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Safety in Automated Transportation Tunnels

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Abstract— **This paper explores the main safety features in Dubai International Airport (DIA) tunnel. The safety levels have been enhanced because of using centrally controlled electromechanical systems and ITS (Intelligent Transportation System) components and all operated by SCADA (Supervisory Control And Data Acquisition) technology. Redundancy of critical devices is ensured to maintain continuous back alternatives in case of systems defects or partial failures. The overall safety aspects whether related to motorists or workers in the tunnel are accordingly improved due to use this sophisticated industrial hierarchy system and carefully designed structure.**

I. Introduction

The modern industrial society of Dubai in particular and UAE in general has witnessed major developments and boomed in recent years and therefore require an efficient and reliable transportation infrastructure. This is applied equivalently to both roads and rails. This inspires the planners and decision makers in Dubai to think carefully about these issues and walked with big steps into this direction. Major road expansions and innovations have been implemented in Dubai with the addition of big components into the existing arterially network. Among many of these new constructions, the DIA tunnel is considered as a shining example of sophisticated transportation structure. The construction and operation of efficient transportation tunnels is increasingly being called for to ensure that traffic can flow speedily without hold-ups.

The intercity DIA tunnel is about 1.5km long consists of two main tunnel tubes primarily intended to ease the traffic flow situation between the two emirates Dubai and Sharjah. Each tube of the DIA tunnel has four lanes per direction in addition to the exit and approach ramps. The structure has been implemented using cut-and-cover method below the airport runway, as shown in Fig. 1 and incorporates the reconstruction of the junctions at both ends of the tunnel.

Figure 1. The reinforced concrete structure and impact of runway

II. Safety Comes First

Many serious incidents on different scales in transportation tunnels encountered before in different places over the world. These incidents created a lot of debates about the benefits of tunnels for public and goods transportation and consequences on economy. Recent studies have shown that the risk of incidents can't be totally eliminated and hence some events might occur [1-3]. It is always emphasized that high safety and reliable availability are essential for such tunnels. This particularly applies to fire incidents in tunnels, which unfortunately can't be entirely excluded. Such fires are characterized by the danger they pose to the persons affected and also, in many cases, by the considerable extent of damage they cause.

Tunnels shall embrace the design for disaster concept, which assumes that something might horribly goes wrong on a busy morning in peak hours when vehicles collision occurred and triggered big fire [1]. What will happen then is that there no flow of traffic and stress is getting high on the agenda of everyone involved. Designers and contractors will acknowledge questions whether or not they did everything appropriately; the tunnel owners and operators will see their asset under threat with a potential loss of revenue of giant proportions; and above all politicians will raise questions within their area of responsibility. More importantly are the users who will be faced with a situation that is fast becoming a trap for those who do not react in time, do the unthinkable, or can't help themselves.

Now tunnels design must incorporate aspects that can control this situation. They now must be designed to save both the occupants and the asset. Experience overseas has shown that these situations can be real. They have in some cases exposed the shortcomings in design for protection of both the people and the tunnel. The first step in the economic risk evaluation of tunnels design is made by investigating the cost effectiveness of various safety measures individually [2]. The investment costs related to tunnel safety are generally related to the following:

- Construction of the tunnel (uni- or bidirectional tube; construction of a shoulder, heat resistant lining)
- Electrical installations (ventilation, cameras, speed detection systems)
- Traffic management solutions (speed reductions, separating transport of dangerous goods)

In as much as more investment put into tunnels by having advanced technology and sophisticated equipment the better safety achieved. Accordingly, the following: components represent the basics for fire and life safety systems in tunnels:

- Escape for occupants and access for emergency workers
- Fire suppression systems
- Fire detection systems
- Smoke hazard management
- Emergency lighting
- Exit signs
- Emergency phones
- Emergency service radio system
- Flame traps for flammable liquid spills and fire water
- CCTV for visualization and traffic flow monitoring
- Fire hydrants and boosters
- Fire extinguishers and hose reels

Another important issue is to have the input feedback from the civil defense and fire brigades for the enhancement of tunnels safety design [3]. It has been a normal exercise in Dubai for such involvement not only for roads but also even in buildings construction by adopting international safety standards. The personal working relationships that have been formed are extremely important in fostering trust and comprehending each other's position. It has taken a number of years and projects to come to the point where the Dubai civil defense and fire brigades can feel comfortable in where they fit into tunnels and roads design.

Dubai tunnels are now designed by applying a risk assessment approach. Risk workshops have involved all the necessary players including:

- Clients or owners
- Project consultant and managers
- Operators
- Civil defense and fire brigades
- Police risk service
- Ambulance service
- Fire and safety engineers
- Ventilation experts

Figure 2. The fire meetings and drill

As for the DIA tunnel project, multiple round table meetings were held to discuss safety design issues and practice, as depicted in Fig. 2. The DIA tunnel was subjected to extensive revisions at early design and construction stages to evaluate full compliance with the international and local safety rules and regulations. Mock-up fire drills in the tunnel were conducted without a prior note to the fire brigades to assess their availability and response speed. Other services also responded in a timely fashioned without advanced alert simply by having a call from the tunnel in the control room asking for urgent help due to fire incident.

The above drill was carried out while the tunnel was still under construction. However, it has been requested by the safety engineer of the consultancy office to be repeated every three months as minimum after opening. The safety engineer also developed relevant response plan in case of any emergency incident including fire in the tunnel. The response plan manual is considered as life document subject to severe revisions after the successful completion of future drills taken place with life traffic but with false incidents of course.

III. Safety Measures in DIA Tunnel

Taken into consideration all of the above risk assessment and safety measures and codes, the DIA tunnel has been designed and constructed to maintain high level of safety for diverse public users. Starting with construction, the main tunnel tubes have exit emergency doors placed approximately every 150m. These doors are easy to open in both directions by pushing a handle bar and equipped with proximity switch to indicate opening events to SCADA operator as shown in Fig. 3.

Figure 3. The emergency doors and equipment in the tunnel tubes

As for the road shoulders, previous studies showed that they are not a cost effective safety measure, even if the indirect risk resulting from traffic delay are taken into account [2]. However, the DIA tunnel has wide emergency shoulders, about 2.5m on the right and about 1.5m on the left, for efficient maintenance requirement without creating obstacles against moving traffic. Another advantage of shoulders is to be utilized for safe parking of stopping vehicles and also for removal in case of small car accidents without delaying the traffic. Moreover, both tunnel tubes are unidirectional and hence the chance of vehicles collisions is further reduced. Footpaths between 1.1m to 1.3m are also there for emergency and maintenance walking intentions.

Wall-mounted self-contained emergency and exit luminaries are located in various locations in the tunnel to show distances to exit doors and fixed above telephones and fire extinguishing and hose cabinets (FEC and FHC) as obvious in Fig. 3. The DIA tunnel is provided with a full package of addressable emergency telephone system complete with switching box and wall-mounted emergency handsets and also installed in substations. Manual pull stations (MPS) of two stages are equally distributed in certain areas in the tunnel tubes and in the substations. Crushing these MPS will activate the sounder in the control room and the CCTV closest to that location will be immediately switched on the video wall to attract the operator attention. There are two fire pump stations (FPS) in DIA tunnel, one in each of the ancillary buildings. These two FPS are connected to the same water pipes network and hence starting one of them depends on pressure drop at the FHC nearest to that FPS. Each of these FPS consists of two main pumps and one jockey pump in addition to control panels as shown in Fig. 4 and the fire standpipe network is shown in Fig. 5.

Figure 4. The main and jockey pumps and fire controller

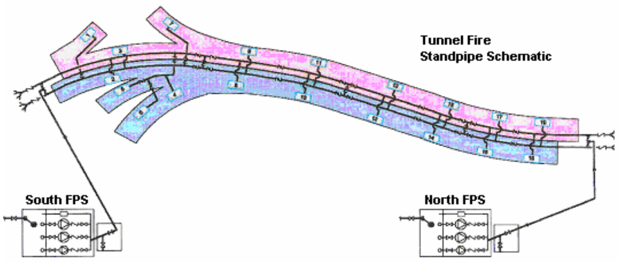

Figure 5. The fire standpipe network

From another hand, the tunnel is provided with a fully addressable Public Address (PA) system with emergency speakers located within the tunnel substations and north and south building facilities. The operator eventually can monitor any activity in substations using dome cameras and call up the workers to evacuate their place at once upon major incidents. Previous studies showed that the use of PA speakers in the tunnel tubes is almost impractical in most situations because of traffic noise and the nature of drivers by keepings their windows closed especially in hot climate [4]. Hence, such feature was cancelled at the early stages of DIA tunnel design.

As for fire detection, the tunnel is provided with fibrolaser technology to conduct accurate linear heat detection (LHD). This modern technology is very much reliable, provides readings through SCADA system for small values of temperature variations over small spatial distances, and hence triggers critical alerts to operators to activate certain response plans and coordinate with civil defense.

IV. What to do in Case of Fire

Fire occurs in confined places like tunnels is far worst than open spaces [3]. People panic and rapid access of rescue teams becomes dangerously burden. People captured by fire will suffer of rapidly rising heat radiation, fast release of fire gases and a related decrease in visibility, and above all potential risks. Many tunnel users could not understand the nature of fire and hence will contribute in a wrong manner to worsening the situation. Therefore, it is required to give some leading directions and useful information in advance to be well prepared in case of emergencies. The lack of such knowledge by motorists contributed to the catastrophe of Mont Blanc Tunnel fire. Full story of most recent fire events can be found in the literature [1-3] and photos of two disasters are shown in Fig. 6 in order to show fire impact on tunnels.

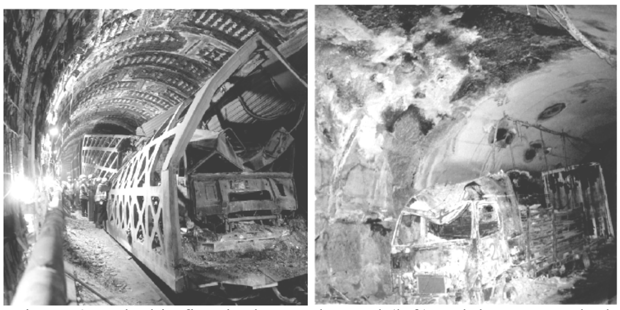

Figure 6. The big fires in the canal tunnel (left) and the Monte Blank tunnel (right) [3]

As lessons learned from the abovementioned major fires in tunnels, the DIA tunnel is very strict against the heavy goods and big trucks of passing through. Fixed direction signs at the tunnel entrances instructing drivers of such vehicles to not use the tunnel for transportation if they exceed 2.5tons. Trucks carrying chemical and hazardous material are also banned of using the tunnel.

To overcome such situations, it is recommended that the following guidelines [3] to be distributed to the tunnel users, modified to match the DIA tunnel equipment and local rules:

1. When driving through the tunnel:
- switch on lights and remove sun glasses
- make sure you observe the speed restriction
- observe the variable message and lane closure signs
- keep a safe distance to the vehicle in front
- drive with increased attention

2. Should you have a breakdown:
- move over as far to the right as possible - ensure you use the available hard shoulder, otherwise use the footpath
- secure your vehicle (warning flasher, warning triangle)
- at once inform the tunnel control room via emergency telephone (or call police via mobile)

3. In the event of a traffic jam in the tunnel:
- observe the variable message and lane closure signs
- keep your distance to the vehicle in front (do not edge up bumper-to-bumper)
- do not get out
- on no account turn
- do not reverse

4. In the event of a vehicle fire in the tunnel:
- observe the variable message and lane closure signs
- stop as far to the outside as possible
- keep your distance to the vehicle in front (do not edge up bumper-to-bumper)
- give way to civil defense and police vehicles and don’t block the road shoulders
- switch off engine at once
- switch on warning flasher at end of tailback, get out at once, do not lock car door

- escape at once by moving away from the smoke direction
- use specially marked emergency exits. On no account turn
- do not reverse

V. Safety in Service Culverts

Utility tunnels (or culverts) are usually designed to accommodate urban services with emphasis on human factors in terms of accessibility and safety while doing repair or maintenance works [5, 6]. Utility services have been placed underground in order to achieve less visual impact and more protection against adverse climate, vandalism and natural disasters.

Many aspects of culverts safe design are to be considered, including ventilation, lighting, communication, alarm and escape. These systems should include, at least, emergency telephones and exits clearly marked and fire alarm pull boxes beside each telephone. Smoke detectors are also important to detect the presence of smoke hazardous in culverts.

Figure 7. The service culvert arrangement

The DIA tunnel has two main culverts for cabling systems to feed power to the main tunnel and substations equipment. All data and power cables are passing through these culverts over GRP tray system. There must be enough vertical and horizontal clearance for the worker to enter and leave the utility tunnel and to perform any other task as shown in Fig. 7. Escape shafts with GRP ladder installations are available in the culverts for rapid exit in case of emergency events. Proximity switches are fixed on these covers to detect their removal on SCADA screens. Moreover, all of the minimum safe design parameters are equipped in these tow culverts. Additional features are also feasible like CCTV, however, they are considered as a waste of resources since these culverts are rarely used and only maintenance people get access to such places. Maintenance and cleaning jobs normally carried out every six months and hence monitoring tools are considered unnecessary burden to the system and budget.

VI. Communication Systems

Two communication systems are installed in the DIA tunnel to facilitate public and police transmission bands. Tunnels users and motorists can use their mobile phones inside the tunnel and inside service rooms thanks to the powerful coverage of GSM transmission provided by Etisalat, the local service provider in UAE. Boosting base stations and antennas are located in predetermined locations to accommodate proper transmission in all directions in the tunnel as shown in Fig. 8. People driving into DIA tunnel should not expect disruption to the continuity of their mobile calls while approaching and getting inside the tunnel. From another hand, this feature is accounted for emergency conditions when a person suffers trouble in his car and needs a lift or to call for emergency or car incidents. Therefore this is realized as an enhancement to the safety level of DIA tunnel.

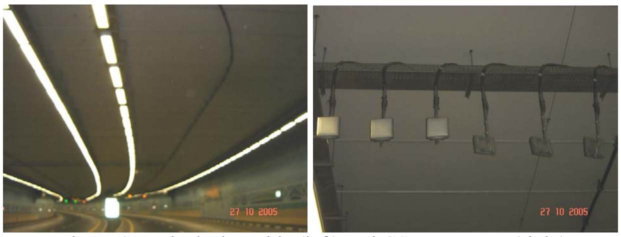

Figure 8. The leaky cable (left) and GSM antennas (right)

Police and civil defense radio channels are covered by using a thick leaky cable fixed on the tunnel slabs as illustrated in Fig. 8. These channels are only accessible by especial personnel as usual and considered extremely important for continuity of communication in emergency situations in the tunnel. The leaky cable spans both tubes and connected to a central communication unit in the control equipment room. The locations of the GSM antennas, and other electrical equipment in the tunnel, have been determined to provide better visualization by drivers, easy maintenance, and good coverage of services along the entire space of the tunnel.

VII. Electrical Systems

The DIA tunnel is on every scale rich of advanced and modern technology and versatile electrical equipment. All equipment have smart controllers or relays allowing them to work in standby mode in case something wrong happened to the main backbone network or data cables. Extreme care has been exercised while developing the preliminary and final design concepts to maintain full availability of each system in unexpected situations like power disruptions or communication failures. Moreover, all systems can be operated manually at site or by remote control from SCADA system. Redundant communication scheme is especially designed to interrogate operational status of each intelligent relay and hence power feed can be decided to any system. The following is brief description of the major electrical systems.

The main electrical power supply for the complete DIA tunnel facilities is provided by six substations feeding from DEWA (Dubai Electrical and Water Authority) 11KV power grid connected using ring topology. The ring scheme ensures redundancy by having two backup power feeds for the entire electrical network in the tunnel. Thus if one power incomer fails then the other one will supply energy for the rest of systems. This connectivity plan will consolidate the safety measures of DIA tunnel by reducing power disruptions and hence maintaining continuity of services without affecting the traffic.

The main electrical panels are equipped with smart or intelligent relay devices transmit essential operational status data to the PLCs (Programmable Logic Controller), like trip signals, abnormal condition, power consumptions, etc. At the same time these devices can receive command signals sent by the same PLCs, which are coming from the main SCADA system, to open or close that particular feeder.

Two PLCs are installed in the PLC cabinet of each panel. Modbus communication protocol is maintained between these PLCs and the smart relays of the same panel. Both the PLCs and communications gateways are built in a hot standby redundancy configuration in addition to the DC power supplies. One PLC will act as master and the other as slave and switching between them will be bumpless. Therefore, this scheme is used to achieve an efficient uninterrupted data transfer to the main SCADA PLCs using redundant Profibus network.

Figure 9. The LV panels (left) and PLC (right)

Furthermore, two standby diesel generators with capacity of 2.25MVA are installed in the ground floor of the ancillary buildings with their fuel tanks, as shown in Fig. 10. The north standby generator provides essential power supply to the distribution panels of essential load of north tunnel substations. The south standby generator provides essential power supply to critical loads of south tunnel substations. Proper earthing should be maintained to the fuel tanks to avoid any static electricity hazardous.

Figure 10. The fuel tank (left) and standby generator (right)

Both standby generators are interfaced with SCADA system in order to perform emergency automatic sequence of operation in case of power supply failure. For further improvement of precaution and redundancy levels, the north and south facilities are furnished with 250kVA fully functional UPS Systems (Uninterruptible Power Supply). These UPS systems are monitored by SCADA. The UPS power supply is used mainly for part of tunnel lighting and critical loads such as control and PLC panels, CCTV, and the electronic VMS and LUS (variable message and lane use signs). The SCADA equipment and control rooms are also fed from the UPS unit installed in the south. This will keep the traffic monitoring and management functionality in full operation despite occasional power failures.

On the other hand, the DIA tunnel ventilation system comprises quantity of 40 of fully reversible JFs (jet fans) complete with remote monitoring units connected to SCADA. These JFs are designed to run under two conditions. The first when the CO concentration gets higher than permissible levels (0-250ppm) due to slowly moving traffic in the tunnel. While the second JFs starting condition occurs when there is a fire to suck away the smoke out of the tunnel and hence visibility enhances and suffocation chances reduced. As for the CO detection there are different levels upon which one pair of JFs starts and then two pair and so on until the level gets within predetermined standards. Sample photos of JFs and CO detector are shown in Fig. 11.

Figure 11. The JF (left) and CO detector (right)

The tunnel JFs are very powerful and have thrust value of 1456N and velocity of 29m/s. These JFs are supplied with monitoring unit specifically designed to be integrated into a global control system for tunnels, based on Profibus open communication protocol. The unit is able to monitor simultaneously several mechanical and environmental parameters. This unit also constitutes specific signal conditioning circuits for different kinds of measurement probes, both standard and non-standard. The unit also continuously monitors internal parameters, like voltages, currents and inner temperature, axial and longitudinal vibrations. Both the JFs and the CO detectors are routed to the PLCs and intelligent peripheral devices using Profibus cables. Not to forget that there are 33 pieces of CO detectors evenly distributed all over the tunnel.

From another perspective, the DIA tunnel lighting is designed as per the recommendations of the latest version of the CIE88 (Commission Internationale de'lEclairage) regulation, which in summarized in [7]. The following are the main design criteria applied for the complete tunnel lighting system:

- The design speed for the main tunnel is 100km/h
- The design is based on counter beam lighting (CBL) method
- The level of reinforcing lighting is continuously adjusted using dimming controllers dependent upon the external luminance conditions
- The external luminance is measured using L20 photometers located at the tunnel entrances at distances equivalent to the stopping distance
- The lighting level in different zones as per CIE88 regulation
- The threshold, transition and exit zone lighting is realized by High Pressure Sodium Vapor Lamps (HPSV)
- Interior zone lighting is realized by Fluorescent Lamps (FL)
- Night time lighting in all tunnel tubes is realized by FLs
- A minimum of 20% lighting will be available in all zones in case of power failure. This is achieved by UPS feed provided for these circuits

In case of power failure and generator malfunction then the critical lighting circuits will be realized through the UPS units installed in the north and south facilities. This will ensure proper level of lighting inside the tunnel and eventually the drivers can recognize road objects adequately as shown in Fig. 12.

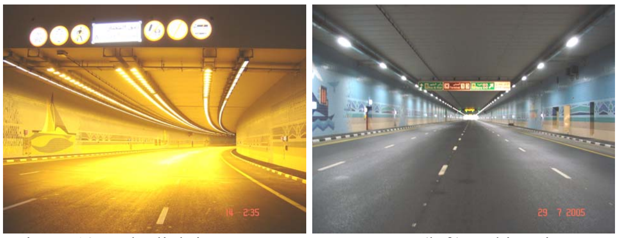

Figure 12. The lighting system, entrance zone (left) and interior zone (right) with 20% backup lighting

Figure 13. The lighting HMI (left) and dimming controllers (right)

The entire lighting system in DIA tunnel is controlled automatically by means of photo meter system consisting of photo meters, PLCs and dimming controllers. There are lighting control dimmer panels located in six locations, namely in the north and south buildings, and four tunnel substations. All the above six locations have their own PLC cabinets with operator interface and powered by UPS to ensure the safe operation of control and monitoring of the system. A master PLC is located in the main control room and complete dual redundant communication network is provided using fiber optic cabling. The master PLC is connected to the tunnel SCADA system to achieve the control and monitoring requirements of the complete tunnel lighting. Five sets of L20 photometers and photocells are located at the main entrances and ramps. This will continuously monitor the external luminance and transmit data to the control panels to determine the appropriate dimming level. The dimming and control system is designed to dim and monitor all HPSV lamps and to switch and monitor the fluorescent lamps. The access and exit zones luminance varies with changes in day light conditions. While on other hand, the day and nighttime lighting in the interior zone is controlled by the switching of fluorescent lamps by the dimming controllers. During nighttime, it is possible to select the lamp duty by automatic or manual method and hence the maximum life of lamps can be achieved. The dimming system will provide the end user with the substantial amount of power savings as specified. Sample photos of dimming control cabinets and corresponding local Human Machine Interfaces (HMI) are shown in Fig. 13.

VIII. CONCLUSIONS

The DIA tunnel is on every scale rich of advanced and modern technology and versatile electrical equipment. All equipment have smart controllers or relays allowing them to work in standby mode in case something wrong happened to the main backbone network or data cables. Extreme care has been exercised while developing the preliminary and final design concepts to maintain full availability of each system in unexpected situations like power disruptions or communication failures. Moreover, all systems can be operated manually at site or by remote control from SCADA system. Redundant communication scheme is especially designed to interrogate operational status of each intelligent relay and hence power feed can be decided to any system. Redundancy is also achieved for power supply in DIA tunnel to ensure continuous energy flow during blackout. Very powerful and remotely monitored and controlled standby generators and UPS units are installed to serve this purpose.

The centralized control system of DIA tunnel successfully integrates all environmental, plant and traffic management systems into a highly complex SCADA system with five operator terminals. The system retains a user-friendly interface thanks to the intuitive graphical screens closely worked out with the client. The remote terminals at the civil defense and police offices represent an added feature to this tunnel with regard safety concepts.

Moreover, wide shoulders and footpaths proved to be extremely advantageous in situations like maintenance and small accidents car parking and evacuation, and retain an ease access to services vehicles to tunnel interior even if traffic blocks main carriage lanes.

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