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OPERATIONAL AND MAINTENANCE FEATURES OF THE SV. TRI KRALJA TUNNEL

ZNAČAJKE UPRAVLJANJA I ODRŽAVANJA TUNELA SV. TRI KRALJA

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Ključne riječi: održavanje, upravljanje, sustavi tunelske opreme, ključni pokazatelj radnog učinka

Abstract

The paper focuses on the features of the operation and maintenance of tunnels on the Zagreb-Macelj motorway. When it comes to the operation and maintenance of a series of six tunnels on the Zagreb-Macelj motorway, Sv. Tri Kralja Tunnel is the most challenging structure on the motorway, where it is necessary to provide an adequate level of safety and operability. Tunnel operation is ensured by the concession model of public - private partnership, which is applied to the Zagreb – Macelj motorway. Features of the tunnel infrastructure maintenance are emphasized, as well as importance of the extraordinary maintenance of the tunnel infrastructure. The goal of the tunnel operation and maintenance is to ensure undisturbed and safe traffic flow through the tunnels, by keeping the tunnel in normal functional conditions.

Sažetak

U radu su prikazane značajke upravljanja i održavanja tunela Sv. Tri Kralja na autocesti Zagreb – Macelj. Prilikom upravljanja i održavanja nizom od šest tunela na autocesti Zagreb-Macelj, tunel Sv. Tri Kralja predstavlja najzahtjevniji objekt na autocesti na kojem je potrebno osigurati odgovarajuću razinu sigurnosti i operativnosti. Upravljanje nizom od šest tunela prikazano je putem koncesijskog modela javnog – privatnog partnerstva koji je primjenjen na autocesti Zagreb – Macelj. Istaknute su značajke održavanja tunelske infrastrukture prilikom upravljanja tunelima kao i važnost razdoblja pripreme izvanrednog održavanja tunelske infrastrukture. 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.

1. Introduction

The Zagreb-Macelj Motorway is marked as A2 motorway in Croatia, and it is classified as E-59 motorway in European road routes, connecting northern and central parts of Europe with its southern-eastern part. The motorway stretches from the interchange Jankomir (part of the Zagreb ring road) up to the interchange Trakošćan (Slovenian border; border crossing Macelj).The length of the motorway is 60 km. When analysing the motorway profile from Zagreb to the direction of Macelj, the greatest part of the motorway passes through flat area, with the section Krapina – Macelj (length 17,9 km) passes through mountainous area. Summary length of structures (viaducts, **bridges, tunnels** etc.) on this section is 32% of the section length. The section Krapina – Macelj was constructed and opened for traffic in May 2007. This section includes the total of 6 constructed tunnels, with the total of 10 traffic tunnel tubes, and one service tunnel tube, as shown in Table 1, which provides an overview of tunnel length.

Table 1. Tunnels length in the direction south (Zagreb) – north (Macelj)
***Tablica 1.** Dužine 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

The section Krapina – Macelj includes half-motorway 3.7 km in length for two-direction traffic, with two tunnels (Sv. Tri Kralja Tunnel and Brezovica Tunnel) that have one tunnel tube each. The other four tunnels have two tunnel tubes each, i.e. they are constructed for full profile motorway. When it comes to its length and bidirectional traffic, tunnel Sv. Tri Kralja is the most demanding facility in terms of maintaining appropriate safety and operational level. Figure 1 presents a schematic view of the Sv. Tri Kralja Tunnel, with basic data about tunnel clearance.

Tunnel Sv. Tri Kralja consists of one traffic tunnel tube, which serves the purpose of ensuring bidirectional traffic, and one service tunnel tube. The service tunnel tube is used for access of emergency vehicles and evacuation users in the event of an accident, and also for access of maintenance vehicles during maintenance activities. As shown on Figure 1, the service tunnel tube is connected to the traffic tunnel tube via 5 cross passages. Furthermore, the service tunnel tube has only one portal entry – the south portal – and its length is approximately two-thirds of the traffic tunnel tube length. In accordance with design documentation, the service tunnel tube is constructed only as primary support.

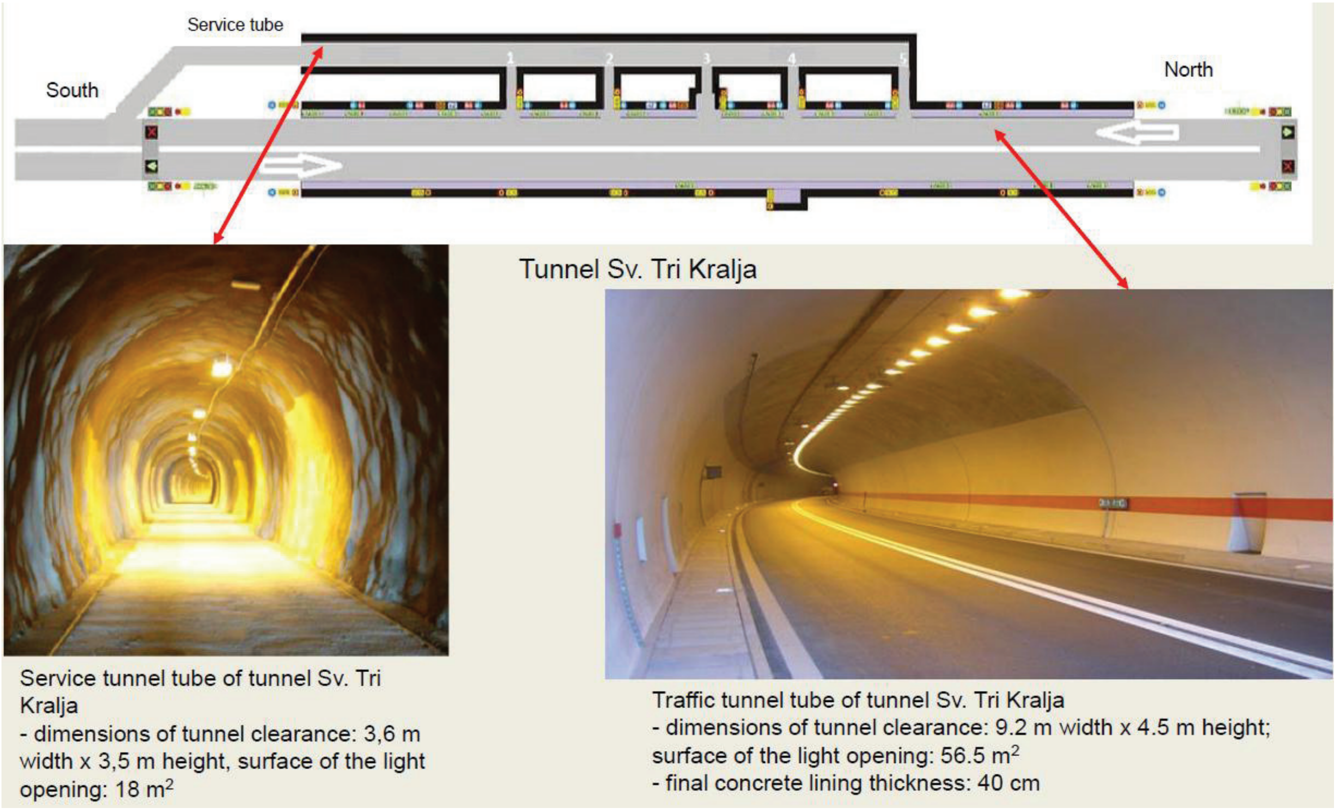

Figure 1. Schematic view of the Sv. Tri Kralja Tunnel
Slika 1. *Shematski prikaz tunela Sv. Tri Kralja*

2. Operational features of Zagreb-Macelj Motorway tunnels

Since 2004, Concession Company Autocesta Zagreb-Macelj Ltd, which had been awarded the concession by the Republic of Croatia, manages the Zagreb-Macelj Motorway. This motorway is a typical example of infrastructure project within the public-private partnership (PPP) model, with Strabag as private partner and the Republic of Croatia as public partner. The Concession Company signed the Operation & Maintenance Contract with the company EGIS Road Operation Croatia Ltd, representing the Operator Company. Figure 2 shows the relations and interactions between the Concessionaire and the Operator.

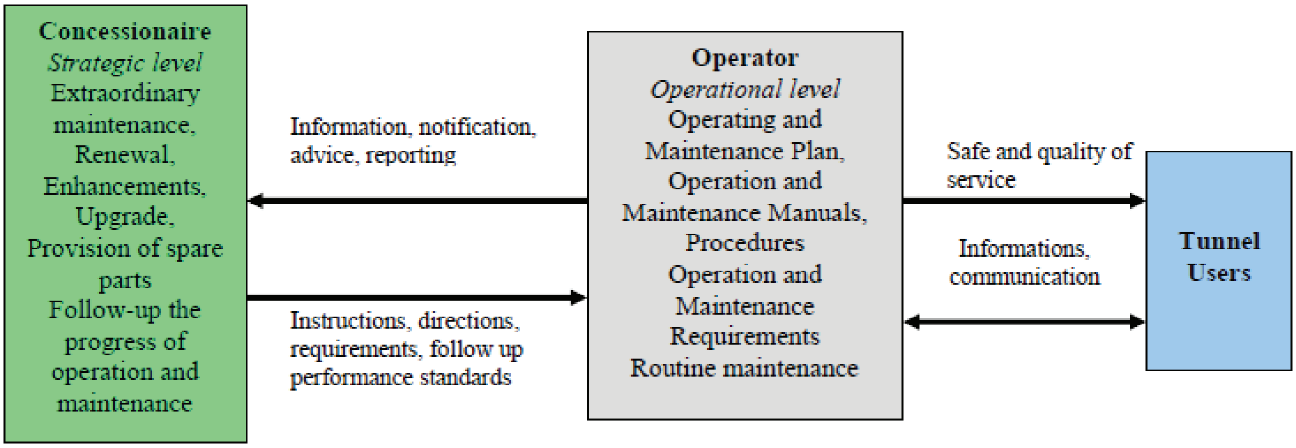

Figure 2. Relations and interactions between the Concessionaire and the Operator
Slika 2. *Odnosi i interakcije između Koncesionara i Upravitelja*

As displayed in Figure 2, the Concessionaire manages strategic decisions in regard to the tunnels (the motorway), while the Operator carries out activities within the operational scope of responsibility. The responsibility of the Concessionaire includes extraor-dinary maintenance, renewal, enhancements, provision of spare parts, upgrading of tunnel equipment systems, follow-up regarding the progress of operation and maintenance. Extraordinary maintenance, renewal and enhancement programme is prepared by the Conce-ssionaire, with the assistance of the Operator. The Concessionaire is following up progress and perfor-mance standards of the operation and maintenance of tunnels (motorway) in accordance with the Operation and Maintenance Contract, and in accordance with the bylaws pertaining to operation and maintenance. The Operator is obligated to perform routine maintenance (preventive and corrective maintenance), in accor-dance with the Operating and Maintenance Plan. This Plan includes proposed actions by the Operator for the implementation of operation and maintenance of the motorway (tunnels). For each operating year, the Operator is developing its operating and maintenance plan, which has to be acceptable for the Conce-ssionaire. Such annual plans are based on the relevant bylaws, operation and maintenance manuals, require-ments and procedures. The Operator is continually informing the Concessionaire about the status and condition of the structures and technical equipment on the motorway, trough reports (monthly, quarterly and annual), regular meetings, and notifications. The reports cover the situation regarding the tunnels as integral part of the motorway. 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 optimise 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. When it comes to traffic safety, operation of tunnels includes the following basic factors: tunnel infrastructure (passive safety measures); tunnel Operator (active safety measures); tunnel users; tunnel traffic analysis (traffic structure and traffic volume). Tunnel infrastructure, or passive safety measures, pertains to structural features of the tunnel, as well as the features of tunnel equipment systems. Structural features of the tunnel include the number of tunnel tubes; geometry of tunnel; lining type; escape gallery; number of cross passages; drainage types; rock mass characteristics; excavation method and support type; etc. Features of tunnel equipment systems include 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, the implementation of these procedures, cooperation and communication with emergency services, and maintenance of tunnel infrastructure. Operator's procedures consist of 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 the operational process. Standard operating procedures include defined activities that are required when the operator is reporting malfunction and rectification of equipment. The idea is to ensure normal and reliable operability of all tunnel systems, with the minimum disturbance of traffic, to protect data integrity, and to reduce non-availability of the equipment to minimum. One component (Pili, 2008) of Standard Operating Procedures, in connection with the reporting on defects and maintenance response, is the Disaster Recovery Procedure, ensuring business contingency of the Zagreb–Macelj Motorway. Emergency procedures are used in emergency cases, such as accidents or undesirable events that represent a serious interruption of traffic safety. Such cases require quick implementation of temporary measures or use of resources until the end of the accident or interruption. Tunnels are the most demanding facilities for maintaining appropriate safety and operational level in order to ensure continuous availability. Special attention is dedicated to fire protection. In accordance with the relevant bylaws, 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 include checking the readiness to start the intervention at the required speed, under full fire fighting equipment), as well as two "wet" drills (where the simulation includes undesirable events, together with the consequences of fire), and one technical intervention drill. 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. Figure 3 shows the detail from fire fighting drill in the Sv. Tri Kralja Tunnel.

Figure 3. Detail from firefighting drill in Sv. Tri Kralja Tunnel
Slika 3. *Detalj s vatrogasne vježbe u tunelu Sv. Tri Kralja*

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. Actual traffic structure and traffic volume are essential part of the tunnel operational process. Monitoring and analysis of traffic structure (the structure of load traffic, buses and dangerous goods traffic in overall daily or periodical traffic, etc.) and traffic volume in tunnels is needed in order to reach the required operational level in implementation of active safety measures, in accordance with the actual traffic situation in the tunnel. An important issue in the implementation of traffic safety in tunnels is the transport of dangerous goods through tunnels. In accordance with the regulations and the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR), book of regulations for transport of dangerous goods through tunnels is issued. This book of regulations applies to the longest tunnel on the Zagreb–Macelj Motorway – the Sv. Tri Kralja Tunnel. Furthermore, the Concessionaire issued the risk assessment for transportation of dangerous goods through tunnels longer than 500 m (Šimara, 2011), based on QRAM (Quantitative Risk Assessment Model). Traffic safety strongly depends on the behaviour of tunnel users. Respect for the safety rules in tunnel, as well as the usage of safety devices by tunnel users in case of accident or undesirable event, are crucial for safe tunnel use and the operational process. Informing users about the safety rules and usage of the safety devices in tunnels is an important contribution to the tunnel traffic safety. It is essential that users become familiar with tunnels as safe traffic structures. In order to manage these aspects as successfully and effectively as possible, it is necessary to ensure quality maintenance of tunnel infrastructure, founded upon the following: data and knowledge transfer from project documentation and the period of tunnel construction; continuous training of staff; monitoring of state-of-the-art technological achievements; exchange of experiences and information with other concession holders in Croatia and Europe, via the Croatian Association of Toll Motorways Concessionaires (HUKA). Maintenance of tunnel infrastructure is carried out in accordance with maintenance manuals, requirements and regulations, including and implementing the relevant steps in operation and maintenance procedures. Operation and maintenance documentation is issued in accordance with environmental protection standards required by regulations, and the Environmental Management and Social Plan is also being implemented on the Zagreb–Macelj Motorway. Transfer of data and knowledge from design and construction phase to tunnel operation phase is one of the essential tools in tunnel operation and maintenance. Design documentation (main, detailed and as built design), records, tests and reports about quality of used materials and works during the construction, all represent basic data for the operation and maintenance phase. Keeping up with the latest technology developments, together with knowledge from design and tunnel construction phase, constitutes the 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 a substantial tool for improving the work at the operational level. In Croatia, this is possible through the Croatian Association of Toll Motorways Concessionaires (HUKA) which is full member of ASECAP (*Association Européenne des Concessionnaires d'Autoroutes et d'Ouvrages á Péage*). In accordance with the mentioned basic factors, tunnel operation should at the same time be considered as a complex and flexible system based on the four-phase cycle: planning, implementation, monitoring and analysis, as shown in Figure 4.

The first phase of the cycle begins with planning. The planning phase includes development, evaluation and establishment of the operational plan, as well as potential anticipated impacts and their assessment.

The process continues with the realisation of operational plan. Realisation of operational plan requires proper and timely maintenance of safety facilities in tunnels, which includes defect report and maintenance response. Active monitoring of the realisation of the operational plan is the following phase. Analysis of operational efficiency is carried out through monitoring results and performance indicators that are specific for each phase of the operational process. As seen in Figure 4, 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 techno-logical 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.

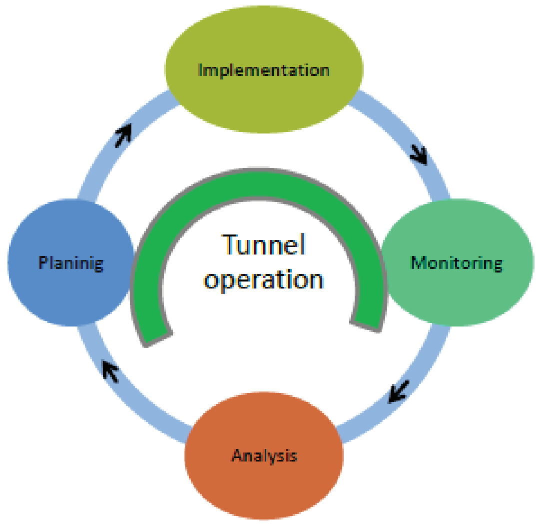

Figure 4. Tunnel operation phases
Slika 4. *Razdoblja upravljanja tunelom*

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.

3. Maintenance features of the Sv. Tri Kralja Tunnel

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. Table 2 shows the distribution of tunnel maintenance works. Maintenance works on tunnels as structures include the following: tunnel inspection; tunnel cleaning; and construction maintenance of the tunnel. Maintenance works on the tunnel equipment system include routine maintenance (regular inspections, corrective maintenance works, regular certification, measurements and testing) and extraordinary maintenance (extraordinary inspection, renewal, urgent interventions).

Table 2. Tunnel maintenance works distribution
Tablica 2. *Raspodjela radova održavanja tunela*

<table>
<tr><td></td><td colspan="2">Tunnel maintenance works</td></tr>
<tr><td></td><td>Maintenance works on the tunnel as structures</td><td>Maintenance works on the tunnel equipment system</td></tr>
<tr><td rowspan="4">Routine maintenance</td><td>tunnel inspections: periodical inspections, general inspection</td><td>regular inspections</td></tr>
<tr><td rowspan="2">tunnel cleaning: all elements of tunnel drainage system, tunnel walls, tunnel equipment, tunnel washing</td><td>preventive maintenance</td></tr>
<tr><td>corrective maintenance works (smaller repair, replacement of worn parts)</td></tr>
<tr><td>construction maintenance of tunnel: smaller repair works in accordance with technical requirements</td><td>regular certification, measurements and testing</td></tr>
<tr><td rowspan="3">Extraordinary maintenance</td><td rowspan="3">construction maintenance of tunnel: extraordinary inspection, repair or reconstruction works of segments of tunnel or tunnel as a whole (preparation of technical documentation is needed)</td><td>extraordinary inspection</td></tr>
<tr><td>renewal</td></tr>
<tr><td>urgent interventions (due to worsened functional and operative conditions in the system)</td></tr>
</table>

3.1. Maintenance of tunnel as structure

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 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. Upon each inspection, cleaning, or regular construction maintenance of the tunnel, the operator of the tunnel prepares the reports, which are then delivered to the Concessionaire. Based on need, these reports can be separate, e.g. dedicated to tunnel cleaning, tunnel drainage system cleaning, etc.; or they can be part of the report on regular periodical tunnel inspections. The link between routine and extraordinary maintenance can be seen in the example specialized external expert company. Tunnel inspections provide insight into possible damage and shortcomings of a tunnel, in terms of its structural 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.

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. 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. of cracks that appeared on the concrete lining of the tunnel, and the monitoring of stability of the service tunnel tube of the Sv. Tri Kralja Tunnel. During the regular periodical (seasonal) tunnel inspection, performed in the spring of 2011, cracks on the final concrete lining of the Sv. Tri Kralja Tunnel were detected. Vertical cracks, with the width of gap ranging from 0.6 mm to 2.0 mm, were noticed in the right tunnel tube (the traffic tube) of the Sv. Tri Kralja Tunnel, just after the first and the second emergency niche. Figure 5 shows one detail of the crack in the concrete lining close to the first emergency niche in the right tunnel tube of the Sv. Tri Kralja Tunnel.

Figure 5. Crack detail of the concrete lining in the right tunnel tube of Sv. Tri Kralja Tunnel
Slika 5. *Detalj pukotine betonske obloge u desnoj tunelskoj cijevi tunela Sv. Tri Kralja*

In addition to the originally noticed vertical cracks close to the emergency niches, the preliminary inspection performed by the designers in the right tunnel tube of the Sv. Tri Kralja Tunnel also pointed to other issues: a range of thin, radiant cracks, as well as several longer horizontal cracks in the area of anchoring of the ventilator, installed close to the second emergency niche. Given the fact that the cracks were detected in the zone of the ventilator anchor, additional research was performed in order to determine the causes and the scope of detected cracks. Additional research works (Mavar, 2011) included the determination of the position of reinforcement in the final concrete lining using the non-destructive method, and the extraction of cylinders with 50 mm diameter in characteristic spots with visible cracks. Figure 6 shows one detail of the concrete layer sampling in the Sv. Tri Kralja Tunnel. Using the non-destructive electromagnetic method, it was determined that the installed reinforcement is located roughly 10 to 20 cm from the surface of the tunnel's final concrete layer.

Figure 6. Sampling from concrete lining of the Sv. Tri Kralja Tunnel (Mavar, 2011)
Slika 6. *Uzimanje uzoraka iz betonske obloge tunela Sv. Tri Kralja (Mavar, 2011)*

The analysis of extracted samples has shown that the cracks extend to the depth of 0.5 cm to 7 cm, and that they have a very low gap of 0.05 mm to 0.2 mm. Additional performed research has pointed to the conclusion that the detected cracks have a low clearance and that they mostly remain in the surface layer of the final concrete lining of the tunnel (Mavar, 2011) thus not impacting upon the stability or load-bearing capacity of the concrete lining.

The condensed moisture in the ventilator zone is retained in the surrounding cracks, with dust attaching to these spots due to the circulation of air from the ventilator. Due to this fact, such cracks become more visible than other cracks that can be found in other areas of the final concrete lining of the tunnel. The detected vertical cracks on the final concrete lining of the Sv. Tri Kralja Tunnel were repaired by injection (implementing the usual sequence of repair injection works: processing and preparation of cracks; installation of packers for injection; crack injection using the two-component epoxy resin as injection mixture; removal of packers; final processing of cracks). The provided examples of crack repair in the concrete lining of the tunnel point to the systematic approach in the operation of tunnels on the Zagreb-Macelj Motorway. The systematic approach is founded upon information on the current state of tunnel infrastructure, and on the required reactions necessary for maintenance, or – in this case – required reactions in regard to the preparation and execution of extraordinary maintenance works. On the basis of the report on periodical tunnel maintenance, prepared by the Operator, information was obtained on the condition of the final concrete lining of the tunnel. After the analysis of the report on periodical tunnel maintenance, representatives of the Concessionaire and the Operator performed joint inspection, based on the report and the marked locations on the concrete lining of the tunnel. Upon the joint inspection, the conclusion was made to perform extraordinary maintenance works, which are subject to the decision-making level of the Concessionaire. Given the fact that the Concessionaire is the responsible entity when it comes to financing and organizing extraordinary maintenance, the Concessionaire ordered the preparation of the technical design for the repair of cracks in the concrete tunnel lining, and selected the contractor for the works, as well as supervision in the course of repair works on the tunnel's concrete lining. When preparing the technical documentation required for extraordinary maintenance works, whether reconstruction or repair, it is necessary to ensure active cooperation of the Concessionaire and the entity in charge of preparation of the technical design, in order to prepare the technical design on the basis of relevant information. When it comes to the relevant information on the condition of the concrete lining of the tunnel, it was obtained by analysing data from the period of tunnel construction, implementing periodical inspections by the Operator, preliminary inspection by the designer of the technical design, together with additional research on the concrete lining of the tunnel. Additional research was also conducted in order to obtain a more detailed set of information on the condition of the concrete lining of the tunnel on locations where cracks might represent a potential risk for undisturbed and safe traffic through the tunnel. The provided example of repair of the concrete tunnel lining clearly shows that active cooperation between the Concessionaire and designer in the preparation of the technical design is of paramount importance in order to reach an economical and technically optimal solution.

Apart from the mentioned example of the execution of extraordinary maintenance works, proactive preventive approach to tunnel maintenance can also be seen in the example of the monitoring of the service tunnel tube (the left tube) of the Sv. Tri Kralja Tunnel. Given the fact that the service tunnel tube was constructed using only the primary support, project documentation foresees the implementation of periodical controls of the stability of the service tunnel tube. In the course of performing periodical seasonal inspections of the service tunnel tube, no traces of instability were discovered; instead, moisture and dripping of water was detected on several locations – as expected, given the high level of groundwater in the rock mass, and lack of waterproofing of the service tunnel tube. Geological and technical measurement and analysis program was created for the purpose of stability control (Stojković, 2012), which prescribes control measurements in an economical manner, as well as monitoring absolute movements of points along the rim of the service tunnel tube in geodesic terms, as shown in Figure 7.

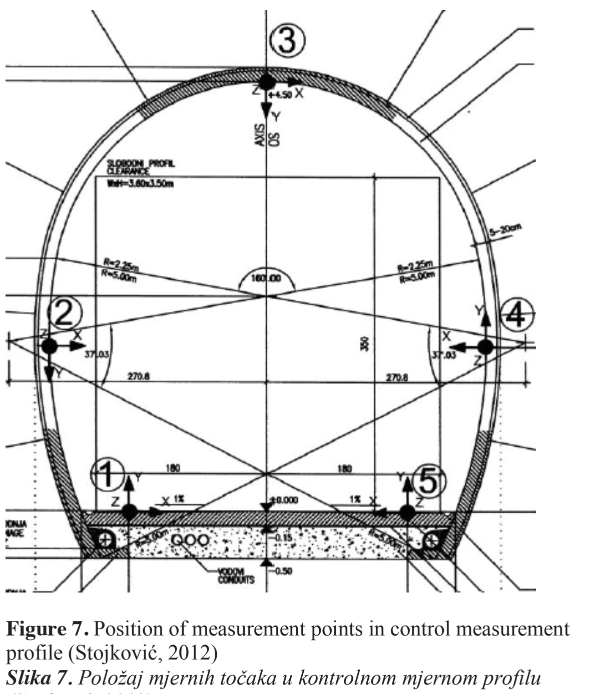

Figure 7. Position of measurement points in control measurement profile (Stojković, 2012)
Slika 7. *Položaj mjernih točaka u kontrolnom mjernom profilu (Stojković, 2012)*

The distribution of control measurements (Stojković, 2012) was influenced by the quality of the rock mass along the route of the service tunnel tube, as well as by the position of spots critical for tunnel tube stability (connection points of cross passages and the service tunnel tube). Based on the engineering geological profile of the actual field situation, the quality of the rock mass can be divided into two geotechnical units. In the first geotechnical unit, higher-quality rock mass is dominating, represented by sandstone, conglomerates and limestone. In the second unit, the dominant rock mass has a very poor quality, represented by loosely connected clastic sediments. Mentioned program provides for the installation of a total of 17 control measurement profile, the distribution of which is conditioned by the quality of the rock mass. Figure 8 represents the results of measurements on the typical control measurement profile. Until the present, seven control measurements have been performed, in the recommended frequency of one measurement per month. On the basis of the analysis of undertaken measurements, the conclusion was that the service tunnel is stable, and the frequency of periodical shift controls has decreased in control measurement profiles. The example of stability monitoring in the service tube (the left tube) of the Sv. Tri Kralja Tunnel shows the importance of data and knowledge transfer from project documentation and the period of construction into the period of operation, which constitutes a necessary part of the operational tool when dealing with tunnel operation.

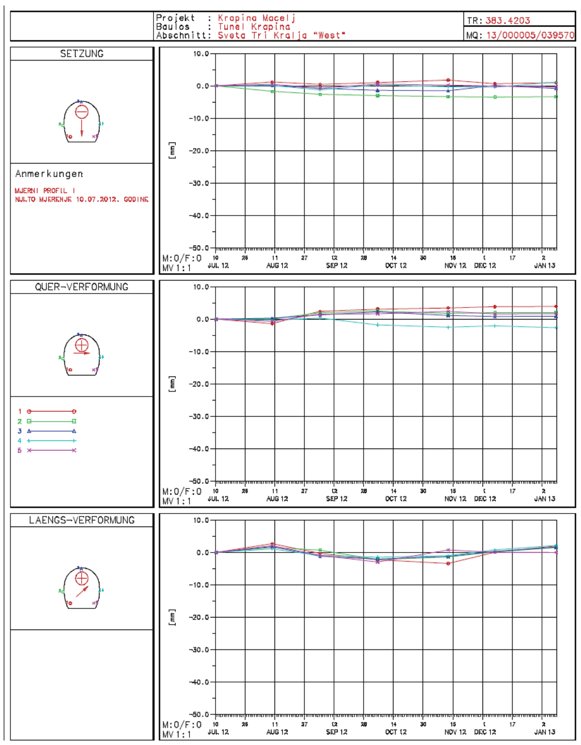

Figure 8. Measurement results on typical control measurement profile
Slika 8. *Rezultati mjerenja na tipičnom kontrolnom mjernom profilu*

3.2. Maintenance of tunnel equipment systems

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 for the preservation of tunnel systems in technical working order. 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. Tunnels on the Zagreb–Macelj Motorway have been designed in accordance with the laws and regulations of the Republic of Croatia, and the 2002 issue of the Austrian RVS guidelines (*Der Richtlinien und Vorschriften für den Straßenbau*, issued by the Austrian association for roads, railways and transport *FSV – Die Österreichische Forschungsgesellschaft Straße, Schiene, Verkehr*). In accordance with these regulations, tunnels can be divided into two groups, based on their length and traffic direction. The first group consists of tunnels under 500 m in length, with two tunnel tubes, with each tunnel tube dedicated to one traffic direction. Tunnels Levačica, Vidovci, Đurmanec and Frukov Krč belong to that group. The second group of tunnels includes tunnels Sv. Tri Kralja and Brezovica – over 500 m in length, with a single tunnel tube and bidirectional traffic. Tunnels on the Zagreb-Macelj motorway include the following installed equipment systems: tunnel lighting; tunnel ventilation and CO, wind speed and visibility devices; fire announcement and 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.

Table 3 includes the overview of the share of individual equipment systems per tunnel tube of Sv. Tri Kralja tunnel. Table 3 shows that traffic tunnel tube of the Sv. Tri Kralja Tunnel is equipped with following equipment systems: electricity supply; ups system; lighting system; ventilation system, CO, visibility and wind speed devices; fire announcement and fire detection system; traffic management system; ERT system; public address loudspeaker system; radio diffusion system; water supply and hydrant network system; SCADA and CSS system.

Table 3. Share of various equipment systems in tunnel Sv. Tri Kralja
Tablica 3. *Zastupljenost različitih sustava opreme u tunelu Sv. Tri Kralja*

Tunnel equipment system	Service tunnel tube	Traffic tunnel tube
Tunnel electricity supply	yes	yes
Tunnel lighting	yes	yes
Tunnel ventilation	yes	yes
CO, visibility and wind speed devices	no	yes
Fire announcement and fire detection	yes	yes
traffic management	no	yes
Tunnel SOS phones (ERT system)	yes	yes
Public address loudspeaker	yes	yes
Radio diffusion	no	yes
CCTV	no (only in portal area)	yes
CSS (SCADA) system	yes	yes
Tunnel ups system	yes	yes
Water supply and hydrant network	no	yes

The service tunnel tube includes the following installed equipment systems: electricity supply; lighting system; ventilation system; fire announcement and fire detection system; ERT system; CSS (SCADA) system; ups system. 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. 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. In order to fulfil the outlined goals, it is necessary to ensure the functionality of tunnel equipment, which can be done by maintaining tunnel equipment systems in technically appropriate state. In doing this, it is necessary to define the acceptable level of disruption to the functionality of individual tunnel equipment systems, or the level of malfunction. Recovery Point Objective (RPO), the acceptable level of system loss in a situation of distress that needs to be recovered, is determined for each tunnel system of the Zagreb–Macelj Motorway, within the Minimum Operating Conditions procedure. Mnimum Operating Conditions are defining measures to be undertaken per each system condition described in four system states: nominal, bearable, critical, and endangered state, as shown in Table 4. Operation and maintenance is based on information on the current stage of the equipment system, and relevant reactions necessary for maintaining high security levels and reliable functionality of the comprehensive tunnel equipment system.

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

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

Life cycle of tunnel equipment systems determines the point at which replacement becomes more appropriate then continued use, having in mind the economic aspects in regard to operating and maintenance cost, and elevated risk of failure and unreliability that impacts upon the level of safety, endangering tunnel availability. The life cycle of tunnel equipment systems depends on various external factors that have a significant impact on the achieved life cycle duration. Systematic approach with comprehensive methods, monitoring and mitigation of such factors, are essential elements in order to extend the intended life cycle duration. Essential tools for reaching the intended life cycle duration of tunnel technical equipment include the implementation of preventive and corrective maintenance, as well as monitoring of tunnel equipment systems errors. In the course of motorway operation, tunnel Sv. Tri Kralja represents a location of potentially higher risk on the motorway, compared to other tunnels. Therefore, implementation results of preventive and corrective maintenance of tunnel equipment systems are analysed for all tunnels, and separately for the Sv. Tri Kralja Tunnel. Figure 9 shows preventive and corrective maintenance ratio in regard to tunnel equipment systems from the beginning of tunnel use, in the period from the year 2007 until 2012. The number of tunnel equipment systems failures is shown in Figure 10.

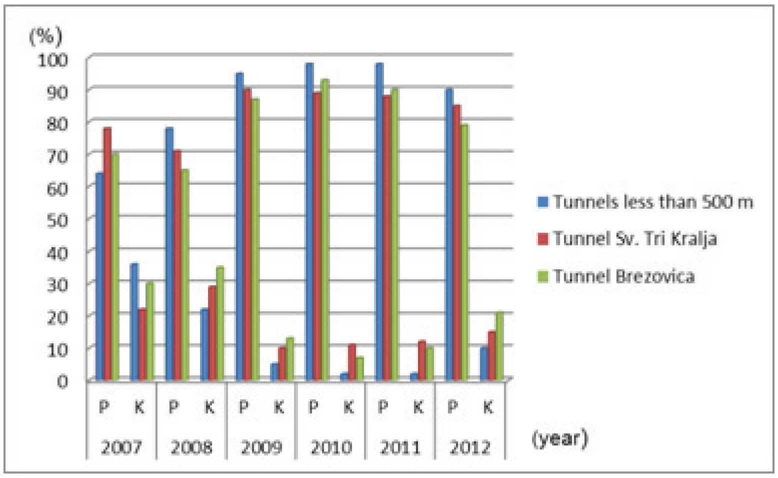

Figure 9. Average ratio of preventive and corrective maintenance per year of tunnel use
Slika 9. Prosječan odnos preventivnog i korektivnog održavanja po godini uporabe tunela

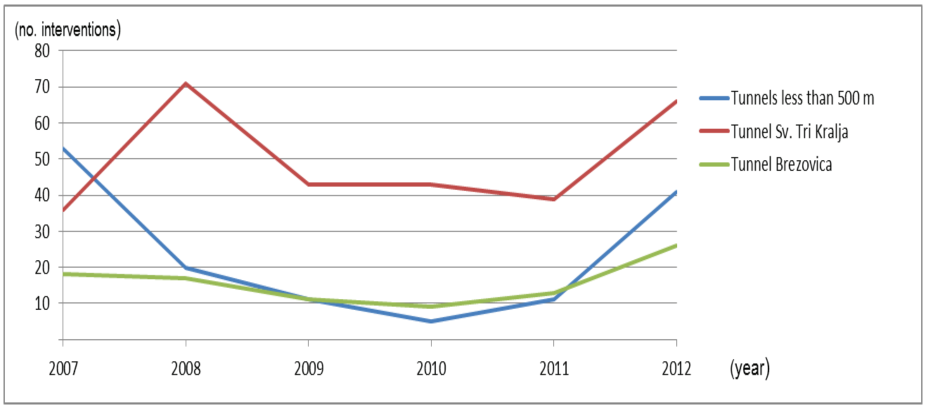

Figure 10. Average number of equipment systems failures per year of tunnel use
Slika 10. *Prosječan broj pogrešaka sustava tunelske opreme po godini uporabe tunela*

The charts presented in Figures 9 and 10 show that the number of errors in the system was elevated at the very beginning of tunnel use, which led to a higher need for interventions within corrective maintenance. That was to be expected, given the fact that a certain optimisation of the system is needed in the initial period of system use; i.e. it is necessary to "balance" the individual systems. In the subsequent years of tunnel use, until 2012, one can notice the trend of stabilization of the average number of system errors, as well as the average number of corrective maintenance interventions; the efficiency of preventive maintenance was rising. In 2012, the number of system errors was clearly noticeable, as well as the increase of corrective maintenance representing smaller repairs and replacement of worn parts. On the basis of date presented in Figures 9 and 10, it is to be expected that the share of extraordinary maintenance in the overall maintenance of tunnel equipment systems would increase during the next maintenance year. A constituent part of the systematic approach to tunnel operation and maintenance is the technical feedback. On the basis of technical feedback regarding the state of the system, behaviour and malfunctions, key work effect indicators are monitored and analysed. Useful key work indicators identify the so-called weak spots, i.e. problems that cause malfunctions, thus assisting in the selection of the right maintenance strategy, in order to combat undesirable developments, ultimately resulting in the improvement of reliability and efficiency of equipment and maintenance. When it comes to various relevant work effect indicators, one of the key indicators is the availability factor of the tunnel equipment, consisting of the reliability factor and maintenance factor. The availability factor has proven to be an appropriate tool for analysing the functionality of tunnel equipment systems (Deković, 2011), when it comes to the use of the tunnel group along the Zagreb – Macelj Motorway. 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 the number of nines following the decimal point, such as "five nines" for 0.99999. It is expressed by the 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 it can be expressed as follows:

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

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 as (3):

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

In general terms, it does not include the time required for the procurement of parts, or other administrative or logistical causes of non-availability. Figure 11 represents the availability factor of the tunnel equipment system, based on tunnel groups and years of tunnel use. The situation with the availability factor presented in Figure 12 points to the conclusion that systems in appropriate functional conditions are at a very high availability level. However, by 2012 one can see the trend of stabilization of the average functionality, which is complementary with the trend of balancing of the average number of system errors, as well as the stabilization of the average number of corrective maintenance interventions presented in previous Figures 9 and 10 during the same time period, which is a result of the increase in efficiency of preventive maintenance.

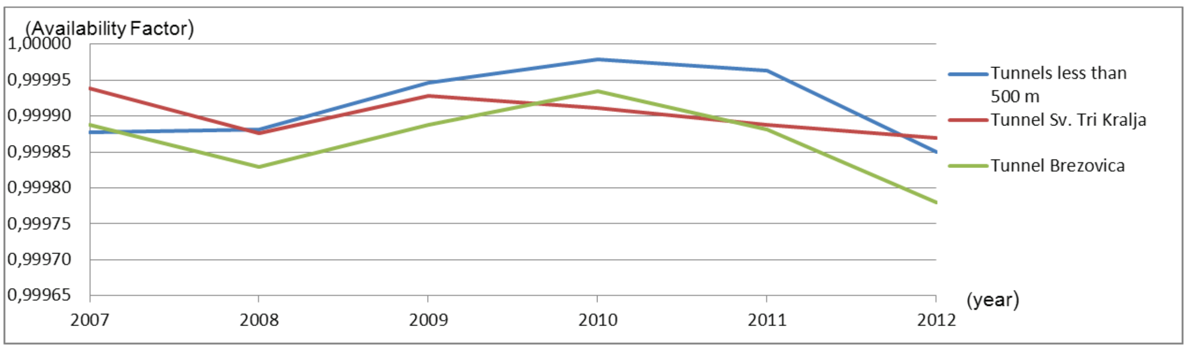

Figure 11. Availability factor of tunnel equipment systems
Slika 11. *Faktor korisnosti sustava tunelske opreme*

When analysing Figures 9, 10 and 11, it becomes clear that a lower share of preventive maintenance results in the increase of the number of system errors, resulting in somewhat poorer average functionality of the system; however, it is beyond dispute that the systems are in appropriate functional conditions, and at a very high availability level. Figure 12 shows the availability factors for each individual tunnel equipment system of the Sv. Tri Kralja Tunnel.

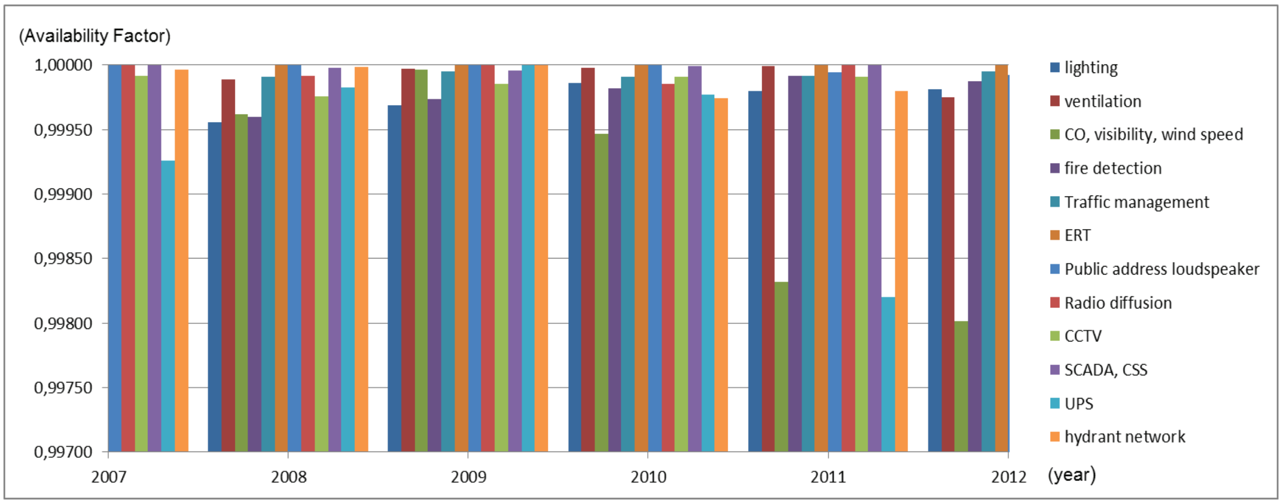

Figure 12. Availability factor of tunnel equipment systems in the Sv. Tri Kralja Tunnel
Slika 12. *Faktor korisnosti sustava tunelske opreme tunel Sv. Tri Kralja*

The presented detailed overview of the tunnel equipment system for the Sv. Tri Kralja Tunnel shows that the comprehensive system has exemplary functionality, with smaller deviations shown in greater detail in Figure 12. On the other hand, Figure 13 shows the situation with the tunnel equipment for the measurement of CO, visibility and wind speed, together with the system of permanent electricity supply (UPS). These systems required more elaborate corrective maintenance works, which therefore made their usefulness during the same time period somewhat lower when compared to other tunnel equipment systems, such as, for example, the lighting system shown in the same Figure.

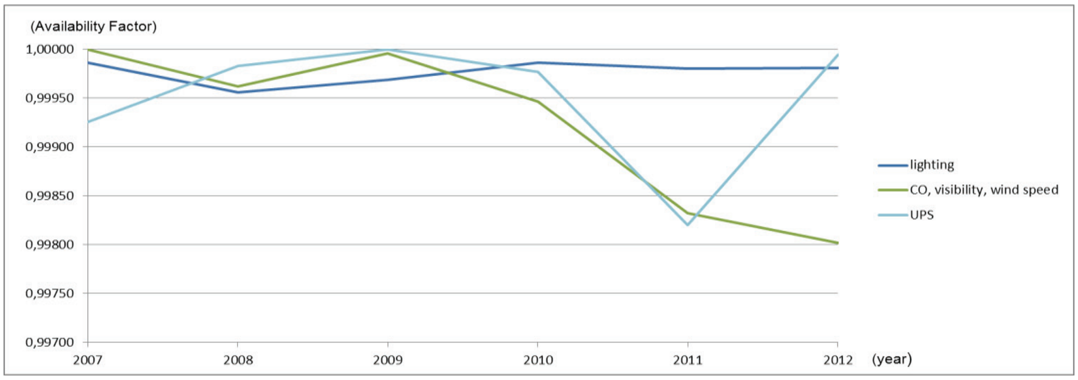

Figure 13. Specific availability factors for specific tunnel equipment systems in the Sv. Tri Kralja Tunnel
Slika 13. *Pojedini faktori korisnosti za pojedine sustave tunelske opreme u tunelu Sv. Tri Kralja*

The presented monitoring of trends when it comes to the average functionality of tunnel equipment systems in a given time period points to the fact that the availability factor is appropriate for the monitoring of average functionality of the system, and for the assessment of efficiency of regular maintenance, or the assessment of the need for and scope of extraordinary maintenance. This means that a comprehensive systematic approach is necessary in order to ensure optimal efficiency or regular maintenance, which is directly linked to the appropriate level of functionality of tunnel equipment systems, and thus to the fulfilment of the purpose and function of the tunnel, which is to ensure undisturbed and safe traffic flow through the tunnel.

4. Conclusion

When it comes to the continuity of business operations – i.e. undisturbed flow of traffic – tunnels as motorway sections are the most demanding facilities in terms of operation and maintenance. The aim of tunnel operation and maintenance is to preserve normal functional conditions in tunnels, thus ensuring undisturbed and safe traffic flow through the tunnels. The analysis of operation and maintenance of a series of six tunnels along the Zagreb-Macelj Motorway points to the tunnel of Sv. Tri Kralja as being the most demanding facility on the motorway, requiring particular effort in terms of ensuring the appropriate level of safety and operability. Tunnel operation is a complex system, with flexibility being one of the fundamental characteristics, based on information on the current status of tunnel infrastructure, and timely, high-quality execution of works is of particular importance in this context. Examples of maintenance of tunnels as structure, primarily when it comes to extraordinary maintenance works, point to the importance of active collaboration between the concession holder, the operator, and the designer in the preparation and drafting of the technical design. This must be done based on the relevant information obtained by analysing data from the period of tunnel construction and tunnel maintenance, as well as additional research, ultimately resulting in economically and technically optimal solution. Active monitoring of parameters of each individual system, as well as tunnel equipment systems in their totality, via key performance indexes, constitutes the foundation for optimal maintenance of tunnel equipment systems. Analysis of the maintenance of tunnels as structure, and the maintenance of tunnel equipment systems, points to the presence of expert maintenance teams, together with strong organizational components within the companies of the Concessionaire and the Operator, as being crucial in order to achieve optimal efficiency of the maintenance of tunnel infrastructure.

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