ENERGY EFFICIENCY – ABB MATHEMATICAL MODEL FOR TUNNEL VENTILATION CONTROL

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ABSTRACT

An advanced system of tunnel ventilation control was put into operation at the end of 2009 in tunnel Učka. The ventilation control system is based on ABB’s predictive fuzzy logic mathematical model. The first year of operation is analyzed and compared with ten-year averages. Operation based on mathematical model resulted in reliable control of pollutant concentration within given levels, reduced number of on- and off-switching of ventilators, increased lifetime of ventilators and electrical switching equipment, savings in maintenance costs and increase of tunnel safety. Significant savings of electrical power consumption are achieved as well as increase of energy efficiency.

Keywords: tunnel, tunnel Učka, ventilation, fuzzy logic, mathematical model, control system, energy efficiency

1. INTRODUCTION

Tunnel Učka is an important transport link of the peninsula of Istria and the rest of Croatia. The tunnel construction began in 1976 and opened in 1981. Since 1995 Bina-Istra d.d. has had concession for the tunnel.

Tunnel Učka is 5,062 m long. Traffic runs in both directions along one lane in each direction.

Two smaller tunnels "Zrinščak I" (196 m) and "Zrinščak II" (45 m) and viaduct, together with the main tunnel, make one unit controlled remotely from the control centre located in a building on the Istrian side of the tunnel.

During the past period the concessionaire asked for two security checks of the tunnel (see Tomašević G., Modernisation of Učka Tunnel, 2010, [3]), the first in 1996 and the second one in 2005 to get recommendations that will raise the level of safety in the tunnel. Thereby, consultants considered the following:

- Directive 2004/54/EC on minimum safety requirements for tunnels in the Trans-European Road Network,
- European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR),
- Regulation RABT 02/2002 – Guidelines for equipment and operation of tunnels (Germany),
- Regulation RVS – Guidelines and Regulations for Road Construction (Austria),
- Recommendations of Permanent International Association of Road Congresses (PIARC) and other relevant studies.

During recent years, respecting these recommendations, extensive modernization of many technical systems in tunnel Učka was conducted and is still undergoing. As the final phase of modernization of ventilation, two software modules were introduced in the remote control system:
• The ventilation control in normal mode, based on a predictive mathematical model and fuzzy logic.
• The ventilation control in emergency (fire) mode

Algorithm and implementation of the ventilation control in normal mode, results obtained and analysis of energy savings in the first year of operation i.e. in 2010 are also described in this herein.

2. VENTILATION SYSTEM OF TUNEL UČKA

The ventilation system of tunnel Učka is of longitudinal type and consists of 144 jet-fans arranged in 48 fan groups. Each group comprises of three jet-fans powered by electric motors suspended from the tunnel ceiling. Jet-fans are unidirectional, i.e. they always operate in one direction (operation direction cannot be changed). They are arranged so that groups operate alternately in one or other direction. Fan groups are not evenly spaced along the tunnel tubes, but are grouped toward the tunnel, so that there are no jet-fans in the central part of the tunnel.

The power of built-in fan motors is 30 kW. Ventilation is supplied from six substations 20/0, 4 kV located inside the tunnel (TS2 - TS7), which are, via two external substations 20/0, 4 kV, TS1 (Istria) and TS8 (Kvarner) connected to the power distribution network. Each substation in the tunnel supplies eight fan groups. Depending on needs, by control of MV distribution, all the jet-fans can be supplied from the grid from the Istrian or Kvarner side. In normal conditions, each network supplies half of the tunnel.

Ventilation is controlled from the control centre through remote control, and during maintenance jet-fans can also be controlled from the local electrical cabinet.

3. MATHEMATICAL MODEL FOR VENTILATION CONTROL

Pollution resulting from the traffic of vehicles driven by internal combustion engine, carbon monoxide (CO), soot and nitrogen oxides (NOx), create particular difficulties in tunnels.

• Natural ventilation is generally insufficient, and therefore mechanical tunnel ventilation system should be installed in order to keep the level of pollution within the given limits.
• Besides controlling the pollution concentration, mechanical system plays a role in preventing the spread of fire and fire fighting in case of an emergency situations.
• A specific case is the control of air flow velocity to increase safety in normal operation, e.g. regulation of air flow velocity in transport of hazardous substances in conditions of strong natural flow of large, i.e. bura (strong north wind).

In most of modern tunnels (depending on the tunnel length, traffic intensity, etc.) mechanical ventilation systems are installed which are classified in two basic types - longitudinal and transverse. Ventilation is controlled from the control centre via the remote control. In general, ventilation control i.e. switching-on and -off of individual jet-fans, or fan power control, can be made in "manual mode" (operator in control centre) or with the help of a software module for automatic ventilation control.

In "conventional" automatic control system (Figure 1) the pollutant concentrations, i.e. the concentration levels of carbon monoxide (CO), opacity ("visibility") and nitrogen oxides (NOx) are taken into account as variables used as the basis for control in the control loop.
Figure 1: Control loop of conventional ventilation control

The advanced algorithm (see Bogdan S.; Birgmajer B.: Model Predictive Fuzzy Control of Longitudinal Ventilation System in a Road Tunnel, 2006, [1]) based on predictive mathematical model and fuzzy logic (Figure 2) takes into account the tunnel parameters (shape, cross section, differences in elevation of tunnel portals etc.), the current weather conditions (pressure, temperature, air speed and direction), and current traffic condition (direction, intensity, speed and class of vehicles). Mathematical modelling provides prediction of pollutants concentrations and fresh air requirements, and thereby is advantageous over the "conventional" algorithm of automatic control. The algorithm also takes into account the actual measured current values of pollutant concentrations (CO, visibility, NOx) in the tunnel.

Figure 2: Mathematical model of tunnel ventilation control

By analyzing both models of control using simulation software for the same given conditions the advantages of mathematical models in relation to the "conventional" model of ventilation control is seen (Figure 3):

- control of pollutant concentration within predefined limits with saving of energy,
- reduced number of on- and off-switching of jet-fans, i.e. increased lifetime of jet-fans and electrical switching equipment and savings in maintenance costs,
- increase of tunnel safety.
During control using the mathematical model, smaller number of jet-fans is switched on and lower peak air velocity is achieved, which is of particular advantage in case of emergency situation (fire), because in such situation switch over to mode with small air velocity required to establish smoke stratification in the tunnel will be faster.

Figure 3: Comparison of conventional and mathematical model of tunnel ventilation control

4. MODERNIZATION AND ADDS-ON OF VENTILATION SYSTEM

During modernization and add-on of the remote control system for ventilation control in 2005 using the mathematical model, tests and measurements of the tunnel parameters were carried out, and functioning of mathematical model was made. However, significant adds-on and modernization of the ventilation system had to be done before that.

In 2007 The ventilation study (see Drakulić, M.; Lozica, M.; Herve, F.; Binacchi, M. and others, The ventilation study of Učka Tunnel, 2007, [2]) was made to upgrade the system. A group of authors engaged in preparation of the study collected data on the existing equipment, examined the ventilation system and gave guidelines for modernization of existing equipment. Simultaneously, the Preliminary design of remote control system add-on was made, aimed to modernization, expansion and the planned admission of new subsystems in the tunnel.

The remote control system of tunnel Učka is based on DCS (Distributed Control System) ABB System 800xA, and it integrates monitoring and control with all the subsystem in the tunnel: power supply, ventilation, lighting, traffic signalization, fire alarm, SOS telephones, etc.

Completion of this modernization and adds-on created conditions for implementation of predictive mathematical model of ventilation control in normal mode, and algorithm for air flow control in emergency (fire) mode as well.

5. IMPLEMENTATION OF MATHEMATICAL MODEL IN TUNNEL UČKA

Design and implementation of mathematical model of ventilation control began in 2005 as part of modernization and add-on of remote control. In late 2009, completion of reconstruction of ventilation equipment ensured all the preconditions and so, after preliminary tests were done, the system was put into trial operation in December of the same year. The software module of mathematical model is designed as a component of remote control.
The input parameters for predictive mathematical model of tunnel Učka are:

- tunnel physical parameters, taken from project documentation and determined by testing and measurements at the system start-up,
- measurement of carbon monoxide (CO), visibility and air speed at five acquisition station in tunnel,
- measurement of atmospheric pressure at tunnel portals,
- measurements from traffic counters - four traffic counters in tunnel and two traffic counters installed at six kilometres before tunnel.

Besides the basic requirement of ventilation control, i.e. keeping pollutant concentration within defined limits, the concessionaire required the following:

- equalization of power load per both power supply networks, during operation roughly the same number of jet-fans is supplied from the Istrian and Kvarner side;
- load equalization at all substations, i.e. during operation roughly the same number of active jet-fans at all substations;
- equalization of the fan operating hours over longer period i.e. during exploitation all the jet-fans have roughly equal number of operating hours.

During trial period and the first year of mathematical model of ventilation control at tunnel Učka, it was shown that all requirements are met, with simultaneous significant increase of energy efficiency and energy savings.

6. ENERGY SAVING IN THE FIRST YEAR OF EXPLOITATION

By following up the consumption, substantial savings in electricity consumption (Figure 4) were recorded already in the first months of operation. Comparison of the average energy consumption per a vehicle in 2010 with the previous ten-year period - from 2000 to 2009 shows substantial decline in consumption in 2010. It should be noted that the total power consumption of tunnel Učka is being followed up, which includes: lighting, consumption of the building, installed systems, and ventilation. The consumption of lighting, building and installed systems that is mostly constant throughout the day and year, i.e. it does not change significantly compared to the daily and seasonal changes in traffic through the tunnel, while consumption of the ventilation system depends highly on the traffic through the tunnel. Data on total electricity consumption, trend of total number of vehicles, ratio of heavy and light vehicles, and data on average energy consumption per a vehicle (kWh / vehicle) at annual level in the period from 2000 to 2010 is presented in -> Table 1.

Saving in the average consumption (total) of energy per a vehicle for 2010 compared to the previous ten-year period amounts to 16.89 %.

Financial indicators of savings are also very significant. Taking the average consumption per a vehicle in the previous ten year period and the traffic realized in 2010 as a starting point, the estimated financial savings amount to 16.28%.

It should be noted that the savings are achieved during the day when the traffic is increased, and electricity is more expensive, and higher financial savings are to be expected with rising annual traffic levels. Also, as a significant result of the applied model is equalization of consumption per supply networks and reduction in subscribed demand which will further contribute to savings and reducing the financial cost.
Figure 4: Energy consumption per month - a comparison of average energy consumption from year 2000 until 2009 compared with year 2010

Table 1: Trends in the number of vehicles, the relationship between heavy and light vehicles, and total energy consumption in the period from year 2000 to 2010

<table>
<thead>
<tr>
<th></th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
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<tbody>
<tr>
<td>I</td>
<td>1,610,413</td>
<td>1,718,815</td>
<td>1,786,891</td>
<td>1,871,356</td>
<td>2,061,164</td>
<td>2,036,864</td>
<td>2,170,110</td>
<td>2,358,830</td>
<td>2,357,546</td>
<td>2,319,438</td>
<td>2,215,666</td>
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<tr>
<td>II</td>
<td>175,119</td>
<td>199,131</td>
<td>217,967</td>
<td>225,403</td>
<td>261,729</td>
<td>268,754</td>
<td>280,368</td>
<td>297,123</td>
<td>299,460</td>
<td>271,179</td>
<td>268,855</td>
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<tr>
<td>III</td>
<td>174,470</td>
<td>192,171</td>
<td>201,443</td>
<td>212,362</td>
<td>216,638</td>
<td>196,869</td>
<td>202,368</td>
<td>212,571</td>
<td>208,934</td>
<td>188,214</td>
<td>178,794</td>
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<tr>
<td>IV</td>
<td>95,816</td>
<td>107,899</td>
<td>113,955</td>
<td>124,433</td>
<td>140,599</td>
<td>141,060</td>
<td>143,259</td>
<td>155,009</td>
<td>156,834</td>
<td>148,205</td>
<td>138,342</td>
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<tr>
<td>TOTAL</td>
<td>2,055,838</td>
<td>2,218,226</td>
<td>2,320,254</td>
<td>2,433,554</td>
<td>2,682,110</td>
<td>2,643,543</td>
<td>2,796,256</td>
<td>3,023,553</td>
<td>3,022,774</td>
<td>2,927,036</td>
<td>2,799,657</td>
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<tr>
<td>Light vehicles</td>
<td>1,785,552</td>
<td>1,918,546</td>
<td>2,004,858</td>
<td>2,096,709</td>
<td>2,242,893</td>
<td>2,305,618</td>
<td>2,498,478</td>
<td>2,655,931</td>
<td>2,657,006</td>
<td>2,590,673</td>
<td>2,482,521</td>
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<td>Heavy/Light vehicle (%)</td>
<td>15,74</td>
<td>15,62</td>
<td>15,73</td>
<td>16,06</td>
<td>15,36</td>
<td>14,06</td>
<td>14,11</td>
<td>13,84</td>
<td>13,77</td>
<td>12,99</td>
<td>12,77</td>
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<tr>
<td>Energy (kWh)</td>
<td>4,189,709</td>
<td>4,304,995</td>
<td>4,673,424</td>
<td>4,148,368</td>
<td>4,228,985</td>
<td>4,071,334</td>
<td>4,423,493</td>
<td>4,027,845</td>
<td>4,169,258</td>
<td>3,738,675</td>
<td>2,964,599</td>
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<tr>
<td>kWh/vehicle</td>
<td>2,04</td>
<td>1,94</td>
<td>2,01</td>
<td>1,70</td>
<td>1,58</td>
<td>1,54</td>
<td>1,58</td>
<td>1,33</td>
<td>1,38</td>
<td>1,28</td>
<td>1,06</td>
</tr>
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Note: energy consumption is overall consumption including ventilation, lighting, control building, etc.

7. EVALUATION OF THE EFFECTIVENESS OF MATHEMATICAL MODEL

The analysis performed has shown the efficiency of mathematical model and cost savings in relation to total consumption. Looking at a part of energy consumption influenced by the applied model of control, i.e. energy consumption by the ventilation system, energy efficiency of the mathematical model can be expressed as the ratio of energy savings and energy consumption of the ventilation system.

\[
\eta = \frac{\Delta Ev}{Ev}
\]

where:

\(\Delta Ev\) – energy saving achieved by mathematical model

\(Ev\) – energy consumption of ventilation system
The mean value of saving in energy consumption per a vehicle for all months in 2010 compared to the ten-year average which is 16.89% is used as the value of efficiency. The share of consumption of the ventilation system (estimate) is 50.87% of total energy consumption, and efficiency of the mathematical model is:

$$\eta = 33\%$$

8. CONCLUSION

Mathematical modelling provides prediction of pollutant concentrations, providing significant advantages over "conventional" algorithm for automatic control. The result of mathematical model is:

- reliable pollutant concentration control within predefined limits,
- number of on- and off-switching of jet-fans, i.e. increased lifetime of jet-fans and electrical switching equipment and savings in maintenance costs,
- savings in maintenance costs,
- increase of tunnel safety (by reducing peak velocity of air flow),
- significant saving in electricity and
- increase of energy efficiency.

In hierarchical control level, mathematical model of tunnel ventilation control is a separate unit superior to the basic functions of the Control and Monitoring System, and it can be applied as Add-on in other tunnels, too.

9. REFERENCES

