New Optimization and Decision Support Technologies in Tunnel Design, Operation and Traffic Management

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Abstract

In the context of recent increases of traffic loads, traffic dynamics, uncertainties, urban space vulnerability and infrastructure availability requirements, the number of decision-making factors are growing. Tunnel operators, traffic managers and tunnel designers therefore recognize the need to alleviate the consequences of those changes by improving connectivity of databases, which can be established during particular phases of tunnel design, operation or traffic network management. Large number of requirements poses not only a challenge in general and in relation to database connectivity; it poses also an opportunity for the use of new information communication technologies (ICT). These offer considerable opportunities in the direction of better decision making and search of optimal solutions in design of real time traffic management systems in the future. The experiences gained through implemented projects or projects in the development are described in the article, together with some theoretical background.

Keywords: Multi-Criteria Optimization, Decision Support, Evolutionary Algorithms, Algorithmic Design, Traffic Management, Tunnel Operation, Tunnel Design, Traffic Management Systems

Povzetek

V luči povečevanja dinamike prometnih obremenitev, negotovosti, občutljivosti urbanih območij in potreb po razpoložljivosti infrastrukture je število dejavnikov odločanja vse večje. Zato strokovnjaki za obratovanje predorov, upravljanje prometa ter projektiranje predorov prepoznavajo potrebo/smiselnost večje povezave podatkovnih baz, ki jih lahko pridobimo v posamezni fazi projektiranja, obratovanja in upravljanja

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cestnega omrežja. Veliko število zahtev ne predstavlja samo velik izziv, združevanje podatkovnih baz predstavlja tudi priložnost za nove informacijsko komunikacijske tehnologije (IKT). Te predstavljajo precejšen korak v smeri boljših odločitev ter optimalnih rešitev za projektiranje bodočih stanj in sistemov za upravljanje predorov v realnem času. V članku so opisane izkušnje izvedenih projektov ali projektov v razvoju s teoretičnim ozadjem.

Ključne besede: Večkriterijska optimizacija, podpora odločanju, evolucijski algoritmi, algoritemsko projektiranje, upravljanje prometa, obratovanje predorov, projektiranje predorov, sistemi za nadzor in vodenje prometa

1. Introduction

We live in a very dynamic society featuring large number of challenges related to safe, reliable and effective tunnel operation and traffic management on the road network in general. These challenges become particularly obvious in the context of:

- Fast development of traffic technologies for users.
- Changes of societal habits resulting in more frequent commuting or migration.
- Increased requirements in society for minimal impacts on neutral and urban effects of roads operation.
- Design infrastructure lifespan is 100 years or more. It is impossible to foreseen future traffic and transport network conditions during the design of the tunnel.
- Legislative requirements for the design are changing but it hardly follows the requirements of the environment.

Even though, some solutions explained in further text are very difficult to implement, they represent a way to include new information communication technologies (in following text ICT) in engineering praxis. ICT is used as a support/tool for good/optimal tunnel design, operation and traffic management decisions and solutions.

When speaking of good/optimal decisions/solutions, we need to have clear understanding of the term "good decision/solution". All the decision makers – stakeholders need to understand the question: "What is good". This is the crucial part of every decision-making process; for the support of the ICT, "good decision/solution" needs to be formalized. Particularly in consideration of societal impacts, this question represents a specific decision-making challenge.

The following emphasises need to be considered:

1. Effective use of ICT greatly depends on the data collected from vehicle users, infrastructure sensors and equipment, user's data as well as societal and other data. The amount of data grows rapidly and serves as an input for future decision-making and optimizations.
2. ICT requires formalization and digitalization of processes which are traditionally performed by humans. This is relevant for decision making as well as automatic, algorithm-based testing of numerous possible conditions. Therefore, new models need to be developed for the use in operation, design and traffic management.
3. We need to emphasize that our approach uses ICT to support decision-making, and not to leave decision-making to ICT. The responsibility for decisions is still left to the experts in specific fields.

There are three main reasons, why we consider design, operation and traffic management together:

1. The first one is already mentioned in the beginning: In recent years, the list of criteria (a basis for decision-making) is getting longer, resulting in the necessity to combine data platforms of each stage. Main decision-making criteria are:
   - safety,
   - traffic demands,
   - travel time,
   - investment costs,
   - operation and maintenance assets, equipment and manpower,
   - tunnel closure costs and impacts,
   - protection of urban areas, natural and other assets etc.,
   - civil initiatives and public participation,
   - other considerable factors.

2. The second reason is the cost benefit ratio of measures providing specific function or requirement. In the case of existing infrastructure or designed infrastructure, we have to consider the limitations due to its long-lasting conditions after the construction. Even in the case of refurbishments, tunnel needs to be closed or operate under specific conditions with reduced capacity. After the construction or refurbishment, we need to rely on the tunnel operation and traffic management measures. This leads into necessity for mutual consideration of all phases. Following measures can be distinguished (if applicable):
   a. When costly measures are considered, cost/effectiveness score becomes vital decision-making criteria to decide, if new infrastructure, refurbishment, operation or traffic management measures will be implemented. This consideration is extremely important in the fulfilment of new legislative requirements. In some cases, time for measure implementation or refurbishments can be evaluated in the form of costs.
   b. Traffic loads fluctuate over time and with that, the load on the infrastructure and effects on the assets. In many cases we can (have to) reduce the impacts of infrastructural drawbacks during traffic peak hours by tunnel operation measures and traffic management to fulfil requirements. Real time technologies can support us in those cases.

3. ICT enables the analysis, examination and evaluation of a large number of possible states – much larger than we could with traditional approaches. In many cases, algorithms, after the model is properly designed, can recognize better solution that we could hardly see without examining a very large number of possibilities (e.g. few hundred thousand). Examination of very complex systems or systems that have to be evaluated very fast (in real time) are particular challenges as well as potentials.

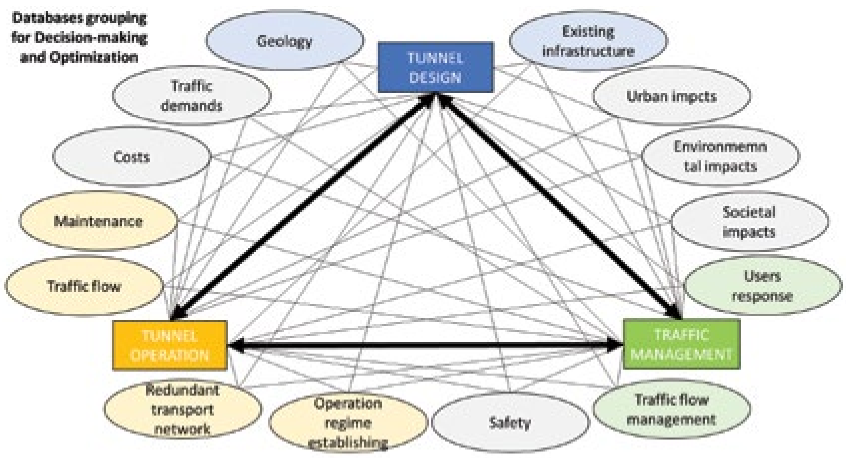


Fig. 1: Connectivity of Data basis in the process of design, operation and traffic management

This calls for the approaches, which can be new, tailored for the purpose and use, or already developed and well established in other engineering services e.g. mechanical, electrical engineering, autonomous vehicles, production, robotics etc. Since ICT are developing constantly and the number of fields/branches is larger every day, article focuses on technologies which are followed by authors or are already in use in practice:

- Parametric design models for algorithmic analysis of several – infinitely possible states;
- Multi-criteria / Multi-attribute decision models for tunnel design - knowledge representation;
- Optimization and artificial intelligence algorithms for optimal tunnel alignment recognition;
- Systems for real time data collection, data distribution and data analysis for traffic control and management.

The goals of presented technologies are:

- Better communication with users and public in all considered phases (design, operation and traffic management);
- Better design solutions, based on the data collected from realistic traffic flow conditions. This is vitally important in the conditions of increased traffic loads and traffic incidents;
- Economically efficient and sufficient preparation for future infrastructure operation and planning;
- Fast communication with infrastructure users for efficient traffic management on road network.

In the article we share part of our experiences and knowledge as a motivation for further development of ICT in civil engineering.

2. New Decision Support and Optimization Technologies

In the scope of the article, the decision support and optimization technologies are the field of methods and technologies that enable the use of algorithms, models and communication systems for solving practical problems in tunnel design, operation and traffic management. The technologies explained are:

1. Decision Support Systems
   - Knowledge Representation is an important aspect of decision models, which serve also as a formalization of domain knowledge about various decision factors and their relations. By applying algorithmic reasoning and analysis capabilities on structured and formalized human-provided domain knowledge, we are combining the best capacities of humans and computers. Decision models therefore serve as knowledge representations and mechanisms for transparent and elaborate reasoning and simulations. This relates well with decision making in tunnel design in urban areas, which is influenced by many goals, opinions and interests, which are hard to grasp for a human to reason about, but also impossible for a computer to efficiently learn from empirical data. Even by using the models for knowledge representation only, one can recognize a limited set of good options from a large number of acceptable ones that are gained from optimization algorithms.
   - Multi-Criteria Decision Modelling (MCDM) is aimed at formal (mathematical) modelling of decision problems that consider a multitude of criteria. This kind of model represents a formalization of the specified problem and usually enables assessment, visualization and comparison of decision alternatives. There are several established and mature decision modelling methodologies like MAUT (Keeney and Raiffa, 1993), AHP (Saaty 2008), Electre (Figueira, 2005) and DEX (Bohanec et al., 2013). The last one is especially well suited for problems that are hard to quantify and influenced by many goals, opinions and interests, such as the problems related to Smart cities.

2. Multi-Objective Optimization by Evolutionary Algorithms are iterative methods that improve on solutions using principles that mimic the natural evolution such as selection, crossover and mutation (Eiben & Smith, 2003). Because they operate on populations of solutions, they are especially appropriate to handle multi-objective optimization problems, where, due to conflicting criteria, multiple optimal solutions exist—each representing a different trade-off among the criteria (Deb, 2001). The use of AI technologies in optimization and decision support helps automate and speed up the tunnel design process, while the final decision is still made by humans (the decision-making team). Additional benefits of using AI technologies in the proposed process are:
   - Effective exploration of the decision space that enables us to find a large number of admissible solutions, some of which could not be conceived by the designers.
   - The objectiveness (given the provided inputs and rules) and increased transparency of the decision-making process reduces the risk of subjective judgements of stakeholders, omission of important consequences, lack of design goals and violation of valid constraints.

   On the other hand, using AI technologies in such application has its limitations:
   - If the decision space is large and the partial models very complex, there might not be enough time for the optimization algorithms to find all the optimal solutions. In such cases, the final decision has to be made on near-optimal solutions.

- Although AI techniques speed up and automate the design procedure, they are only as good as their input. If the problem is not defined well, the returned solutions might not be appropriate or even admissible.

3. Parametric models are digital models of engineering systems that generate particular elements or enables algorithmic investigation of concerned system. They can bee seen as transformations or functions that perform the human procedures in automated process. Parametric model can be seen as digital twin and is prerequisite for algorithmic approaches (ICT). They are constituted by:
   - Variables of the decision space: Technically, we made a model as we do in traditional design approach with the exception of variables, not bounded to particular value. Those variables are called decision space variables. By changing a variable, a new solution is generated. This leads to many solutions, which can be generated by parametric model. For complex problems we leave the algorithms to manipulate these values according to optimization goals.
   - Constraints are model definitions that do not change by optimization process. Engineering and legislative rules, existing infrastructure, desired conditions and states falls in this group of model definitions. These definitions are digitized and stored in the form of digital project task.
   - Objectives/criteria which are subject of optimization or decision support process. There can be more than one objective and they can be in mutually conflicting relation.
   - Solutions which can be of a following type:
     – Feasible/infeasible solutions. If solution is infeasible, it is excluded from the group of candidates for optimal solution,
     – Final/chosen solution – algorithmic approach serves as the support for decision making. Decision is accepted by decision-maker.
     – Optimal solution. In the case of multi-criteria analysis, the number of optimal solutions can be larger than 1.

4. Systems for detection and traffic management by devices in front of the tunnel, in the tunnel or behind the tunnel:
   - Traffic data:
     – traffic queues, number of vehicles in the tunnel, driving direction, distance between vehicles, vehicles types etc.
     – meteorological data to detect meteorological conditions (wind, rain, snow, ice etc.).
   - On this basis the program scheme and algorithms support the traffic control officer decisions in determining safety measures for traffic control and management e.g.: lowering the vehicles speed, ban of overtaking for heavy goods vehicles, various warnings etc.
   - Tunnel incidents detection (fire, stopped vehicle, vehicle driving in opposite direction etc.). The system proposes possible scenarios of traffic management after the incident detection. Scenarios are then chosen by traffic control officer in control centre on the basis of available data, his/her experiences and training. The safety measures and procedures for traffic management follows confirmed scenario.

5. Data collection and distribution by the mobile phone applications (e.g. DARS TRAFFIC +). After real time data is collected, it is analysed by data fusion approach combining different data from different data sources in such a way, that combined information is more accurate, more complete and more precise. Such technologies are used, when data / measurements are available with different views of the same properties. In the case of traffic flow, different data sources are available, for example inductive loops, GPS probe data, etc. Data is combined using machine learning algorithms and average speed per road segment is estimated. The technology is supported by Floating car data (FCD) system. It is a GPS based system for vehicle speed monitoring on the road network. It is also a basis for real time algorithmic prognosis of traffic density trends on the road network.

3. Implementation Examples

The description of implemented technologies or research is given in the following paragraphs. First two examples relate to technologies: decision support systems, multi-objective optimization and parametric models. The last two examples show the implementation of the support by systems for detection and traffic management and communication technologies.

3.1 Artificial Intelligence Support for Tunnel Design in Urban Areas (TOPP)

The aim of the TOPP[2] project is developing a decision-making process for optimal tunnel alignment design and integrating all stakeholders in a single, cloud-based IT platform supported by artificial intelligence algorithms. The drawbacks of traditional design approaches were overcome by synthesising fast developing BIM and artificial intelligence algorithms (e.g. by integrating information communication technologies). This introduces accessibility, efficiency, reliability and transparency to the decision-making process.

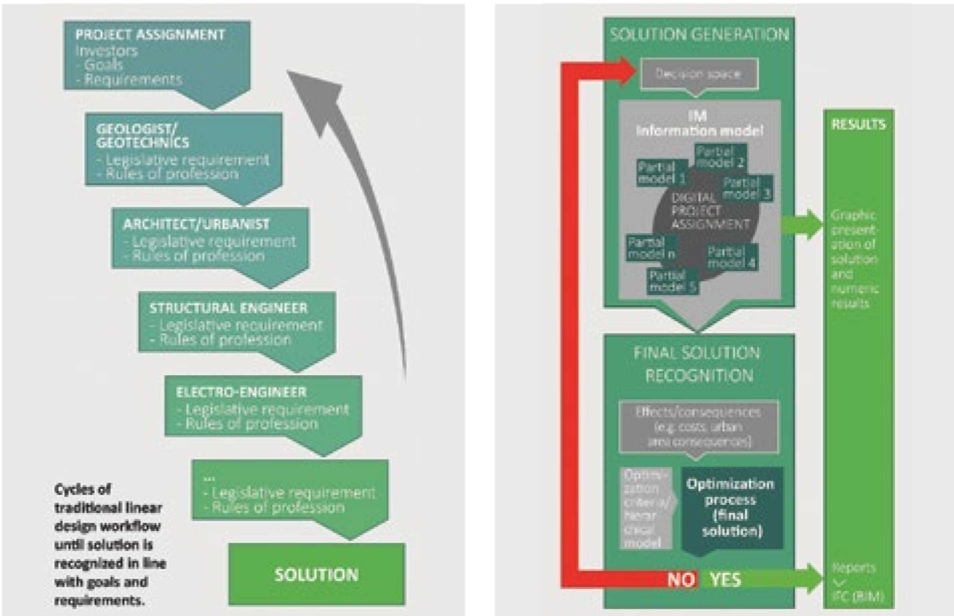


Fig. 2: Transformation from traditional design workflow (left) to proposed process (right)

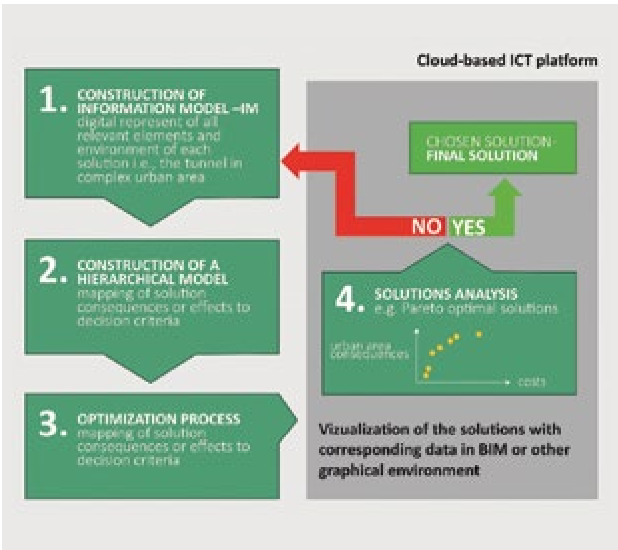
[2] The investment is being co-financed by the Republic of Slovenia and the European Union under the European Regional Development Fund

The goal of the project is to develop procedures, models and analytical methods that:

- provide engineers with effective tools for coping with highly complex urban project requirements,
- enable the use of efficient state-of-the-art decision support and optimization algorithms,
- enable the active involvement of all possible stakeholders including non-experts (e.g.: the public),
- enable effective real-time communication between stakeholders using a cloud-based IT platform,
- establish interdisciplinary collaboration, data sharing, secure access and multi-tenancy within a common data environment.

The development starts by transforming project data into the parametric partial models of relevant decision makers, e.g.: tunnel experts, geologists, hydrogeologists, urbanists, traffic experts, public participants, etc. These partial models are then combined into a common information model. This enables the calculation of an evaluation score for any tunnel alignment e.g.: tunnel costs, impact on natural assets, interaction with existing infrastructure, etc. Since the number of possible alignments is infinite, it is not easy to find the optimal solution. Therefore, we use state-of-the-art algorithms to find a mathematical optimum based on project-specific criteria, restrictions and decision-making rules. These are defined in the form of a hierarchical model designed to transform stakeholder values into a language suitable for numerical operations performed by information communication technologies (ICT).

Fig. 3: Cloud based ICT platform



Processes are focused on collaboration between stakeholders, the recognition of optimal solutions and the interpretation and analysis of the results.

The result of the project is optimal tunnel alignment recognition process that has a clear decision-making capacity to interpret results to the user. This is not possible using the traditional design approaches. Nevertheless, the confirmation of the final solution/alignment is made by humans – artificial intelligence technologies are only providing support to decision makers.

The project ends in November 2020. It is actively connecting three leading Slovenian institutions: Elea iC (project leader and tunnelling expert), XLAB d. o. o. (ICT specialist) and Institute Jožef Stefan (central national scientific research institute). The investment is being co-financed by the Republic of Slovenia and the European Union under the European Regional Development Fund.

3.2 Risk Based Dynamic Traffic Control in Tunnel Markovec

An advanced multi-criteria decision analysis was performed in order to support decision making for optimal operation of the tunnel during specific tunnel operation conditions. Results of the analysis is real time decision support framework for tunnel operator to manage risk at the time of bidirectional tunnel operation (tunnel is originally designed as a unidirectional tunnel). A need for the bidirectional operation emerged due to a change in the road network (unavailability of a parallel/alternative road Istrian road).

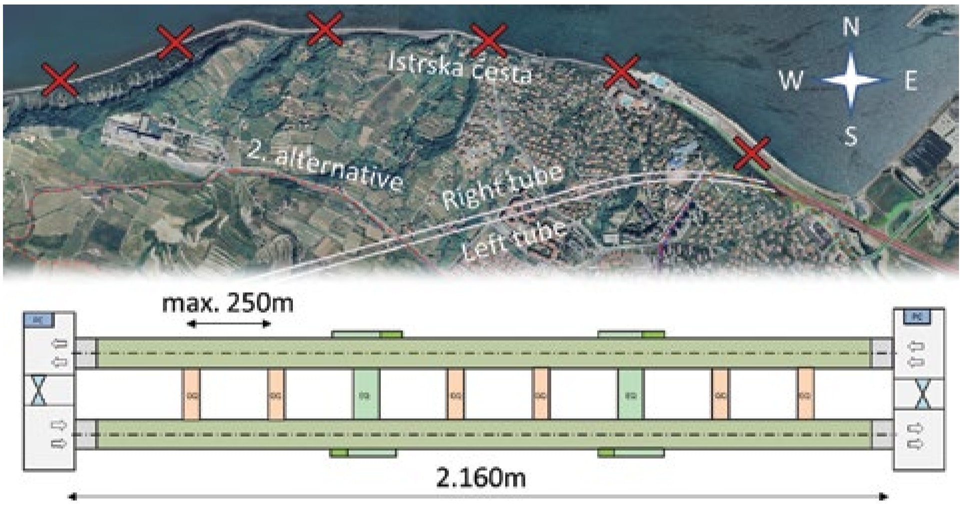
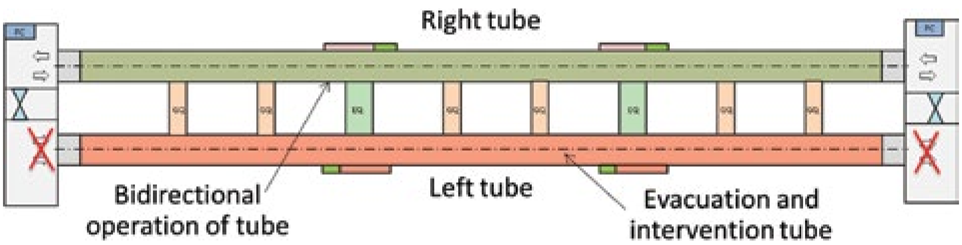


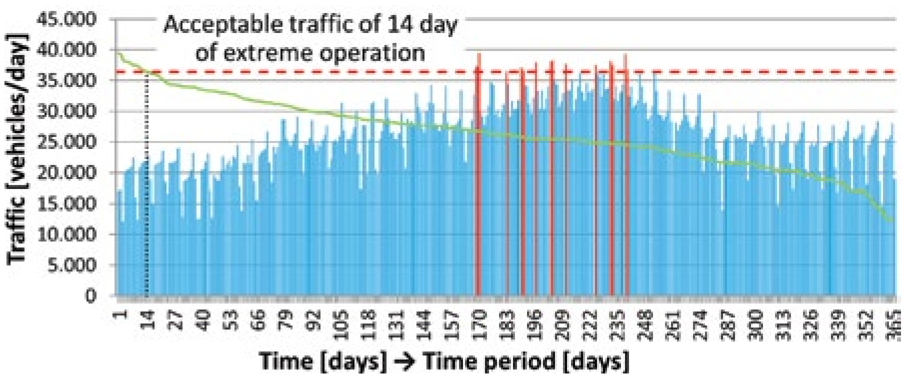
Fig. 4: Closure of Istria road parallel to unidirectional Markovec tunnel

A solution is a method that allows utilisation of alternative, cost-effective safety measures, with which an acceptable safety level is achieved at optimal transport capacity of bidirectional tunnel operation in one tube. In order to reach the goal, the methodological change of the traditional approach was needed – a method of a parametric analysis of effects in various tunnel conditions was implemented. This approach allows us to determine an optimised acceptable multi-dimensional state of tunnel operation and not only a single acceptable state of infrastructure operation.

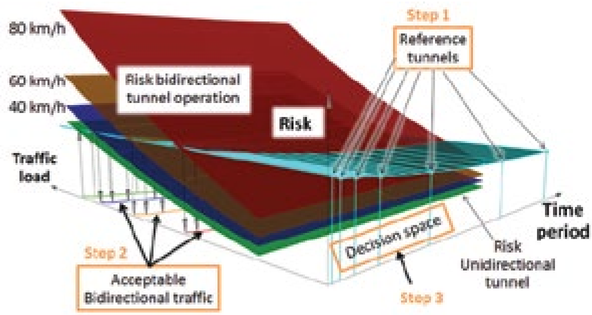
Fig. 5: Main elements of the model and solution



Short-term bidirectional tunnel operation (example)

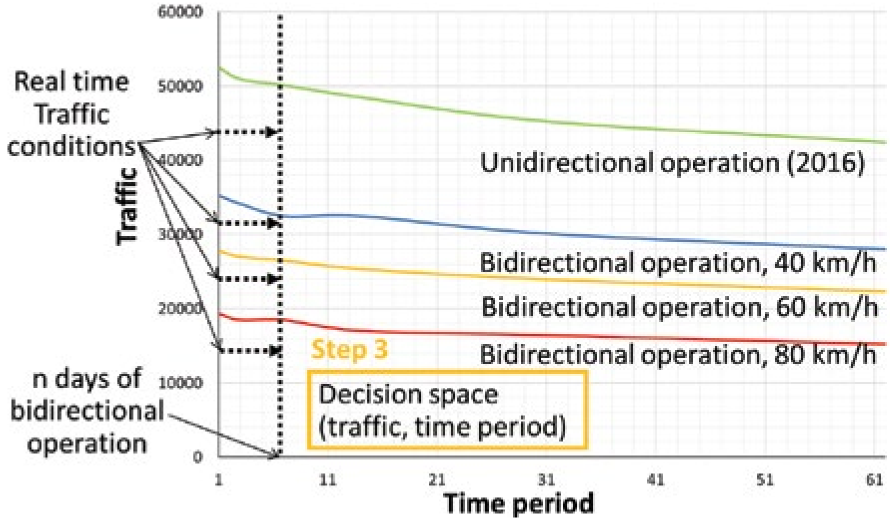


Risks variation with time periods due to traffic load variation



Acceptable risk determination as a basis for the acceptable operation regimes determination

Safe tunnel operation depends on many factors. For this reason, numerous possible safety measures, effects and traffic conditions in the tunnel were taken into account.



Acceptable operation regimes according to different decision space conditions

3.3 Traffic Management Support Systems for Traffic Rerouting in the Case of the Tunnel Closure

Since the Slovenia is a small country (the length of motorways is roughly 700 km) and small changes in the network affects international transit routes network, the regular measures have to be implemented.

The traffic management decisions in the cases of relevant incidents are made on the basis of international traffic management plans (TMP - Traffic Management Plan). The plans are pre-prepared and confirmed by all relevant states (Italy, Hungary, Croatia and Slovenia).

On this connection we have 10 tunnels (Cenkova, Golo Rebro, Pletovarje, Ločica, Jasovnik, Trojane, Podmilja, Golovec, Rebrnice and Podnanos). In the case of several hours tunnel closures the informational decision system is triggered to inform traffic control officer in Main Traffic Control Centre. Possible options with relevant data are offered e.g.: traffic conditions, work on parallel networks, weather, expected events on relevant network etc.

Fig. 6: Example of road network on the rout Hungary–Italy

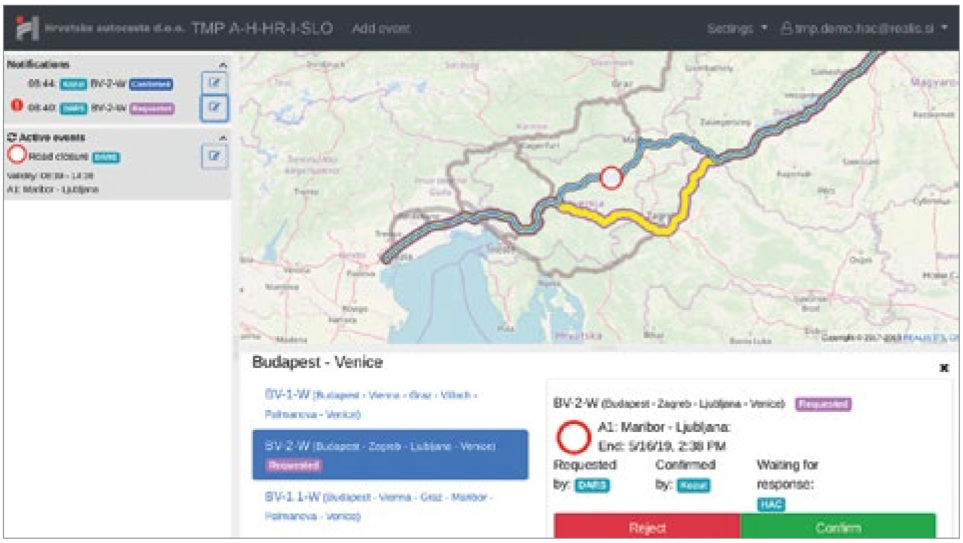


Fig. 7: The example of tunnel Trojane closure with rerouting on Croatian highway

On the basis of algorithm and data, the traffic control officer decides, whether the rerouting will take place or not. The rerouting activities start when the confirmation from all the neighbouring countries is obtained. Rerouting can be stopped by any of the involved countries.

3.4 DARS Traffic + Application

The application DARS TRAFFIC + is available to users of federal roads in Slovenia. The application is also used in the international project C Roads, where the application is tested for the communication with roadside infrastructure and communication between vehicles. Based on this data, the traffic manager will be able to close the tunnel, the users in or in before of the tunnel will be alarmed directly via application (it communicates by roadside infrastructure). The application will inform traffic manager in the cases of fast vehicle acceleration/deceleration and by that, the alarm procedure will start for the potential accident or traffic jam.

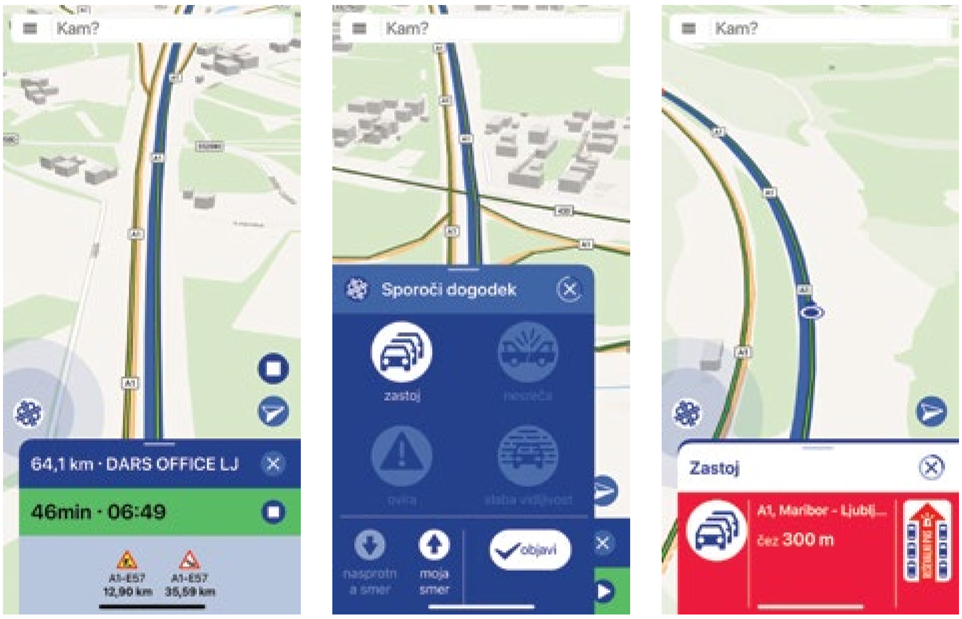


Fig. 8: International project C Roads (left); the information from driver to the control centre - traffic jam, accident, obstacle on the road, reduced visibility (middle); the information from control centre to the driver – traffic jam after 300 m (right)

DARS established a new system of data collection and distribution in the year 2018. Real time data collection is established with the application DARS TRAFFIC + on highways. With the application, data is communicated from the driver, or it is transmitted by the application automatically. System enable two-way communication between the driver and traffic control centre. Application follows the vehicle during the driving and informs the driver in the case of relevant events in front of the vehicle on the road (incidents, work on the road etc.). If the vehicle is approaching the traffic jam, the driver is warned on necessary emergency lane for intervention vehicles. If driver defines its destination goal, he/she is informed of driving duration.

Application enables the data transfer from driver to data control centre. It enables the driver to quickly and efficiently communicate the incident during the driving (traffic jam, accident, obstacle on the road, reduced visibility etc.). The information sent by driver is instantly visible to traffic control officer through information system. This way the traffic control officer is informed faster on potential threats compared to other communication channels. Additionally, this approach is much safer for the driver than phone call communication. Based on the collected data, traffic control officer starts necessary protocols. The number of information collected in the area of tunnels, is increased.

Following data is collected automatically: vehicle location, speed and significant acceleration/deceleration. Acceleration/deceleration are analysed by advanced intelligent algorithms to recognize patterns of strong vehicles breaking or accidents. Those are communicated to control centre in real time. Vehicle speed and location are part of the inputs for the system to determine traffic flow and average speed on the particular network segment (Floating car data – FCD platform). Platform normalizes and localizes the data and by machine learning technologies combines the data with data from other sources (data fusion). Based on this, the speed profiles are calculated for individual network segments. The profiles are then graphically presented to control centre and drivers. Data of travelling time, suggested measures in the case of traffic jams and actual traffic events are also presented.

4. Conclusion

Article describes author's experiences, examples, development and approaches to solve data based multicriterial problems in tunnel design, operation and traffic management. Specific attention is given to necessary data bases interconnectivity and decision criteria in the phases design, operation and traffic management. Examples with relevant/implemented ICT are explained in the article. Following challenges and potential solutions are described:

1. The number of traffic related data collected from the devices on the infrastructure, in the vehicles or society increases rapidly,
2. Technology for data distribution and analysis is already well developed and it develops very fast. Two types of problems can be distinguished:
   - Real time problems solving e.g.: problems involving high traffic fluctuation and incidents in tunnels.
   - Solutions of the complex problems with lots of constraints, decision variables, and criteria e.g.: problems involving new infrastructure, refurbishments involving operation and traffic management measures etc.

3. Infrastructure and refurbishment measures for medium and long-term solutions become very important. For these measures real-time data is becoming of vital importance.
4. Legislative requirements for the design are changing but it hardly follows the requirements of the environment.
5. ICT enables the analysis, examination and evaluation of large number of possible states – much larger than we could cope with traditional approaches. After the model is properly sett, algorithms can:
   - recognize better solution, we could not even see without examining a very large number of possibilities (e.g. few hundred thousand);
   - help us understand the effects or consequences different decision possibilities have.
6. Technologies named as intelligent or smart are only providing the support for decision makers - transfer of responsibility would be a misuse of technology. Even the results of the procedures may look like intelligent/smart, it has to be pointed out, that algorithms execute procedures as we define. Therefore, the suitability of procedures or technology for particular purpose is human decision as well as the confirmation of the final solution/measure.

We can conclude, that new technologies can greatly support decision making in tunnel design, operation and traffic management on the road network in the light of present and future challenges. Presentation of some of the approaches and technologies are the motivation for the use of ICT. By that, we would like to rise the technology level in civil engineering on the new level, comparing to other technological branches.

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