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MANAGEMENT OF TUNNELS ON THE ZAGREB – MACELJ MOTORWAY IN THE COURSE OF TUNNELS EXPLOITATION

UPRAVLJANJE TUNELIMA NA AUTOCESTI ZAGREB – MACELJ TIJEKOM UPORABE TUNELA

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Abstract

The paper focuses on the features of management of tunnels on the Zagreb-Macelj motorway. Management of tunnels is represented trough public-private partnership model that is applied on the Zagreb-Macelj motorway. In the course of tunnel operation and maintenance in the first five years of tunnels exploitation, the emphasis is put on the maintenance of the tunnel equipment systems. Tunnels as part of the motorway alignment are the most demanding facilities for maintaining appropriate safety and operational level in order to rich continuous availability providing safe and quality of service to the motorway users. The goal of the tunnel operation and maintenance is to ensure undisturbed and safe traffic flow through the tunnels by keeping the tunnel at the normal functional conditions.

Sažetak

U radu su prikazane značajke gospodarenje tunelima na autocesti Zagreb – Macelj tijekom eksploatacije tunela. Gospodarenje tunelima prikazano je putem modela javnog – privatnog partnerstva koji je primjenjen na autocesti Zagreb – Macelj. Prilikom upravljanja i održavanja u prvih pet godina eksploatacije tunela naglasak je na održavanju tunelskih sustava opreme. Tuneli kao dio autoceste najzahtijevniji su objekti za održavanje kao i za očuvanje razine upravljanja koje osigurava sigurnu i kvalitetnu uslugu korisnicima autoceste. Upravljanje i održavanje tunela ima za cilj održati normalne funkcionalne uvjete u tunelima te na taj način osigurati nesmetano i sigurno odvijanje prometa kroz tunele.

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1. Introduction

Zagreb – Macelj motorway is a part of the Pyhrn road route. The motorway is marked as A2 in Croatia, while it is classified in European road routes as E-59 connecting northern and central parts of Europe with its southern-eastern part. The motorway stretches from interchange Jankomir (part of the Zagreb ring road) up to interchange Trakošćan (Slovenian border, border crossing Macelj). The length of the motorway is 60 km and it is divided into the following sections (from south to north): section Zagreb (interchange Jankomir) - Zaprešić with length of 7.4 km; Zaprešić – Krapina with length of 34.7 km; Krapina – Macelj with length of 17.9 km. The greatest part of the motorway passes through flat area while at section Krapina – Macelj it passes into a mountainous area. Section Krapina – Macelj represents a new motorway section through a mountainous area that consists of a two new interchanges (interchanges Đurmanec and Trakošćan) with toll stations, six tunnels, nine viaducts which were constructed and opened for traffic in May 2007. On portion of this section 3.7 km half motorway for two-direction traffic was constructed. This subsection consists of two tunnels and three viaducts. Since 2004 Concession Company Autocesta Zagreb-Macelj Ltd, which had been awarded the concession by the Republic of Croatia, manages motorway Zagreb-Macelj. Zagreb-Macelj motorway is a typical example of infrastructure project of public-private partnership (PPP) where Strabag is a private partner and the Republic of Croatia is a public partner. Tunnels on the Zagreb-Macelj motorway are in use as of May 2007. The Concession Company contracted an Operation & Maintenance contract with company EGIS Road Operation Croatia Ltd, a company which is part of EGIS Road Operation S.A. that belongs to GROUPE EGIS. The tunnels are operated from the O&M Centre Krapina, located at the Krapina interchange, which marks the beginning of the Krapina-Macelj motorway section. The paper focuses on the features of operation and maintenance of tunnels on the Zagreb-Macelj motorway which is in use as of May 2007. In the course of tunnel maintenance in the first five years of tunnels exploitation, the emphasis is put on the maintenance of the tunnel equipment systems.

2. Operation of tunnels on the Zagreb-Macelj motorway

There are six tunnels on Zagreb – Macelj motorway. All six tunnels are located at section Krapina – Macelj. Table 1 shows lengths of the tunnels. On portion of section Krapina – Macelj with length of 3.7 km half motorway was constructed with two tunnels (Sv. Tri Kralja Tunnel and Brezovica Tunnel) which have one tunnel tube each. Both tunnels are constructed for bidirectional traffic. Other four tunnels have two tunnel tubes each, that is, they are constructed for full profile motorway. As it is presented in table 1, tunnels, Levačica, Vidovci, Đurmanec and Frukov Krč, less than 500 m in length have each tunnel tube dedicated for one traffic direction. In total that is ten traffic tunnel tubes and one service tunnel tube.

Table 1. Tunnels length in direction south (Zagreb) – north (Macelj)
Tablica 1. *Dužina tunela u smjeru jug (Zagreb) – sjever (Macelj)*

Tunnel	Right Tunnel Tube (m)	Left Tunnel Tube (m)
Levačica	358	374
Vidovci	261	266
Sv. Tri Kralja	1740	1242 (service tube)
Brezovica	590	not constructed
Đurmanec	204	204
Frukov Krč	354	354

Tunnel tubes are parallel with 25 m axis distance. The final concrete lining thickness amounts to 40 cm. The dimensions of tunnel clearance are 9.2 m in width and 4.5 m in height, while the light opening is of 56.5 m^2 surface. Figure 1 shows typical view on tunnel tube of tunnels that are constructed for full profile motorway.

Figure 1. View on tunnel tube
Slika 1. Pogled na tunelsku cijev

The left tunnel tube of Sv. Tri Kralja Tunnel was constructed as a service tunnel tube (escape gallery) and the dimensions of tunnel clearance are 3.6 m in width and 3.5 m in height, while the light opening is 18 m^2. The service tube of Sv. Tri Kralja Tunnel was constructed only with primary support with 20 cm thick shotcrete support, while final concrete lining was not envisaged. The service tube of Sv. Tri Kralja Tunnel has one entry/exit portal on south side and it is connected to the traffic tunnel tube with five cross passages for pedestrians from which three cross passages served for vehicles. This service tunnel tube served like evacuation route in case of accident or unwanted events for tunnel users and access for emergency vehicles as well as operator's service vehicles. Figure 2 shows service tunnel tube of Sv. Tri Kralja tunnel.

Figure 2. Sv. Tri Kralja Tunnel view on service tunnel tube
Slika 2. *Pogled na sevisnu tunelsku cijev tunela Sv. Tri Kralja*

On figure 3 is shown view on traffic tunnel tube of Sv. Tri Kralja Tunnel that is constructed for bidirectional traffic.

Figure 3. Sv. Tri Kralja Tunnel view on traffic tunnel tube
Slika 3. *Pogled na prometnu tunelsku cijev tunela Sv. Tri Kralja*

The tunnels are operated from the Operation and Maintenance Centre Krapina, located at the Krapina interchange, which marks the beginning of the Krapina-Macelj motorway section. Operation and Maintenance Centre Krapina is shown on figure 4.

Figure 4. View on O&M Centre Krapina

***Slika 4**. Pogled na COKP Krapina*

The Concession Company Autocesta Zagreb – Macelj Ltd (the Concessionaire) is a special purpose company with limited liability incorporated under the laws of Croatia and has been established to design, finance, construct, operate and maintain the Zagreb – Macelj motorway. The Concession Company (the Concessionaire) subcontracted operation and maintenance of the motorway under the Operation and Maintenance Contract to the company EGIS Road Operation Croatia Ltd (the Operator), a company which is part of EGIS Road Operation S.A. that belongs to GROUPE EGIS. Figure 5 shows relations and interactions between Concessionaire and Operator. As it figure 5 has shown, the Concessionaire manages with strategic decisions of tunnels (the motorway), while the Operator carried out operational scope of responsibility. Responsibility of the Concessionaire is carried out with extraordinary maintenance, renewal, enhancements, provision of spare parts, upgrading of tunnel equipment systems, follow up progress of operation and maintenance. Extraordinary maintenance, renewal and enhancement programme is prepared by the Concessionaire with assistance of the Operator. The Concessionaire is following up progress and performance standards of the operation and maintenance of tunnels (motorway) in accordance with Operation and Maintenance Contract and implementation of the bylaws related to the operation and maintenance. The Operator is obligated to perform routine maintenance (preventive and corrective maintenance) in accordance with Operating and Maintenance plan. Operating and Maintenance Plan has implied proposed actions by the Operator for performing operation and maintenance of motorway (tunnels). For each operating year the Operator is developing operating and maintenance plan, which has to be acceptable for the Concessionaire. Such yearly plan is based on the bylaw, operation and maintenance manuals, requirements and procedures. The Operator is continually informing the Concessionaire about status conditions of the structures and the technical equipment on the motorway trough reports (monthly, quarterly, annually), regular meetings and notifications. Tunnels (motorway) operation phase is starting after construction phase of tunnels is finished, test on completion by Relevant Authority is successfully carried out which resulted with issuing of use permit and finally when the Concession Company hand over the motorway to the Operator for operation and maintenance then tunnels are ready for use (open for traffic).

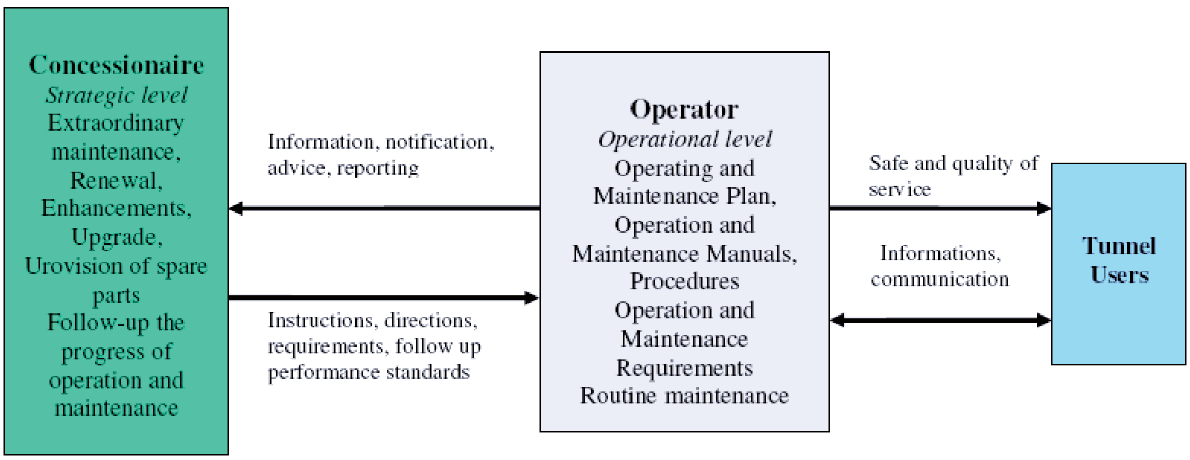

Figure 5. Relations and interactions between the Concessionaire and the Operator

***Slika 5.** Odnosi i interakcije između koncesionara i upravitelja*

Operation of a tunnel requires, first and foremost, a systematic approach to undisturbed and safe traffic flow through the tunnels, which makes it necessary to optimize all the parameters of the tunnel as a whole, ranging from tunnel equipment systems, through maintenance and monitoring of tunnel structure, to the readiness to act in case of undesirable events.

In case of the traffic safety, operation of tunnels include following basic factors: tunnel infrastructure (passive safety measures), tunnel Operator (active safety measures), tunnel users, tunnel traffic structure and traffic volume. Tunnel infrastructure or passive safety measures mean tunnel structural features as well as tunnel equipment systems features. Tunnel structural features understands number of tunnel tubes, geometry of tunnel, lining type, escape gallery, cross passages numbers, drainage types, rock mass characteristics, excavation method and support type etc. Tunnel equipment systems features includes installed equipment systems such as: tunnel lighting; tunnel ventilation and CO, wind speed and visibility devices; fire detection system; traffic management system; tunnel SOS phones; public address loudspeaker; radio diffusion system; CCTV (AID based) control and supervision system (SCADA); tunnel UPS devices; water supply and hydrant network system etc. The function of installed equipment is to improve road safety, while ensuring timely and high-quality information for users and employees regarding the conditions on the motorway. Active safety measures represent operator's procedures, implementation of this procedures, cooperation and communication with emergency services, and maintenance of tunnel infrastructure. Operator's procedures consisted standard operating procedures and emergency procedures. Standard operating procedures are used for coordination, analyses and passing on the information gathered from the various tunnel equipment systems helping the Operator to make the right decisions in operational process.

In standard operating procedures are defined activities needed to be performed when operator is reporting malfunction and rectification of equipment. In order to ensure normal and reliable operability of all tunnel systems with minimum disturbance of the traffic, to protect data integrity and to reduce non availability of the equipment to minimum. As component (Pili, 2008) to Standard operating procedure with defect report and maintenance response is Disaster Recovery procedure ensuring business contingency of Zagreb – Macelj motorway.

Emergency procedures are used for emergency cases such as the accidents or undesirable events that represent a serious interruption of traffic safety. Such cases require quick implementation of temporary measures or usage of resources until the end of the accident or interruption. In accordance with the bylaw, the Operator has the duty to organize fire fighting duty, and fire fighting drills have to be conducted in order to ensure the readiness of staff members and the functionality of the system in case of possible unwanted events. In the course of one year, five "dry" drills are conducted (which includes checking the readiness to start the intervention at the required speed, under full fire fighting equipment), as well as one "wet" drill (where the simulation includes unwanted events, together with the consequences of fire). Wet drills are conducted in the longest tunnels, Sv. Tri Kralja tunnel and/or Brezovica tunnel, both of which are tunnels with two-way traffic. Each year, a different script of an accident is prepared, and all the relevant services (Service 112; the police; emergency health service; public fire fighting unit; etc.) are included in the wet drill. Furthermore, when it comes to tunnels with two-way traffic, there is an increased level of maintenance of systems directly connected with fire protection, which is logical given the flow of activities aimed at the prevention of unwanted events. The Operator is tackling the tunnels with two-way traffic with even more attention than usual, precisely because of the increased risk of unwanted events taking place.

Maintenance of tunnel infrastructure represents one of the operational tools in tunnels operation. It is carried out in accordance maintenance manual, requirements, bylaw that is included and amplified in operation and maintenance procedures.

Tunnel maintenance works can be divided into maintenance works on a tunnel as a structure on the one hand, and, on the other hand, there are the maintenance works on the tunnel equipment system. Maintenance works on tunnels as structures include the following: tunnel inspection; tunnel cleaning; and construction maintenance of the tunnel. Tunnel inspections can be periodical (e.g. seasonal inspections and yearly inspections), and there are also general tunnel inspections, as well as extraordinary inspections. Periodical inspections include the visual inspection of the tunnel. Seasonal inspections are performed after the winter and summer periods (prior to and after the tourist season), and they are undertaken in order to evaluate traffic safety and effectiveness of tunnel equipment, with the aim of recognizing certain characteristics that might point to damage. Annual inspection is conducted at least once every two years, in order to estimate the tunnel condition, and to evaluate possible damage that tunnel elements might be exposed to. There is also the need to evaluate safety and usability of the tunnel in the coming period, until the next annual inspection. General inspection (Mlinarević, 2007) of tunnel as a structure is conducted at least once every six years. It includes a detailed inspection of the tunnel as structure, which is a task performed by the trained staff members of the Operator, together with a specialized external expert company. Tunnel inspections provide insight into possible damage and shortcomings of a tunnel, in terms of its structure stability, traffic safety, and the durability of tunnel structure. When it comes to tunnel cleaning, it includes cleaning of all the elements of the tunnel drainage system; cleaning of tunnel walls and tunnel equipment, accompanied by tunnel washing. The cleaning of the tunnel drainage system is conducted periodically, with prior inspections of the comprehensive drainage system. Drainage systems of dual-tube tunnels are cleaned in the following manner: two times per year sidewall drainage is cleaned together with the drainage of portal areas and portal structures. Lateral drainage connections in carriageway and the main drainage (sewage system) are cleaned once per year. In tunnels with two-way traffic in a single tube the main drainage (sewage system) is cleaned three times per year; sidewall drainage together with additional drainage in invert part is cleaned four times per year; lateral drainage connections in carriageway, and drainage of portal areas and portal structures are cleaned two times per year. The works required in the process of tunnel cleaning for single-tube tunnels with two-way traffic are coordinated in such a way that the cleaning is performed exclusively at night, with traffic redirection. Depending on the findings of tunnel inspection, construction maintenance of the tunnel may be needed. Construction maintenance of the tunnel includes regular and extraordinary maintenance. Routine maintenance pertains to the cleaning and smaller repair works that are conducted in accordance with technical requirements. Extraordinary maintenance includes the works involving repair or reconstruction of segments of the tunnel, or the tunnel as a whole, and such works necessitate the preparation of technical documentation. Operation and maintenance documentations are issued in accordance with environmental protection standards requested the bylaw and enforcement with the Environmental Management and Social Plan during operation for Zagreb – Macelj motorway.

Actual traffic structure and traffic volume are essential part of tunnel operational process. Following and analysing of the traffic structure (content of load traffic, buses, and dangerous goods traffic in overall daily or in periodical traffic and similar) and the traffic volume in tunnels are needed in order to reach required operational level in implementation of active safety measures in accordance with actual traffic situation in tunnel. Important place in the realisation of the traffic safety in tunnels has transport of dangerous goods through tunnels. In accordance with restrictions on transport of dangerous goods through tunnels and categorization of tunnels, book of regulations for transport of dangerous goods through is issued. This book of regulations for transport of dangerous goods through tunnels is founded upon the bylaw and the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR). This book of regulations is related for the longest tunnel on Zagreb – Macelj motorway that is Sv. Tri Kralja tunnel. Furthermore, in year 2011, in accordance with the new bylaw, the Concessionaire issued risk assessment for transportation of dangerous goods through tunnels longer than 500 m based on QRAM (**Quantitative Risk Assessment Model)**. The Concessionaire submitted risk assessment to the relevant authority for confirmation.

Traffic safety is strongly depending on behaviour of tunnel users. Respecting the safety rules in tunnel as well as usage of safety devices in case of accident or undesirable events by tunnel users is crucial for safe tunnel use and the operational process. Informing users about the safety rules and usage of the safety devices in tunnels is important contribution to the tunnel traffic safety. It is essential that users becoming familiar with tunnels like safe traffic structures.

Besides mentioned basic factors one of essential tool in tunnels operation and maintenance is transfer of data and knowledge from design and construction phase to tunnels operation phase. Design documentations (main, detailed and as built design), records, tests and reports about quality of used materials and works during construction represent basic data for operation and maintenance phase. Keeping up with the latest technology developments together with knowledge from design and tunnel construction phase, is representing foundation for strengthening the efficiency and permanently improving the level of operational practices.

Exchanging of experience and information with others Concessionaires and Operators in Croatia and Europe is also the substantial tool for improving the operational level. In Croatia this is possible through the Croatian Association of Toll Motorways Concessionaires (HUKA) that is full member of ASECAP. The Concession Company Autocesta Zagreb – Macelj Ltd is HUKA member. In accordance with mentioned basic factors, tunnel operation shall be consider at the same time as complex and flexible system that is based on four phase cycle: planning, implementation, monitoring and analysis as it is shown in figure 6.

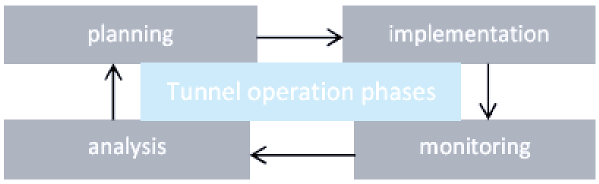

Figure 6. Tunnel operation phases
Slika 6. Faze upravljanja tunelom

First phase of cycle begin with planning. Planning phase includes development, evaluation and establishment of operational plan as well as potential anticipated impacts and their assessment. It is continued with realisation of operational plan. Realisation of operational plan requires proper and timely maintenance of the safety facilities in tunnels that includes defect report and maintenance response. Active monitoring of the realisation of the operational plan is following phase. Analysis of operational efficiency is carried out through monitoring results and performance indicators that are specific for each phase of operation process. From figure 6 emergent that tunnel operation covers two fundamental periods: period of preparation of operation (this is the period of selection and planning of technical and technological solutions for operation, and organizing the implementation of operation) and period of actual operation (introduction and implementation of selected technical and technological solutions for operation as well as organizational tunnel operation structure; monitoring and analysing the operation). When we think of tunnel operation as a comprehensive system, in which certain phases of operation constitute separate (sub)systems, it turns out that the optimum efficiency of a tunnel operation system can be achieved only when we harmonize the performance of all operation functions, having in mind the goals inherent in the comprehensive system, rather than in separate parts. The efficiency of these (sub) systems lies in the function of tunnel operation. For successful tunnel operation, it is important to fulfil the goal of the whole, which means fulfilling the goal of the tunnel function per se: primarily ensuring an undisturbed and safe traffic flow through the tunnel.

2.1. Risks in tunnel operation

In general, key risks that are present in business activity and that are not necessarily connected with construction, operation and maintenance of tunnels can be described as follows: political risk; economic risk; legal risk; force majeure risk; technical risk. The first four risks are general risks pertaining to all types of business activity. However, technical risk is a specific risk for underground constructions and tunnels. Technical risks in the course of tunnelling can be divided into three categories (Dudeck, 1987): risks in connection with the task or purpose of tunnel, or risks connected with mistakes and misjudgements, which makes it impossible to use the constructed tunnel for its purpose (functional risks); risks in connection with the structure as construction – mistakes and misjudgements in constructions (especially primary support and final lining of a tunnel), which render it difficult or impossible to efficiently construct the tunnel, but also to use it safely (construction risks); risks in connection with the contracting of tunnel works (contractual risks). The functional risk is particularly present in the course of tunnel operation and maintenance, and we come across it in the course of tunnel exploitation on a daily basis. Tunnel management has the aim of ensuring, first and foremost, unhindered and safe traffic flow through the tunnels. In this context, it is necessary to optimize all parameters of the tunnel as a whole, ranging from tunnel equipment systems, to the maintenance and monitoring of tunnel structure, as well as readiness to act in case of undesirable events. The very goal of tunnel operation makes it necessary to manage the key risk: functional risk. Managing functional risk is based on an interaction of the four factors outlined above (passive and active safety measures; tunnel users; structure and volume of tunnel traffic), which impact upon the safety of tunnel traffic. Tunnel operation in the course of exploitation can be described using three fundamental factors: risk decisions, which are a consequence of decision-making within the organization of tunnel operation under the conditions of risk; hazards as accidental events of any kind in the environment, or within the management system; risk states in the management system and its environment. These three fundamental factors – risk decisions, hazards and risk states – simultaneously represent the causes of functional risk. Information and corresponding communication, present in the interaction of these factors of tunnel operation, represent the key sources of risk in tunnel operation, or key sources of functional risk. These three key causes of functional risk in tunnel operation in the course of exploitation also constitute the origin of various areas and sources of functional risk. In this context, we can emphasize the following: environment (tunnel traffic) in which tunnel operation is ongoing; management subjects, i.e. organizational tunnel operation structure; information and corresponding communication within the operation system, and including the environment; safety of human beings and property within the management organization, and within the environment (traffic). Given the fact that active safety measures stem from the procedures of the Operator, the efficiency of passive safety measures stems from efficient maintenance of tunnel infrastructure, and all activities stemming from safety measures are taking place during the use of the tunnel (when traffic is in place). Therefore, we can conclude that tunnel operation risk is a functional risk, with maintenance risk and traffic risk as consequences. Based on the issues discussed above, we can define three key functional risks in regard to tunnel operation: tunnel operation risk, tunnel maintenance risk, and tunnel traffic risk. Tunnel operation risk is a composite risk: tunnel maintenance risk and tunnel traffic risk stem from it. After functional risk in tunnel operation was identified, qualitative and quantitative analyses are following. Table 2 presents features of functional risk in tunnel operation in qualitative term. Functional risk in tunnel operation is analysed trough quantitative analysis in accordance with causes, sources and consequences by such risk includes. Functional risk in tunnel operation, in quantitative terms represents cost value in form of lost income. Lost income is consequence of issues such as: traffic jam; possibility of traffic accident or incident that would result in traffic jam and closure of the tunnel and/or entire motorway section; possible loss of traffic in the course of tunnel reconstruction due to a traffic accident or incident; subsequent damage to the reputation of the concession company; etc.

Table 2. Features of functional risk in tunnel operation in qualitative term

Tablica 2. *Obilježja funkcionalnog rizika upravljanja tunelom u kvaliativnom smislu*

		Tunnel operation risk	Tunnel maintenance risk	Tunnel traffic risk
Cause	Risk decisions	from operation and maintenance plan; from operators (adaptability to changes)	in ordinary maintenance procedures	in traffic structure analysis
	Risk states	active safety measures (standard operative procedures, emergency procedures)	terms of quality insurance in maintenance	users behaviour in traffic (respecting of safety rules in tunnel); operator behaviour during unwanted event
	Hazards	condition of passive safety measures; frequency and intensity of traffic accident or undesirable events	tunnel infrastructure state	share of dangerous goods in traffic structure
Source		management subjects, organizational tunnel operation structure (operator experience) environment (tunnel traffic)	management subjects, (organizational tunnel maintenance structure)	structure and volume of tunnel traffic
Consequence		endangers material and financial damage (tunnel closure etc.); influence on safety (users and operators employees)	endangers financial damage; possible safety damage	endangers material damage form possible traffic accidents (destruction of tunnel infrastructure); possible injuries or death of users and/or operators employees

Consequently lost income stems from consequences of functional risk in tunnel operation. Cost value of lost income is carried out by comparing incomes for the same motorway section in cases when mentioned section is opened and closed for traffic in certain period of time (i.e. for same month, week or day of last and current year etc.) and can be expressed as cost value per time e.g. HRK/month, HRK/day or HRK/hour etc.

3. Maintenance of tunnel equipment systems

In the course of tunnel maintenance in the first five years of tunnels exploitation, the emphasis is put on the maintenance of the tunnel equipment systems.

Tunnels on Zagreb – Macelj motorway are designed in accordance with the regulations and the comprehensive legal framework of the Republic of Croatia and Austrian directives RVS issued in year 2002. According to we can divide them into two groups, based on their length and the direction of traffic. The first group consists of tunnels less than 500 m in length, with one-way traffic where each tunnel tube is dedicated for one traffic direction, that are tunnels Levačica, Vidovci, Đurmanec and Frukov Krč. The second group consists of tunnels longer than 500 m, with two-way traffic that are tunnels: Sv. Tri Kralja and Brezovica. Tunnels on the Zagreb-Macelj motorway include the following installed equipment systems: tunnel lighting; tunnel ventilation and CO, wind speed and visibility devices; fire detection system; traffic management system; tunnel SOS phones; public address loudspeaker; radio diffusion system; CCTV (AID based) control and supervision system (SCADA); tunnel UPS devices; water supply and hydrant network system. According to tunnels length, table 3 outlines the share of various equipment systems in tunnel groups. Maintenance of tunnel equipment systems, in a wider sense of the word, includes all the works necessary in order to determine the condition of these tunnel systems and their operational capacity, as well as all the works necessary to preserve the tunnel systems in technical working order.

Table 3. Share of various equipment systems in tunnels
Tablica 3. Podjela različitih sustava opreme u tunelima

Tunnel equipment system	Tunnels length < 500 m	Tunnels length > 500 m
Tunnel electricity supply	yes	yes
Tunnel lighting	yes	yes
Tunnel ventilation	no	yes
CO, visibility and wind speed devices	no	yes
fire detection	yes	yes
Traffic management	yes	yes
Tunnel SOS phones (ERT system)	no (only in portal areas)	yes
Public address loudspeaker	no	yes
Radio diffusion	no	yes
CCTV	no (only in portal areas)	yes
CSS (SCADA) system	yes	yes
Tunnel ups system	yes	yes
Water supply and hydrant network	no	yes

Maintenance (Deković, 2011) of an individual system consists of the works dedicated to routine maintenance, which are performed according to a certain maintenance plan, and the works dedicated to extraordinary maintenance, which needs to be done urgently due to worsened operational and functional conditions. The works on equipment system maintenance can be performed by staff members of the Operator, who have received expert training for that purpose, and by external collaborators or companies as well; these players can act independently or jointly, depending on the needs, and also depending on the type of facilities, specialized systems, devices and installations, and depending on the complexity of works. Routine system maintenance includes the following: regular inspections, preventive maintenance works, corrective maintenance works (smaller repair and replacement of worn parts); regular certification; measurement and testing. Extraordinary maintenance of the equipment system includes extraordinary inspection, renewal, and urgent interventions, which are performed urgently due to worsened functional and operative conditions in the system. Tunnel equipment systems are functional units that together create the comprehensive system for control, management and safety of traffic in the tunnels. Safety measures provided by tunnel equipment systems should enable people involved in incidents to rescue themselves, allow motorway users to act immediately so as to prevent more serious consequences, ensure that emergency services can act effectively and protect the environment as well as limit material damage. Recovery Point Objective (RPO), the acceptable level of system loss in distressed situation which needs to be recovered, is determined per each tunnel system of Zagreb – Macelj motorway in Minimum Operating Conditions procedure. Minimum Operating Conditions are defining measures to be undertaken per each system condition described in four system states: nominal, bearable, critical, and endanger states which are shown in table 4.

Table 4. Minimal Operation Conditions states
Tablica 4. *Stanja minimalnih uvjeta upravljanja*

State	Definition of the state	Measure to implement	Impact/action
Nominal	System in normal functional conditions	—	—
Bearable	Minor system failure	Deferred Maintenance response required	—
Critical	Significant system failure	Urgent Maintenance response required	Additional safety measures required
Endanger	Minimum operating conditions endangered	Urgent Maintenance response required	Tunnel closure

Maintenance and operation of tunnel equipment systems based on Minimal Operating Conditions is represented in figure 7. As it is schematic represented in figure 7, operation and maintenance is based on information on current stage of the equipment system, relevant reactions necessary for maintaining of the high security levels and reliable functionality of the comprehensive tunnel equipment system.

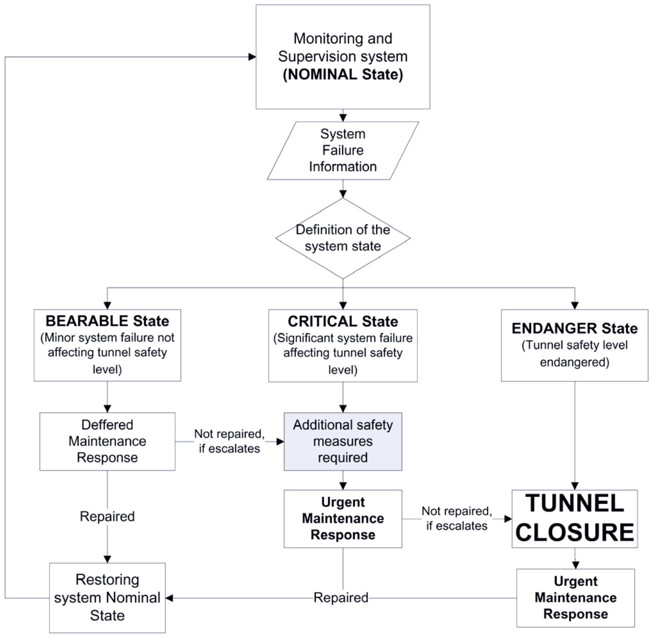

Figure 7. Tunnel equipment system minimum operating conditions flowchart
Slika 7. *Dijagram toka minimalnih uvjeta upravljanja sustavima tunelske opreme*

In terms of business continuity aspect, undisturbed traffic throughout Zagreb – Macelj motorway, tunnels are the most demanding facilities for maintaining appropriate safety and operational level to in order to rich continuous availability. Operational and maintenance procedures and measures are focused in that direction. Tunnels involves high capital investment in construction, operating and maintenance cost in exploitation but also very important cost is for equipment and installations renewal which have service life far less then tunnel structure. The relationship (PIARC, 2005) between the cost of maintenance and the level of influence exercised on these costs can be illustrated as it is shown in figure 8.

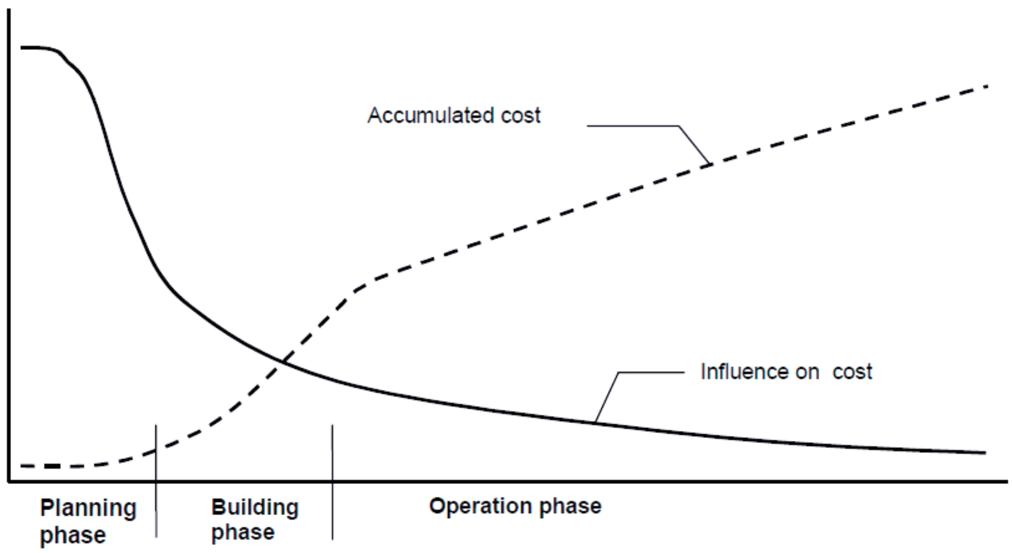

Figure 8. Illustration of accumulated cost and corresponding level of influence on cost (PIARC, 2005)
Slika 8. *Prikaz akumuliranog troška i odgovarajuće razine utjecaja na trošak (PIARC, 2005)*

In general, the planning phase is normally 3 to 10 years, the construction phase 2-3 years while the operational phase may be from 5 to 20 years for installations/systems and 80 to 100 years for the tunnel structure. This does not include possible refurbishment activities. Life cycle of tunnel (technical) equipment systems is a point where replacement is appropriate rather then continued use in economic bases in relation of operating and maintenance cost due to a greater risk of failure and unreliability increase impacting on safety level and endangering tunnels availability. Tunnel equipment systems life cycle depends on various external factors impacting significantly on realized life duration. Systematic approach with comprehensive methods, monitoring and mitigation of such factors are essential in reaching intended life cycle duration or even longer. Essential tools for reaching intended life cycle duration of tunnel technical equipment is implementation of preventive and corrective maintenance as well as monitoring of tunnel equipment systems errors. In the course of motorway operation tunnels with two-way traffic (Sv. Tri Kralja and Brezovica Tunnels) are representing potential higher risk places on the motorway than other four tunnels that are constructed for full motorway profile. Therefore implementation results of preventive and corrective maintenance of tunnel equipment systems is analysed for these two tunnels. Figure 9 shows preventive and corrective maintenance ratio of tunnel equipment systems from beginning of tunnel use in year 2007 until year 2011. Number of tunnel equipment systems failures is shown in figure 10.

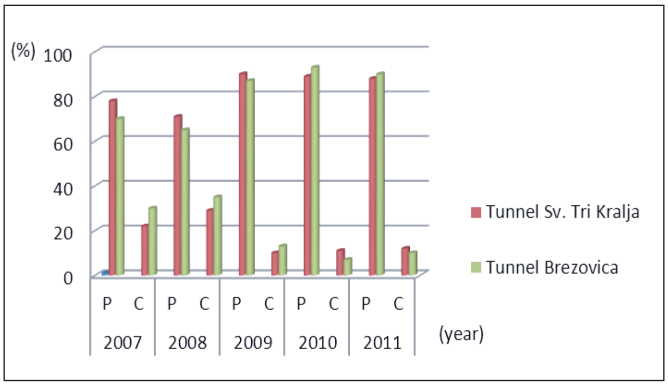

Figure 9. Average ratio preventive and corrective maintenance per year of use Sv. Tri Kralja and Brezovica tunnels

Slika 9. *Prosječni odnos preventivnog i korektivnog održavanja po godini uporabe tunela Sv. Tri Kralja i Brezovica*

Figure 10. Average number of equipment systems failures per year of use Sv. Tri Kralja and Brezovica tunnels

Slika 10. *Prosječni broj pogrešaka sustava opreme po godini uporabe tunela Sv. Tri Kralja i Brezovica*

The figures 9 and 10 make it clear that the number of equipment system failures were increased at the very beginning of exploitation of the tunnels. Therefore the need for interventions in the area of corrective maintenance was also higher. Such a situation is expected, given the fact that certain initial optimization of the system, or the "balancing" of individual systems, was necessary in the initial period of system use. In the following years of exploitation of the tunnels it is visible trend of stabilization of the average number of system failures, as well as the average number of corrective maintenance interventions while efficiency of the preventive maintenance is increasing.

3.1. Optimisation of tunnel equipment systems parameters

All inspections and maintenance works with related methods and techniques are managed and controlled trough specialised Asset Management System. Based (Deković, 2011) on maintenance technical feedback about tunnel equipment systems behaviour related per system and asset, tunnel's equipment systems Key Performance Indicators (KPI's) are following and analysing. A useful Maintenance Key Performance Indicators (KPI's) drives reliability growth while guiding management choices for improving maintenance effectiveness and efficiency. A useful maintenance KPI identifies the issues causing maintenance effects and helps in selecting the right strategy to either support or correct the actions producing the results. Between various, one of the most important KPI's is availability factor. Availability factor is comprised from two KPI's that are reliability factor (MTBF) and maintainability factor (MTTR). **Availability factor** is implied availability (1) like the proportion of time in which the system is in a functioning condition, the ratio of the total time a functional unit is capable of being used during a given interval to the length of the interval. Typical availability objectives are specified either in decimal fractions, such as 0.9998, or sometimes in a logarithmic unit called nines, which corresponds roughly to a number of nines following the decimal point, such as "five nines" for 0.99999. It is expressed with reliability factor (MTBF) and maintainability factor (MTTR):

$$Availability = \frac{MTBF}{MTBF + MTTR} \qquad (1)$$

Reliability factor represents mean time between failures (MTBF). That is the predicted elapsed time between inherent failures of a system during operation. MTBF can be calculated as the arithmetic mean (average) time between failures of a system. The MTBF (2) is the sum of the operational periods divided by the number of observed failures and can be expressed:

$$MTBF = \frac{\sum (start\ of\ downtime - start\ of\ uptime)}{number\ of\ failures} \qquad (2)$$

Mean time to repair or maintainability factor (MTTR) is a basic measure of the maintainability of repairable items. It represents the average time required to repair a failed component or device. It is the total corrective maintenance time divided by the total number of corrective maintenance actions during a given period of time and can be expressed (3):

$$MTTR = \frac{total\ corrective\ maintenance\ time}{total\ corrective\ maintenance\ actions} \qquad (3)$$

Figure 11. Tunnel equipment systems availability factor in Sv. Tri Kralja and Brezovica Tunnels

Slika 11. *Faktor korisnosti sustava tunelske opreme u tunelima Sv. Tri Kralja i Brezovica*

Following the tunnel equipment systems availability factor, presented in figure 11, is arising that systems are in proper functional condition kept on very high availability level. There is also visible functional stabilisation trend like it is shown in figures 9 and 10. Such a stabilization trend stem from high-quality routine maintenance that was performed, given the fact that routine maintenance is a foundation of functionality of each individual system, but also of the comprehensive system as a whole. Analyzes of the tunnel equipment systems throughout Key Performance Indicators represent one of the steps in the optimisation of tunnel equipment systems parameters. Figure 12 is shown optimisation process trough continuous improvement cycle of the operation and maintenance of tunnel equipment systems.

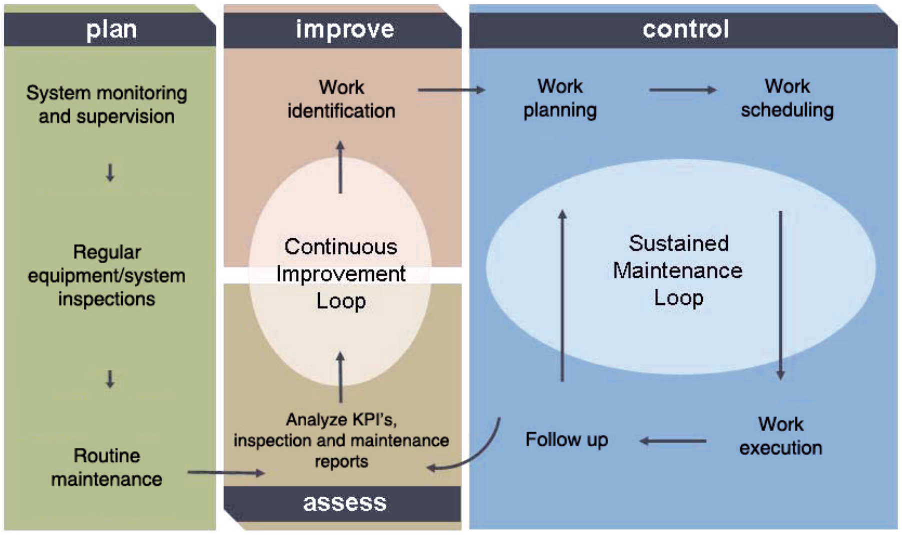

Figure 12. Tunnel equipment systems parameters optimisation cycle
Slika 12. *Proces optimizacije parametara tunelske opreme*

For each individual tunnel equipment system, as well as the comprehensive system as a whole, following phases of optimisation comprised in optimisation cycle as shown in figure 12 are carried out: observation of the tunnel equipment systems throughout system monitoring and supervision, regular inspections and routine maintenance; assessment of the tunnel equipment systems condition trough Key Performance Indicators, inspection and maintenance analyses; work identification; planning, scheduling and execution of work, follow up. Optimisation cycle represents systematic approach to the operation and maintenance of the tunnel equipment systems that is foundation for accomplished of the high safety level of tunnel conditions and functionality of tunnel equipment systems.

4. Conclusion

In terms of business continuity aspect, undisturbed traffic throughout Zagreb – Macelj motorway, tunnels are the most demanding facilities for maintaining appropriate safety and operational level in order to rich continuous availability. Tunnels operation is complex and demand activity that requires the systematic approach to undisturbed and safe traffic flow through the tunnels. As result of the systematic approach stems the optimised operational tunnel system that ensures maximum efficiency in tunnel operation and maintenance. Maintenance of tunnels, as one of operational tools, and in particular the maintenance of tunnel equipment systems, requires a high quality of services in terms of response time in case of malfunction, undesirable event or accident in a tunnel. Active monitoring of each individual system and of the tunnel equipment system as a whole throughout Key Performance Indicators represents basis for optimised operation of the tunnel equipment systems. Optimised operational tunnel system is representing answer on identified and analysed functional risks in tunnel operation. The Concessionaire and the Operator are dedicated to strengthening the efficiency and permanently improving the level of services provided to the motorway users by keeping up with the latest technology developments and the best operational practices.

5. References

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