whole territory of Hungary, including the entire motorway and trunk road network and the national minor road network. The spatial model is consistent with the zoning of the overall transport traffic model developed in the framework of the National Transport Strategy (NTS).

Magyar Közút Zrt. has provided a map of the national road network in sufficient detail, which is included in the National Road Data Bank (hereinafter: OKA), as well as a dataset describing the parameters of the network (e.g. length, identifiers, track and traffic data). The dataset includes the status at the end of 2021. It was necessary to adapt the OKA network to make it seamless and suitable for route planning. Here, the alignment of section ends that end in a node but do not meet spatially had to be carried out.

Traffic counting stations that can provide continuous, online data were coded into the network model. These stations are used in the Optima model. These stations are basically the detectors of the traffic counting loop of the Hungarian Public Road, which are networked.

In the VISUM model, the traffic counting stations are contained in the Count Locations layer. The Count Locations are recorded as half-lanes per direction on expressways and as junction branches at intersections (678 in total). Locations that are not or only partially operational at present have also been included, as they are expected to be put into operation during maintenance. For the Count locations in VISUM, the detectors of the lanes belonging to the count stations are also recorded in the Detectors layer (a total of 1258 detectors recorded).

B. Generation of hourly demand matrices

The dynamic traffic simulation model, Optima, generates traffic forecasts from hourly static demand matrices corrected by actual measured traffic data. It is therefore necessary to produce these static hourly demand matrices from the Visum model.

Day types - For more accurate traffic forecasting, it is possible to define day types in the Optima model. The day type allows to consider separate demand matrices for days with significantly different traffic flows. Three day-types are distinguished:

- Weekday outside summer,
- Weekday summer,
- Weekend.

Generation of raw hourly matrices - The decomposition of the daily demand matrices used in the NKS model into hourly matrices was based on the location databases of the National Toll Payment Service Ltd, NÚSZ and Telekom, by vehicle category, day type and hour.

The toll data from NÚSZ Zrt. allow the determination of the route and the location of the transport from where to where after the on-board OBU declaration of the trucks. These where-to-where pairs are projected and aggregated to the zonal distribution of the model and anonymized by the NÚSZ Zrt. in hourly breakdowns, but aggregating a full year's data for summer and non-summer periods, as well as for weekdays and weekends. However, the where-to-where data (O-D matrices) were only known on the main road network and the expressway network, not the actual starting and ending points of the journey. Therefore, the hourly flow of truck movements thus produced from the NKS data was used to decompose the truck daily demand matrices from the NKS model into hourly and daily types. [12]

A similar approach was used with the Telekom location database to produce hourly demand matrices for passenger vehicles. Magyar Telekom has location data on telecommunication events registered on its network (calls, text messages, mobile Internet usage, cell-to-cell location changes). These events are generated by Magyar Telekom customers and roaming users connected to its network. This raw data includes, among other things, the coordinates and time of the event. Based on this data, Telekom also generates the 'from- to- to-where' (O-D) movement data aggregated to the Visum model area assignment and day types, taking into account data law standards. However, the means used for travel cannot be determined at this level of analysis. Thus, the demand matrices are not directly derived from Telecom's movements to and from. The Telekom location database can also be used to determine the hourly flow of movements by zone. Taking these into account, the daily passenger vehicle demand matrices from the NKS model are decomposed into hourly and daily demand matrices.

Calibration - The hourly demand matrix load for the equilibrium load balancing procedure does not represent the real hourly traffic at a given cross section, as there are trips of up to 6-8 hours on the network. The total path of trips departing in a given hour will show the traffic in that hour. Therefore, the 24 hours of the day have been calibrated over 5 periods to approximate the model to real traffic volumes.

The NÚSZ Zrt. FIX portals of the NUTRS Ltd. were used for the calibration of the demand matrices for the year 2021. The cameras of the FIX portals are used to monitor toll payments. The toll eligibility check also provides the traffic volume by vehicle category and by time. From this, the NÚSZ Zrt. has provided the traffic volumes aggregated by hour for each FIX portal, broken down by direction. For the calibration, the average hourly traffic volumes by day type, broken down by passenger and truck, were taken from the full 2021 data. A total of 184 locations and directions data were processed and used to calibrate the model. The location of the intersections, mainly covering the TEN-T network, expressway and trunk road network relevant to the task (Figure 2).

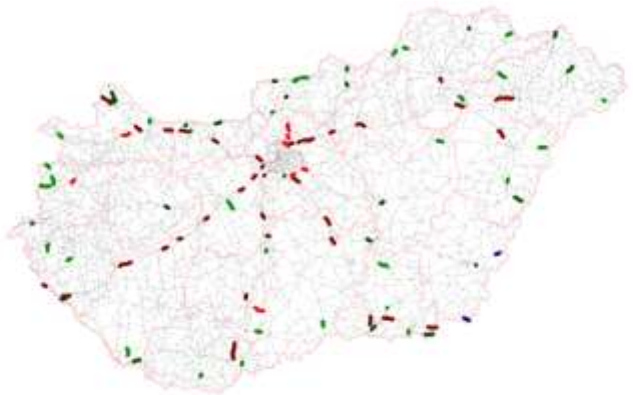

Fig. 2. Calibration cross-sections

For the 5 periods used for calibration, the measured hourly flows were summed. The 5-period demand matrix thus calibrated is then decomposed into 24 hourly traffic matrices based on the ratios of the raw 24 hourly matrix. This is done for all 3 day types and 2 vehicle categories. Making a total of 144 hourly matrices. During calibration, the variation in traffic volumes across the average of the calibration sites was found to be far less than the expected GEH index of 5.0.

VI. THE USE OF THE SYSTEM

A dynamic traffic simulation model built for the Hungarian national expressway network demonstrates the potential of the Optima model system to support traffic management.

PTV's Optima software provides a number of ways to monitor and analyse road traffic and to pre-event analysis. The following options are available in Optima:

- Map view: it is possible to view measured and forecast traffic situations on a map. Traffic volume, speed, capacity utilisation can be displayed. Real time and forecasted.
- Real-Time KPI (Key Performance Indicators): it is possible to display user-defined indicators, which can be point-based, line-based or even area-based. In addition to the data that can be displayed in the map view, travel times, average line speeds, total line lengths by area can also be displayed.
- Scenario: The real-time module of the system can run several scenarios in parallel, each with a different situation. It is possible to test what happens in case of a capacity constraint, a diversion or a heavy traffic event.

Each traffic management centre or area can define for itself where, what indicators it wants to monitor, how and where, and what are the critical values that will lead to the implementation of its intervention plan.

Map - Map view. Figure 3 shows this situation on the M7 motorway. The lane closure is represented in the model as an Event, which reduces the maximum value of traffic exiting the section, so that traffic entering the section in addition to this will form a queue. As can be seen in the figure, based on the prediction, beyond the red line, the section will soon be full, so the queue will extend to the previous section.

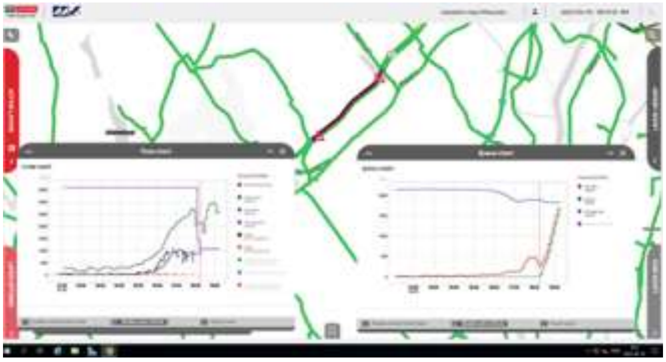

Fig. 3. Incident with capacity drop

Real-Time KPI (Key Performance Indicators): it is possible to monitor the travel time of a route. Figure 4 shows the average travel time on the section of the M7 motorway from Budaörs to Székesfehérvár during the lane closure studied in the map view. It can be clearly seen that the lane closures have the effect of increasing the travel time after the lower travel time at night.

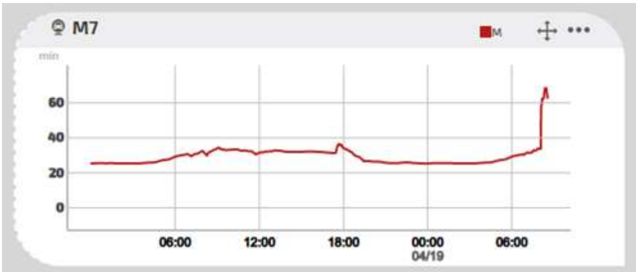

Fig. 4. KPI – Journey time

Scenario: you can test how the traffic situation would evolve in the event of a lane closure. In the example, one lane of the M1 motorway is closed at Tata (Figure 5). Travel time increases, speed decreases, as expected. The map also shows how the speed reduction is propagated to the preceding sections. It is important to note here that there is no real-time route choice in Optima, see Section 4. However, it is possible to select a detour route within the scenario, so that its effect can be investigated. Or even as an Event to take into account the current traffic situation.

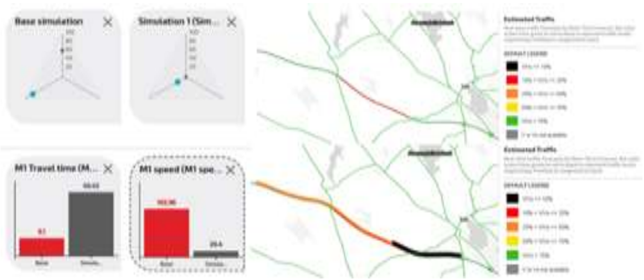

Fig. 5. Scenario - Motorway M1 lane closure

VII. Conclusions

Data has always played a central role in traffic management, which is why the road manager has installed sensors along the roads to ensure that there is enough data to carry out its management and information tasks at the right level. This can now be done using mass data, fleet data, which can be used to build much more accurate models than before. A good example is the national dynamic and static model presented in this article, which takes traffic management to a much higher level and also adds a new element of forecasting that was not possible before. Trends everywhere point in this direction, and traffic management, in order to keep up with the challenges of the times, needs to diversify its data sources as much as possible to overcome the shortcomings of the various methods and improve the quality of the information produced. The traffic models built will form the basis for future traffic management activities at Magyar Közút, and the planned new generation traffic management system will use them to evaluate different scenarios and to select the proposed intervention.

Acknowledgment

The project was implemented in the framework of the CEF-funded project "CROCODILE 3 Hungary" 2016-HU-TMC-0300-W.

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