Model Based Data Verification in a Highway Tunnel

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Abstract: A dynamic model of ventilation, traffic and exhaust inside a highway tunnel has been designed and implemented to simulate conditions inside a brand new highway tunnel *Mrázovka* in Prague, Czech Republic. A simulation has been performed to verify the data collected from the real tunnel. As a result, a statistical analysis of the simulated and real data is possible. Based upon the data analysis, a simulation program performance is judged as well. For the relevant data sets, an identification of possible measurement errors occurring at the sensors inside the tunnel is performed.

Keywords: Ventilation simulation, Traffic simulation, Data verification, Air pollution, Air flow

1 Motivation

The objective of this work is to use a simulation model to verify data collected from a highway tunnel and look for possibly malfunctioning sensors, as well as to see how the simulation model really works.

The tunnel *Mrázovka* in Prague, Czech Republic, has been opened since August 2004. However, after the opening of the tunnel, some indices have revealed several problems with various sensors inside the tunnel. To verify the reliability of the sensors, a model of dynamics has been designed and implemented for this tunnel and a simulation has been carried out in order to find the sensors, that are most possible erroneous.

2 System Description

2.1 Tunnel Mrázovka

The tunnel *Mrázovka* is a highway tunnel consisting of two separate tubes for two traffic directions. It is a tunnel junction in fact (Fig. 1). The overall idea about the complexity of the tunnel can be seen from Table 1.

[1] Q – flow rate [m^3/s], measured by air flow velocity [m/s]

Table 1 – Parameters of tunnel *Mrázovka*

Parameter	Western Tube	Eastern Tube
length	1296 m	1265 m
jet fans	22	15
jet fans input	344 kW	227 kW
NO_X sensors	12	10
CO sensors	6	5
OP sensors	5	8
Q[1]sensors	8	3

2.2 Data measurement

The data are collected from various sensors. The distribution of the sensors has been chosen so as to cover the most critical sections of the tunnel.

Several chemo-luminescence NO_X (nitrogen oxides) sensors are located around the tunnel portals to measure the exhaust output. The CO (carbon monoxide), NO_X and OP (opacity) sensors inside the tunnel are based on spectral absorption analysis. The Q sensors measure the air flow velocity by ultra sound. This velocity is then converted to a flow rate. All the sensors are made by SICK, AG.

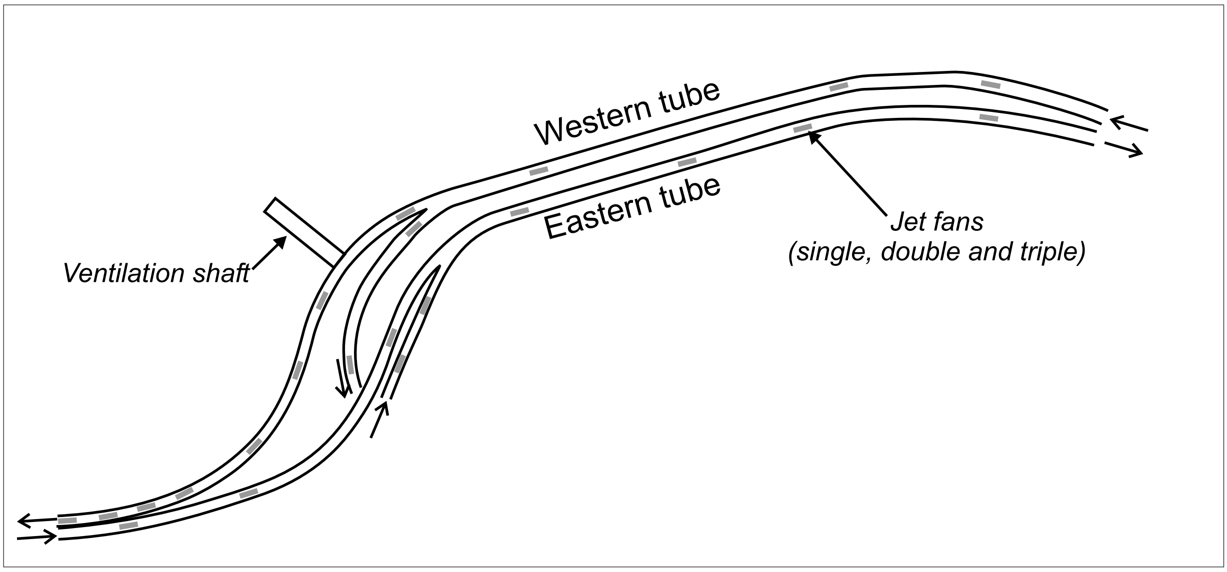

Fig. 1 – Schematic view of tunnel *Mrázovka*.

3 Simulation

For simulation of the tunnel ventilation, traffic and exhaust, a previously made simulation kernel has been used which has been designed for another tunnel to be built in Prague [3]. The simulation program has been written in MATLAB 7.0 [6].

The simulation program enables for a simulation of dynamics inside the tunnel. This feature gives us an option of performing various types of analyses. In this work, the simulation program will be used to compare simulation and real data and to reveal possible error-introducing factors inside the tunnel *Mrázovka*.

Before moving to the analysis part of work, a brief overview of the simulation program will be given.

3.1 System decomposition

The tunnel system is very complex and no simple model can be designed for it. There is a need for decomposition of this system. To handle the system more easily, both *functional* and *spatial* decomposition have been performed.

The *functional* decomposition is very intuitive (Fig. 2). The tunnel model comprises three main functional parts (or subsystems) – ventilation, traffic and exhaust. The inputs and outputs are well defined and the decomposition is quite natural as the system is fully separable.

Upon the analysis of a general tunnel structure, it has been decided to perform a *spatial* decomposition as well, in order to isolate various ventilation and traffic phenomenons. The spatial decomposition will be described in the following sections in more detail.

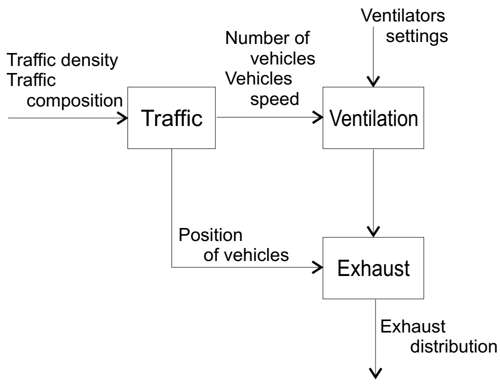

Fig. 2 – Functional decomposition of a tunnel system.

3.2 Traffic

To be able to simulate traffic in a dynamical manner, a microscopic car-following model has been used [5]. This model has been implemented in MATLAB. The implementation was chosen so as to get maximum computational power of MATLAB.

A general two-lane module has been made as a cornerstone for the traffic simulation. This way, the tunnel model is modular, which brings all the advantages of a modular approach, well known in the art.

3.3 Ventilation

The ventilation subsystem is *spatially* decomposed into several ventilation sections. The desired output of this subsystem is the air flow velocity, which is computed by a set of equations of continuity (1) and Bernoulli equations (2).

The equation of continuity (1) is used to connect the ventilation sections together.

$$v_{air} S_{area} = const \quad (1)$$

v_{air} = air flow velocity
S_{area} = tunnel cross section area

The Bernoulli equation (2) is an equation of energy, however, after suitable manipulation, we get an equation describing pressure changes inside a ventilation section.

$$\Delta P_{tot} = \Delta P_{loc} + \Delta P_{fric} \pm \Delta P_{pist} \pm \Delta P_{fans} \pm \Delta P_{atm} \quad (2)$$

P_{tot} = total pressure difference
Pressure drops:
P_{loc} = local losses
P_{fric} = friction
P_{pist} = vehicles piston effect
P_{fans} = jet fans effect
P_{atm} = atmospheric conditions

The set of Bernoulli equations and equations of continuity is a set of non-linear equations. To be able to solve it, a suitable numerical solver has been used [1].

However, the Bernoulli equation and equation of continuity describe a steady-state of a system. Assuming that the tunnel dynamics is very slow, i.e. the inputs to the tunnel (traffic density, jet fans puissance etc.) don't change suddenly, which is a reasonable presumption, we can take a consecutive series of steady states to form a long-term dynamics.

3.4 Exhaust

The exhaust levels depend both on vehicles type and distribution and air flow velocity inside the tunnel. The mass of the exhaust is being observed, because it does not depend on the tunnel geometry.

There are three pollutants measured inside the tunnel – nitrogen oxides (NO_X), carbon monoxide (CO) and opacity (OP), which is a formal representation of visibility range and dust particles concentration. Nowadays, this set of three pollutants is considered as standard [4].

3.5 Simulation implementation

To simulate the exhaust levels in the tunnel *Mrázovka*, the ventilation simulation has been left out, the real ventilation data (i.e. air flow velocities) have been used as a direct input to the exhaust simulation block (Fig. 2). There were two main reasons for that.

The tunnel *Mrázovka* doesn't have enough functional devices to measure the atmospheric conditions outside the tunnel. If there are only few vehicles inside the tunnel (esp. at night), the atmospheric conditions (wind speed and direction, air pressure and temperature) have major influence. The fact, that the influence of the atmospheric conditions

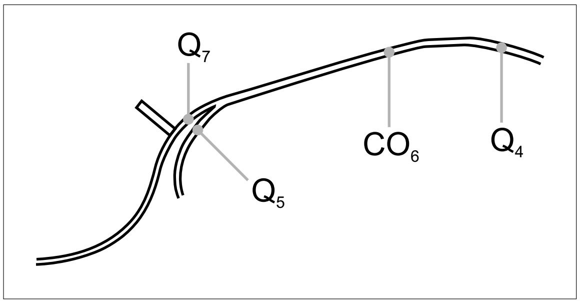

Fig. 3 – Location of sensors in the western tube of the tunnel *Mrázovka*.

cannot be neglected, wasn't known before we tried to simulate the air flow velocities inside the tunnel.

The other reason is that some of the air velocity sensors around the main ventilation shaft are not calibrated yet, so the effect of the main ventilation shaft cannot be computed precisely. In fact, the main ventilation shaft has also a major influence if running.

The data from September 22, 2004 have been used for this paper. This date has no special importance, it has been chosen randomly.

4 Results

The tunnel is very complex and there is a lot of sensors inside. To handle the problem properly, this section will be focused on one sensor only, namely the *CO6* sensor (carbon monoxide sensor), which is located in the western tube (see Fig. 3). For analysis, other sensors will be needed – the air flow velocity sensors *Q4*, *Q5* and *Q7*.

4.1 Measured data

Before verifying the simulation results, an overall analysis of the measurement errors has to be made. All relevant air flow velocity sensors and the CO sensor have to be examined.

As stated above, the air flow velocity measurement is carried out by ultrasound sensors. The sensors relevant for the CO measurement at the point *CO6* are located around a crossroad section inside the tunnel. At low air flow velocities, the air is considered to be incompressible [2], so the three Q sensors *Q4, Q5, Q7* fully describe the air flow around the tunnel junction.

The first thing to do is to check out, whether the measured data satisfy the equation of continuity (1), to be sure that all the air that goes into the chosen tunnel section goes out as well. From the geometry of the tunnel, $Q_4 - Q_5 + Q_6 = 0$. The result is shown at Fig. 4. The data are filtered by a moving average over 10 minutes.

From Fig. 4, it is apparent that the sensors are not calibrated at all. The standard deviation is 26.11 m^3/s (which represents about 0.27 m/s for the air velocity at sensor *Q4*).

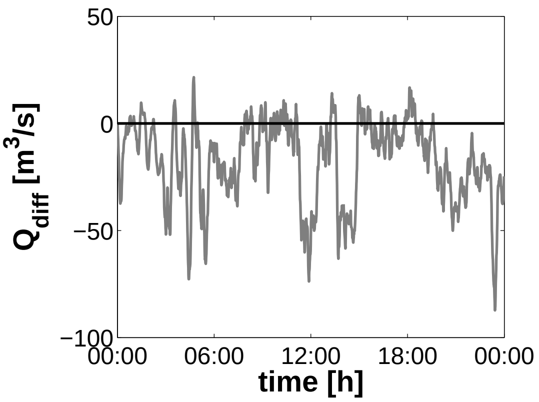

Fig. 4 – Verification, if the equation of continuity holds for sensors *Q4, Q5, Q7*.

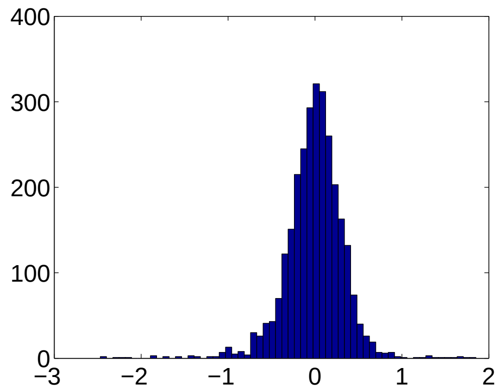

Fig. 6 – Histogram of deviations of the real data from the filtered data from sensor *Q4*.

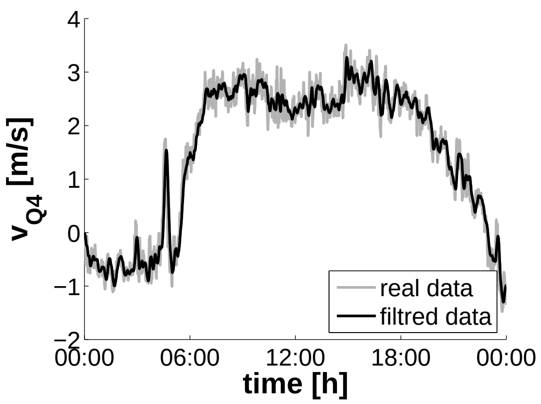

Fig. 5 – The real data from the air velocity sensor *Q4*.

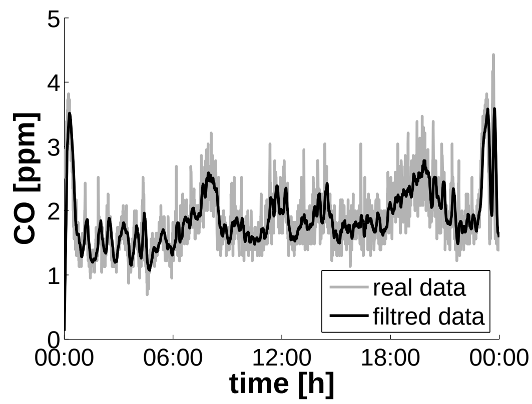

Fig. 7 – The real data from the carbon monoxide sensor *CO6*.

Let's now have a look on the data from the velocity sensor *Q4* as an example. They are shown on Fig. 5. The data were filtered again by a moving average over 10 minutes.

The data filter used in the present paper is a moving average filter over the interval of 10 minutes. This interval has been chosen with respect to the control, that is going to be designed in the future. As stated before, the present model is intended for a controller of the tunnel ventilation system. For this purpose, it seems reasonable to use the filtered data for the control instead of the real data. 10 minutes moving average is just enough to minimize the variations in the real data, but is also short enough to not introduce any serious delay.

Averaging the real data means removing the measurement error as well. Fig. 6 is a histogram of the deviations of the real data from the filtered data. The distribution is close to normal, so we can figure that the data really involve a measurement error and that the filtered data are much closer to the real situation.

The standard deviation of the sensor measurements will now be introduced as a standard deviation of a difference between the filtered data and the measured data:

$$\delta_{sens} = \mathrm{STD}(data_{filtred} - data) \qquad (3)$$

By this approach, it is easier to judge the effect of the measurement noise. The standard deviations according to equation (3) of the three concerned air velocity sensors are as follows:

Sensor	SD [m/s]
Q4	0.25
Q5	0.30
Q7	0.39

Now the focus will be turned to the CO sensor (*CO6*).

As can be seen from Fig. 7, the data have much more noise than the air velocity sensors data. The filtered data represent the real situation better than the real data again. If we draw the histogram of the deviations again, it would be a normal distribution, too.

The CO sensor measurement shows a standard deviation (according to equation (3)) around 0.51 ppm.

4.2 Possible sources of errors

The most possible reason why the data from the air velocity sensors don't satisfy the **equation of continuity** (1) is the placement of the sensors. Comparing the figures 4 and 5, we can easily see that the situation is worst during low air flow velocities.

If the air velocity inside a tunnel is very low, the air flow is not laminar, it is strongly turbulent [2]. Therefore, the sensors measure "some" air flow velocity, which doesn't represent the real mean air flow velocity across the tunnel. However, as the air flow velocity increases, the overall laminarity of the air flow improves and the sensors begin to measure more reliable data.

However, the **standard deviations** of the air flow velocity data are considerably high. Even if the overall laminarity of the air flow is good, the cars passing by create local turbulences. These turbulences present the high measurement noise and introduce the high standard deviations.

Just note the two depressions at Fig. 4 around 12 AM and around 2 PM. Their source is a lower air flow velocity at sensor *Q5* and *Q7*. The relative deviation is not critical though, because the air flow velocity was quite high in this period.

The noise is extremely high in the **CO measurement**. The CO sensors have to be able to measure CO concentrations up to around 200 ppm that appear in emergency situations. But the "normal" CO level is 100 times less. So the CO measurement is under a serious measurement error caused by a low sensitivity of the sensors in low CO concentrations.

4.3 Quality of simulation

The situation for the simulation is now very complicated. Not only that the CO measurement is extremely erroneous, but also because the air flow velocity measurement doesn't satisfy the equation of continuity (1)(Fig. 4). The air flow velocity is a crucial input to the simulation. If it is not reliable, the output (pollution levels) is not reliable as well. Indeed, if the simulation is performed, the simulation data are far from the real data in some intervals (see Fig. 8)

However, the simulation is not entirely useless. If an interval is chosen where the air flow velocities satisfy the equation of continuity (1), the situation is much different. From Fig. 4, it can be seen that the data are best between 7 AM and 9 PM. Indeed, the simulation complies with the real data quite well in this interval (Fig. 9). The absolute values don't really match, but the overall trend of the simulation matches the trend of the real data.

As a measure of quality of our simulation, a correlation of the real signal and of the simulated data is useful (Fig. 10). From the correlation function, we can see that for the entire day, the data don't correlate at all. But for the selected period, the correlation is quite satisfactory.

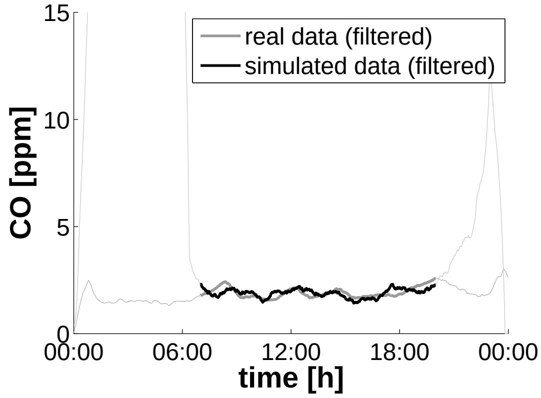

Fig. 8 – Simulated and real data from the *CO6* sensor.

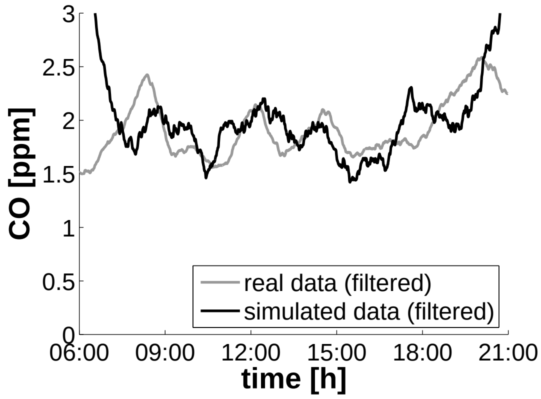

Fig. 9 – Simulated and real data from the *CO6* sensor – detail of the data between 6 AM and 9 PM.

If we now discuss the usefulness of the simulation, we have to admit that it is of no use if the air flow velocities inside the tunnel are really low (and the data don't satisfy the equation of continuity (1)).

But why does this happen? There may be two reasons. One reason is that the air velocity sensors just measure nonsense data. In this case we cannot do anything about it. The other reason is that our simulation computes the movement of the exhaust from the air flow velocity only. If this velocity is very low or zero, the exhaust spread by diffusion, which is not incorporated in the simulation.

For the future control design, the present simulation is good enough if the data satisfy the equation of continuity. For the control purposes, the simulation is being reset all the time with the real measured (and possibly filtered) data. So at every time, it provides a prediction for some time horizon. A short-time prediction is quite satisfactory (see Fig. 11).

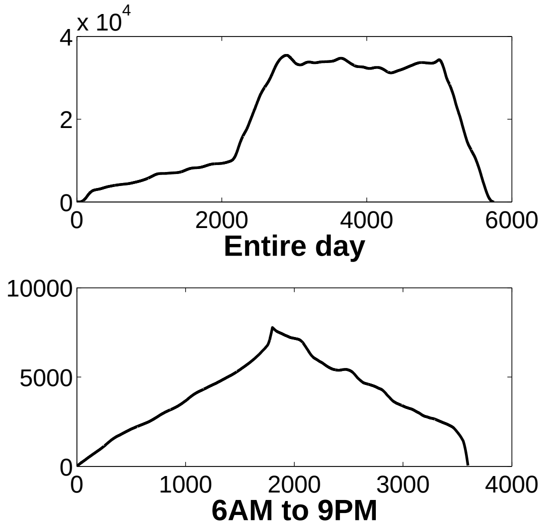

Fig. 10 – Correlation of the real data and the simulated data. Comparison for the entire day and for the selected period.

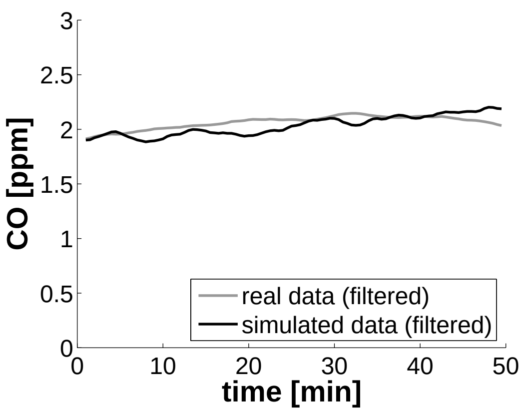

Fig. 11 – CO concentration prediction for control purposes.

4.4 Other sensors

As stated above, this paper is focused on carbon monoxide sensor *CO6* and adjacent air flow velocity sensors *Q4*, *Q5*, *Q7*. However, there are much more sensors inside the tunnel (see Tab. 1 and Fig. 3). A similar analysis has been made for a majority of the sensors. The results are similar for most of the sensors.

5 Conclusion

The simulation program presents a tool for modelling an atmospheric environment inside a highway tunnel. To compare the real and simulated data, it has been necessary to perform an analysis of the real data. This analysis has shown a significant noise in the data.

Therefore, the simulation model itself has limitations for use under uncertain conditions (low air flow velocities etc.) However, its performance is good enough and the simulation model can be used in conjunction with a control system as a predictor.

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References:

[1] Bellavia, S., Macconi, M., and Morini, B. An affine scaling trust-region approach to bound-constrained nonlinear systems. *Applied Numerical Mathematics*, 44:257–180, 2003.

[2] Douglas, J. F., Gasiorek, J. M., and Swaffield, J. A. *Fluid Mechanics*. Prentice Hall, 4^{th} edition, 2001.

[3] Kurka, L., Ferkl, L., Sládek, O., Pořízek, J., and Šebek, M. Dynamical simulation of ventilation in tunnel blanka. In *Proc. of MATLAB 2004*, Prague, 2004.

[4] PIARC. *Road Tunnels: Emissions, Environment, Ventilation*. PIARC, 2004.

[5] Rathi, A. K. et al. Traffic flow theory: A state of the art report. Technical report, FHWA, 2002.

[6] The MathWorks, Inc. Matlab 7.0, Release 14, 2004.