

SIMULATION OF TRAFFIC, VENTILATION AND EXHAUST IN A COMPLEX ROAD TUNNEL

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Abstract: A detailed simulation has been proposed and implemented for a complex road tunnel to be constructed in Prague, Czech Republic. The work brings new approach to functional and spatial decomposition of traffic, ventilation and exhaust tunnel subsystems allowing a simulation of dynamics. The discretization method provides a highly realistic and detailed behavior of the tunnel system. In addition, simulation of emergency situations is available. The simulation has been implemented in MATLAB. *Copyright ©2005 IFAC*

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1. INTRODUCTION

The tunnel *Blanka* is designed to fill in the last gap in Prague inner bypass. It will start in Prague – Břevnov, continue to the tunnel junctions at Prašný Most and Špejchar and it will end in Prague – Trója (Pelc-Tyrolka) (see Figure 2.1). The project is unique not only in the Czech Republic, but concerning its complexity, there are only few tunnels in the world comparable to this one.

2. SYSTEM ANALYSIS

2.1 Requirements

The purpose of this simulation is to prepare a numerical model for detailed analysis of the air flow and air pollution levels inside the tunnel. It

will serve for control design as well. To achieve maximum performance, reliability and accuracy of the simulation model, following requirements have to be met:

- Realistic traffic simulation
 - traffic density control, passing by, slip and turning lanes
 - various vehicle types
 - parameters can be modified during simulation (e.g., the traffic density can be adjusted)
- Ventilation
 - jet fans, shafts, piston effect
 - “slow dynamics” (will be discussed further)
- Exhaust
 - concentration distribution
 - dynamical changes

To maintain sustainable comfort of the simulation, the computer code has to be written in an

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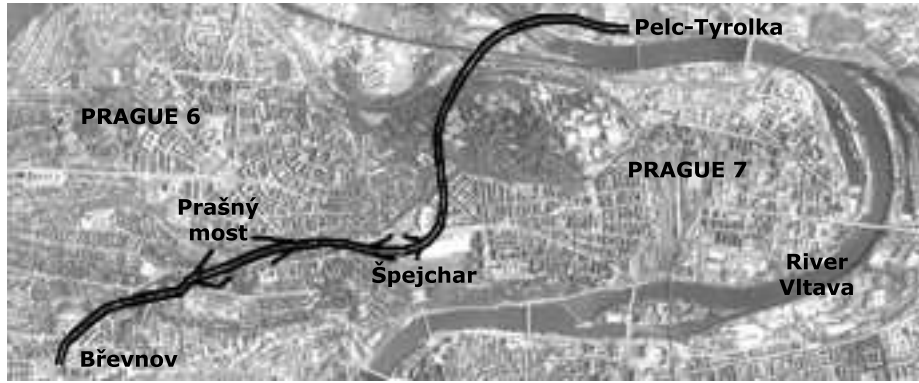


Fig. 1. Aerial map of the tunnel *Blanka*. The tunnel will form the last part of Prague inner bypass.

efficient way. As MATLAB (The MathWorks, 2004) is an interpreter and the present system is fairly complex, unnecessary cycles should be avoided and an advantage should be taken of the computational power of MATLAB, as much as possible.

Table 1. Construction parameters of tunnel *Blanka*.

Length	cca 5 660 m
Fans	cca 40 per each tube
Shafts	3
Onramps	5 per each tube

2.2 System decomposition

The blocks of *functional decomposition* come out naturally from the requirements, which are stated above. The model will be split into three parts – traffic, ventilation and exhaust. The relations and physical dependencies are illustrated in Figure 2.

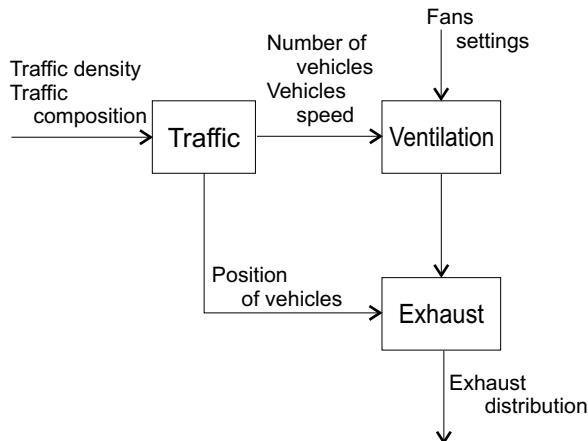


Fig. 2. Functional decomposition of the tunnel.

However, the tunnel is still extremely large and complex. Therefore a *spatial decomposition* is needed. The tunnel model will be divided into separate sections. These sections are chosen upon structural features of the tunnel important for the traffic and ventilation simulation. Based upon construction drawing analysis, it is apparent that

the ventilation requires much finer sections than traffic.

As a result, different strategies have been chosen to decompose the tunnel for traffic and ventilation purposes. *Ventilation sections* are represented by lumped models, i.e., in each section all the parameters (e.g. air velocity, friction, vehicle piston effect etc.) are the same (in space, not in time) and only average values are simulated.

Traffic sections have been chosen to achieve necessary traffic flow and redistribution of vehicles around tunnel junctions.

3. TRAFFIC SIMULATION

3.1 General representation and algorithms

In several air flow simulations of the tunnels that have been made recently, traffic simulation is treated in a purely statistical manner in (Bellasio, 1997)(Bring, A., 1997)(Noekel, 1998). The statistical approach is based on experimental measurements in existing tunnels. The level of pollution is determined on the average traffic density, vehicles speed and tunnel cross section area. In this approach, only static dependencies can be computed, as the measurement data are based on long-term observations.

In the present simulation, traffic is represented not only statistically, but position and speed of every single car is simulated, too. This way, it is possible to compute an immediate exhaust production and a simulation of dynamics is allowed.

Two main objectives have been considered during the traffic simulation – realistic behavior of the traffic situation and the computational speed.

After considering various approaches, a discrete implementation of the traffic has been chosen. The model of the entire tunnel is represented by a single tall matrix, wherein every row fully describes the state of the respective one-meter part of the tunnel (see Figure 2, wherein the

matrix is transposed for illustration). Basically, a row carries three essential types of information – the tunnel construction features, the traffic situation and the exhaust produced by the traffic.

The tunnel construction features are static. They include two pieces of data – one describing the traffic restriction, the second one is the speed limit in the respective part of the tunnel. These parameters either do not change, or their change represents some emergency situation².

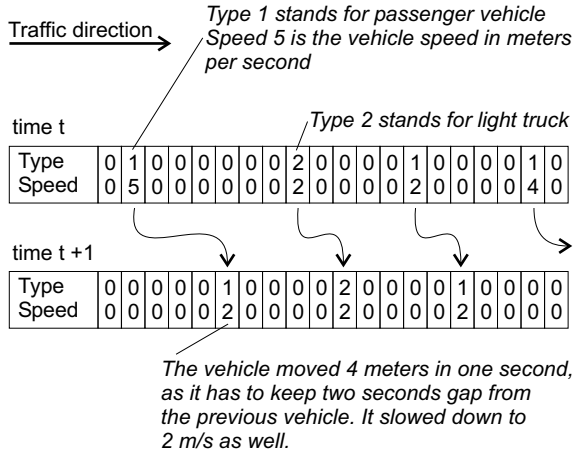


Fig. 3. Movement of the vehicles in the tunnel – principle of algorithm.

The vehicles are described by a pair of parameters – their actual speed and type of the vehicle (passenger car, van or truck).

This representation is very advantageous, as the full computational power of MATLAB can be used. The movement of the vehicles can be implemented quite naturally by the internal MATLAB commands (namely `find`) and indexing. This way, we avoid use of `for` cycles and reach maximum performance. MATLAB is an interpreter and the interpretation is performed in every cycle, whereas the internal functions (like `find`) are interpreted only once. As a result, the movement inside the tunnel is very simple and can be written as follows (for explanation, see Figure 2):

```
>> i = find(TUNNEL(4,1));
>> j = i + TUNNEL(i,2);
>> X = TUNNEL;
>> X(j,3:4) = X(j,3:4) + TUNNEL(i,3:4);
>> TUNNEL = X - TUNNEL;
```

The variable `TUNNEL` represents the entire tunnel, the computation is performed on the columns of the matrix, as MATLAB is column-oriented.

Other features have been implemented as well. They include rules for slip and turning lines, zip-

ping rule, traffic density settings and traffic composition settings (ratios of passenger cars, vans and trucks). The vehicles behave in a realistic manner, e.g., they have 2 seconds intervals between each other and they don't perform a perfect zipping, which is typical for Czech drivers.

3.2 Decomposition strategy

A vehicle entering the tunnel behaves in the following manner:

- enters the tunnel
- zips into the right lane
- tries to find as much space as possible; if the right lane is jammed, it moves to the left lane
- moves on to the desired junction or to the end of the tunnel
- moves to the right lane, later to the turning lane
- leaves the tunnel

In the tunnel *Blanka*, the situation is even more difficult, as three lanes are available in some areas.

After analysis of the situation, it has been decided to build one versatile traffic section to compose the tunnel of. The section has two lanes, redistribution factor can be chosen for the traffic redistribution, and a traffic restriction can be introduced to simulate slip and turning lane or an emergency situation (e.g. car accident). An example of how the model of tunnel is built up is shown in Figure 4.

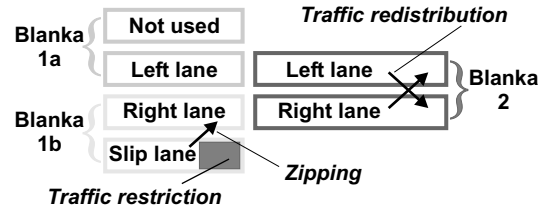


Fig. 4. An example of how the model of tunnel is composed. Represents first 575 metres of the northern tube. This part is composed of three sections – Blanka 1a, Blanka 1b and Blanka 2.

4. VENTILATION

The air flow is generally described by a system of differential equations for mass and momentum balance (Navier–Stokes differential equations). Unfortunately, these are strongly non-linear and it is almost impossible to solve them even with most powerful computers.

Instead, the simplified system of steady-state equations (Bernoulli equations and continuity equations) can be used. Assuming slow changes of input parameters (traffic density, fans output,

² E.g. car accident. If we want to simulate such an event, we simply mark a traffic restriction in the desired section and one lane will be blocked for all the traffic.

etc.), they can describe *slow dynamics* as well. The term *slow dynamics* means that the dynamical changes in the tunnel can be treated as a series of steady states.

As stated above, for the purpose of ventilation simulation the tunnel is divided into *ventilation sections*. The adjacent ventilation sections are mathematically connected by continuity equations (Equation 1).

$$\Delta(v_{air}S_{tun}) = 0 \quad (1)$$

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

For each of the ventilation section, we solve a Bernoulli equation (Equation 2). The Bernoulli equation describes a pressure difference between two ends of a ventilation section. The equation itself consists of several members representing different kinds of pressure drops.

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

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

The pressure drop caused by local losses (Equation 3) depends on loss coefficient ζ , which represents losses due to cross section changes, shape of transition, direction of flow etc.

$$\Delta P_{area} = \frac{\rho}{2} \zeta v_{air}^2 \quad (3)$$

ρ = air density
 ζ = loss coefficient
 v_{air} = air flow velocity

The pressure drop caused by friction losses (Equation 4) depends on wall roughness, traffic signs on the walls etc.

$$\Delta P_{fric} = \frac{\rho}{2} \lambda \frac{l}{d_H} v_{air}^2 \quad (4)$$

λ = friction factor
 l = length of ventilation section
 d_H = hydraulic diameter of the tunnel

The pressure drop caused by piston effect of the vehicles (Equation 5) (which can be a pressure increase as well) represents the influence of the vehicles passing through the tunnel. In the present simulation, different influence of three types of vehicles (passenger cars, vans and trucks) is taken into account.

$$\Delta P_{pist} = \frac{\rho}{2} \frac{l(v_{veh} - v_{air})^2 \gamma_{conv}}{S_{tun} v_{veh}} \sum_i S_i n_i \quad (5)$$

v_{veh} = average speed of the vehicles
 γ_{conv} = convoy polynomial
 S_{tun} = tunnel cross section area
 S_i = average head surface area of the respective vehicle type
 n_i = number of vehicles of the respective type

The last member in the Bernoulli equation (Equation 2) represents the pressure drop caused by fans (Equation 6). The parameters of this part (power efficiency, input power and air velocity) are all catalogue data.

$$\Delta P_{fans} = \frac{\rho}{2} \frac{\eta P_{fan}}{S_{tun} v_{fan}} (v_{fan} \pm v_{air}) \quad (6)$$

η = power efficiency of a fan
 P_{fan} = fan input power
 v_{fan} = fan air velocity

The unknown variables in the system of equations are the air flow velocities and static pressure in the respective ventilation sections. As apparent from above, the set of equations we get for the entire tunnel is a set of non-linear (quadratic) equations with respect to the air flow velocities. As this set cannot be solved analytically, we have to use numeric methods.

When programming in MATLAB, `fsolve` function from *Optimization Toolbox* can be used for the desired numeric solution. This function is a general numeric solver for a system of non-linear equations. It uses several gradient methods to solve the system of equations.

However, another solver has been used in the present simulation program, `strscne` function³ developed by University of Firenze, Italy (Bellavia, S., 2003). This function uses gradient methods as well, but uses affine scaling trust-region method. This function is more accurate for the present system of equations than `fsolve`.

5. EXHAUST

Nitrogen oxides, carbon monoxide and air opacity are observed inside the tunnel (PIARC, 1996). However, the simulation can be adapted to any emission models, as in (McGaughey, 2004).

To represent the exhaust in the tunnel, it was necessary to find an invariant variable. Exhaust mass is such variable – it doesn't depend on geometrical properties of the tunnel (unlike concentration).

A vehicle releases some amount of exhaust. The movement of an amount produced in one second

³ This function can be downloaded from Internet <http://ciro.de.unifi.it/STRSCNE/>

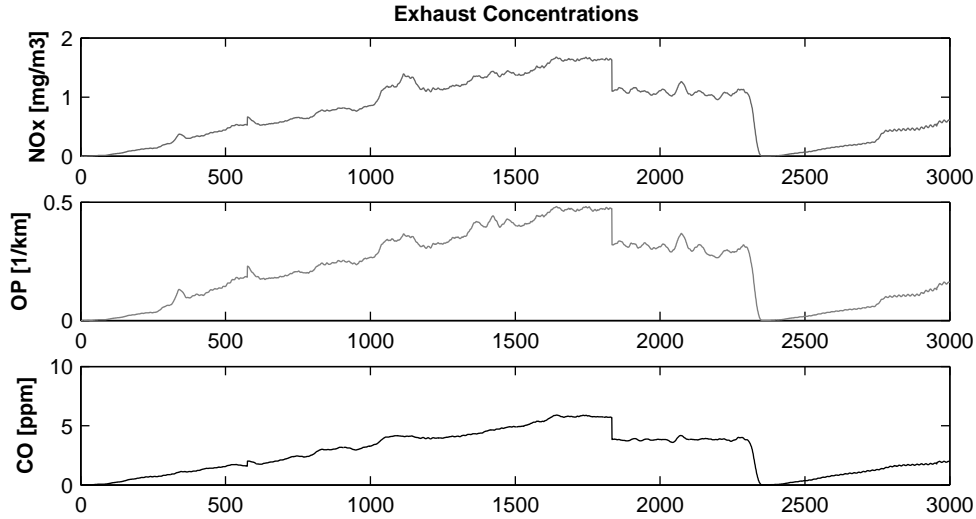


Fig. 5. Simulation of exhaust concentration distribution. Northern tube, first 3000 meters. Traffic density 1600 vehicles/hour, traffic composition 95 % passenger vehicles, 4 % vans, 1 % trucks.

(or an *exhaust package*) inside the tunnel depends on the air flow that we get from the ventilation model (see Section 4). The movement itself is computed by an algorithm similar to the movement of vehicles (Figure 2), we have only *exhaust packages* instead of cars. The algorithm is much simplified, as the exhaust doesn't zip, pass by, etc.

As the exhaust is represented by the exhaust packages, the overall pollution situation inside the tunnel has to be smoothed using moving average. The result values are shown as concentrations (Equation 7).

$$C = \frac{\text{moving_average}(M)}{V} \quad (7)$$

C = concentrations

M = exhaust packages

V = volume of the respective parts of the tunnel

At the tunnel joints, the exhaust is being transferred as follows:

For the slip lane the concentrations are added from the joining tunnel to the main tunnel.

For the turning lane the concentrations are divided into the main and turning tunnels according to their air velocities.

6. SIMULATION RESULTS

Figure 5 depicts simulated exhaust concentration distribution in the northern tube. The observed parameters are carbon monoxide (CO), nitrogen oxides (NOx) and opacity (OP). Traffic density has been set up to 1600 vehicles/hour with 95 % passenger vehicles, 4 % vans and 1 % trucks. The drop of concentration at 1800 m is caused

by sudden tunnel cross section enlargement – a section with two lanes ends and three lanes begin here. The drop at 2350 meters is caused by a ventilation shaft here running at 100% power, which represents 320 m³/s of air outlet and the same quantity of fresh air inlet. The exhaust distribution corresponds to already existing tunnels described in (PIARC, 1996).

In Figure 6, static characteristic of the air flow velocity with respect to the vehicles speed inside the tunnel is shown. To have more vehicles passing through, higher speed is required.

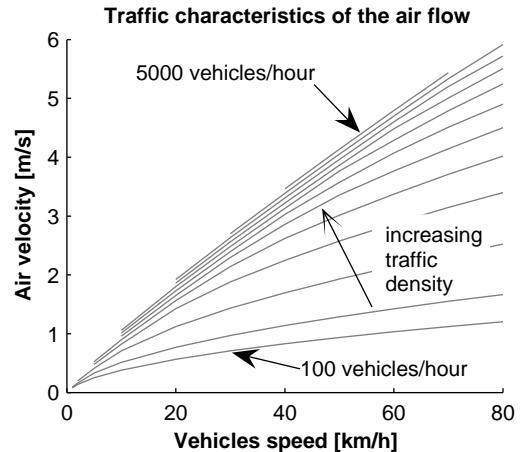


Fig. 6. Static characteristics of the air flow velocity in the tunnel.

The *slow dynamics* of the simulation model can be illustrated by Figure 7. This figure represents the exhaust concentration build-up during the first 8 minutes after opening of the tunnel, a transient response in fact. The simulation parameters are the same as for Figure 5.

As stated in Section 3, the present simulation has a unique feature – actual vehicle distribution.

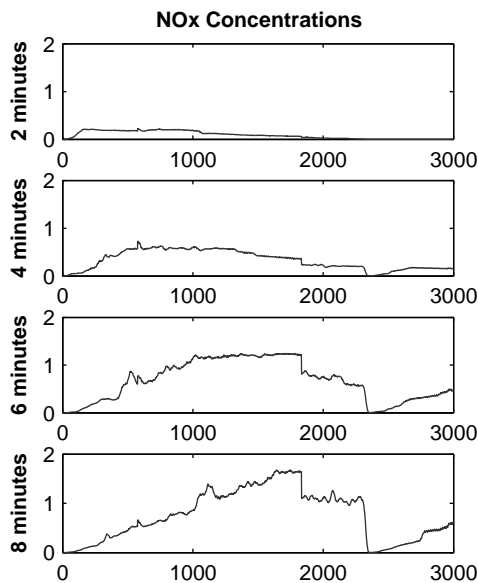


Fig. 7. Simulation of NOx concentration distribution. Dynamic response of the first 8 minutes after opening for traffic.

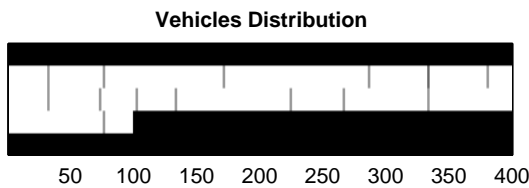


Fig. 8. Vehicles in the northern tube, first 1000 meters. Vehicles are marked by a little gray line.

Figure 8 is a graphical representation of the traffic situation of first 400 meters in the northern tube of the tunnel. First 100 meters have 3 lanes, the rest has 2 lanes. The vehicles are marked as little vertical gray lines.

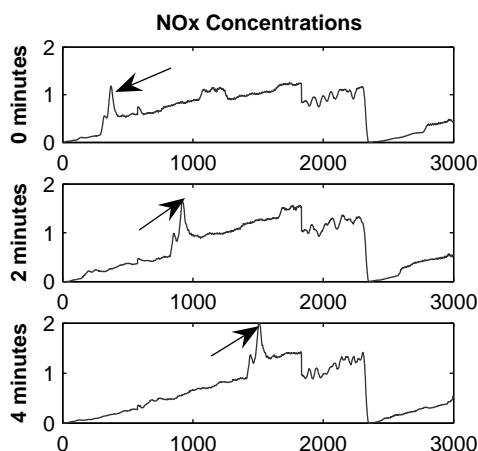


Fig. 9. Simulation of NOx concentration distribution with a heavy truck inside the tunnel (marked with an arrow).

With this unique feature of the present simulation, it is possible to view the influence of a single heavy truck inside the tunnel. The situation is shown in Figure 9. The heavy truck brings a significant increase in exhaust concentration.

Table 2. Comparison of tunnels *Mrázovka* (real data) and *Blanka* (simulation)

Tunnel	CO [ppm]	NOx [$\mu\text{g}/\text{m}^3$]	OP [km^{-1}]
<i>Mrázovka</i>	4.8	3.2	0.9
<i>Blanka</i>	5.2	2.6	0.6

To verify our data, we have used the measurements from already existing tunnel *Mrázovka* (also in Prague). The data are shown in Table 2. As can be seen from this table, the simulation data are basically correct. However, more analysis has to be done on the present simulation model to see, whether the output data are reliable enough⁴.

7. CONCLUSIONS

The present simulation brings novel features in the tunnel traffic, ventilation and exhaust simulation. *Slow dynamics* simulation has been implemented successfully and the results match behavior of existing tunnels very well. The simulation program represents a suitable basis for further tunnel environment analysis and control system design.

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⁴ The proposed method is to simulate the tunnel *Mrázovka* and to compare the simulation with the real data. After finding possible inconsistencies, it is necessary to correct the simulation of tunnel *Blanka* accordingly.