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TIME SCALES IN ROAD-TUNNEL VENTILATION

I. Riess [1], M. Wehner [2] and R. Brandt [1]
HBI Haerter AG, [1] Zürich, CH, [2] Heidenheim, D

ABSTRACT

The paper summarises results from the study of the ventilation system of the Swiss Aecherli tunnel (2071 m long and up to 1400 vehicles/h). Furthermore, it gives an outlook for the use of characteristic time scales for the choice and design of ventilation systems.

Due to reduced costs, the use of a longitudinal ventilation system with one central exhaust port in a bi-directional road tunnel instead of the conventional semi-transverse ventilation is often a competitive alternative. However in the case of asymmetric traffic, the piston effect supports the ventilation in one half of the tunnel and inhibits it in the other half. In this case, traditional steady-state computations would predict the need of an excessive fresh-air supply. Alternatively, our studies of the unsteady behaviour of the flow in the Aecherli tunnel demonstrate that a smaller flow rate is adequate when

- the characteristic time scale for the concentration of the exhaust fume to reach the maximum permissible value is long
- the fresh-air supply due to natural ventilation is sufficient in most traffic conditions
- the tunnel air may exit the portals unhindered

Under these conditions, the limiting design parameter is neither the fresh-air demand from steady-state computation based on the vehicle emissions under constant traffic nor the higher fresh-air demand due to asymmetric traffic conditions. The determining factors are rather the control parameters that are characteristic for the tunnel, traffic and ventilation system, i.e. the time scales of concentration, vehicle emission and ventilation.

1. INTRODUCTION

In order to reduce transit traffic in the village of Giswil, a bypass road is planned. The Aecherli tunnel is part of this bypass road. After a first comparison of ventilation systems, a semi-transverse ventilation was proposed.

As an alternative, a longitudinal ventilation system with one central exhaust port was proposed. The tunnel air is removed through a large damper in the middle of the tunnel and through a duct above the ceiling. In the case of asymmetric traffic, the piston effect supports the ventilation in one half of the tunnel and inhibits it in the other part giving rise to the need of an enhanced fresh-air supply. Therefore, the design of a longitudinal ventilation with one central exhaust port included a large safety margin. In the case of the Aecherli tunnel, the fresh-air requirement in the year 2002 would basically be 50 m^3/s. Stationary computations, however, would predict a required flow rate of 150 m^3/s for the longitudinal ventilation with a central exhaust port [1].

Our study of the unsteady behaviour of the longitudinal ventilation with a central exhaust port [2] showed that this safety margin may be reduced for the Aecherli tunnel, if a suitable control routine is used. In the study, the smoke concentration over time and tunnel length was calculated for various ventilation-control routines.

The study lead to reflections on the unsteady behaviour of alternative ventilation systems. It was found that the behaviour of a ventilation system is governed by relations between few time scales. Comparing the time scales, the results of our study could be applied to other tunnels.

2. AECHERLI TUNNEL

The Giswil bypass is part of the Swiss national road N8. The Aecherli tunnel covers the largest part of it. The tunnel is 2071 m long, with bi-directional traffic on two lanes. The geometric and traffic data are

- length $L = 2071$ m
- inclination $i = 2.52\%$ south to north
- height above sea level $H = 520$ m
- tunnel, cross-section area $A_T = 47$ m^2
- tunnel, hydraulic diameter $D_{hT} = 6.72$ m

- ventilation duct, cross-section area A_K = 12 m^2

- ventilation duct, hydraulic diameter D_{hK} = 2.56 m

- inauguration year 2002

- average mass of trucks m = 16'500 kg

- proportion of trucks 10%

- proportion of cars with diesel engines 5%

- Emissions calculated according to PIARC 7 (1995) [3]

- Daily peak traffic volume in 2002 [4] weekday: 420 vehicles per hour

  weekend: 960 vehicles per hour

  summer-holiday season: 1400 vehicles per hour

Figure 1 shows the longitudinal ventilation with a central exhaust port and a ventilation duct above the ceiling. The polluted air is removed from the tunnel by means of a damper in the ceiling. Fresh air flows through the portals into the tunnel.

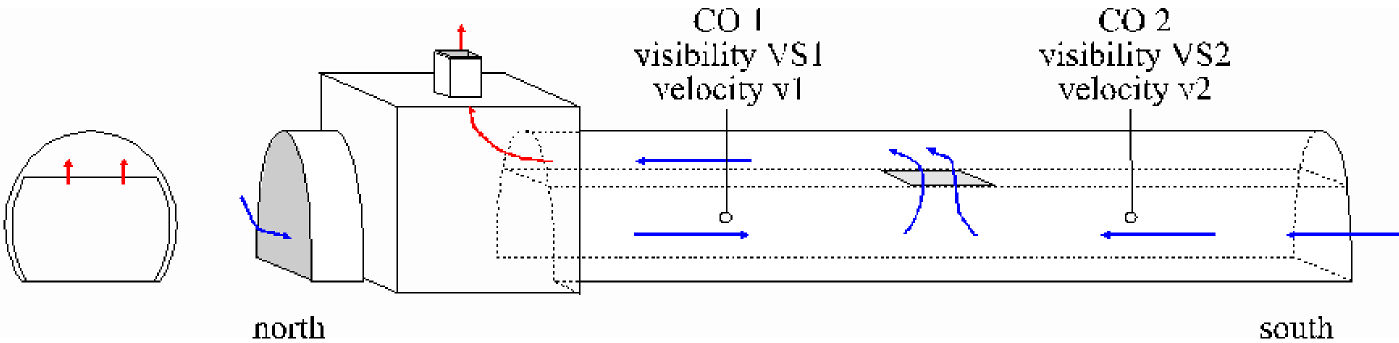

Figure 1: Longitudinal ventilation with central exhaust port

The measured data of carbon-monoxide and visibility are used for the control of the ventilation. Moreover, the measurement of the flow velocity with amount and direction is of special importance for the control routine. In the simulation, the values of CO, visibility and velocity are measured at two locations: one in each half of the tunnel. The true positions for the measurement instruments in the Aecherli tunnel are not yet decided.

In Switzerland, the maximum acceptable extinction is 0.007 /m. The other values are according to PIARC 7 [3]. The admissible values of the extinction coefficient and the carbon-monoxide concentration in the tunnel are

	CO [ppm]	Visibility [1/m] (extinction)
Fluid peak traffic 80 km/h	100	0.005
Exceptional congested traffic, standstill on all lanes	150	0.007

Table 1: Threshold values for air quality used in this study

In all studied traffic conditions, the extinction coefficient determined the fresh-air demand. The limiting design case was congested traffic in both directions. In 2002, such a situation, which is a very rare event for a national-road tunnel, would yield a fresh-air requirement of 50 m^3/s in order to maintain an adequate air quality. With a fresh-air supply of only 50 m^3/s, the flow velocity in the tunnel would be rather low. Therefore, we based this study on a minimum volume flow rate of 60 m^3/s.

3. COMPUTER PROGRAM ROADTUN2

RoadTun2 [5] is a computer program for the simulation of unsteady processes that are relevant for the ventilation of road tunnels. It uses the one-dimensional method of characteristics. It calculates the time variation of flow velocity, static pressure and concentration in the entire tunnel system. RoadTun2 simulates the behaviour due to the time-varying traffic (volume, velocity, composition etc.), the ventilation and the inertia of the aerodynamic system. The tunnel configuration ranges from a single tube to very complex tunnel systems. Beyond the vehicle emissions and the natural ventilation, the influence of the ventilation system is calculated. So far, thermal effects, such as the chimney effect due to hot smoke from a tunnel fire, cannot be calculated. However, the chimney effect can be modelled by prescribing a pressure difference. In order to simulate the behaviour of various ventilation-control routines, measurement points were defined. The calculated values of concentration, velocity and pressure at the control points can be used as input data for the ventilation control.

4. VENTILATION CONTROL

Prior to designing the ventilation system, we computed the pollution dispersion caused by the polluted air leaving the portals of the tunnel [6]. In the case of the Aecherli tunnel, the flow was permitted to exit the portals, which would not lead to a violation of the legislation for the environment. Hence only the fresh-air demand in the tunnel is relevant for the ventilation control.

Two entirely different ventilation-control routines have been tested:

- The simple routine:

  Inside both tunnel sections, the values of visibility and carbon-monoxide concentration were measured. The maximum value of the two measured extinction coefficients was used as the control parameter:

  - If it exceeds 0.003 /m, the ventilation is switched ON (flow rate: 60 m^3/s).
  - If it drops below 0.002 /m, the ventilation is switched OFF.

- The advanced routine:

  Additionally, the velocities in both tunnel sections were used for the control system. A time average over a period of 10 min was calculated. The minimum value of the two velocities was used in the control loop. The main philosophy is to alter the condition of the ventilation system using one single criterion, i.e. if the ventilators were switched ON (flow rate: 60 m^3/s) they will be switched OFF and vice versa.

  - The criteria for switching ON (respectively OFF) is

    if the maximum of the extinction coefficients exceeds 0.003 /m,

    the minimum of the velocities drops below 0.3 m/s and

    the switching using this criterion has not followed within the previous 15 min.

  - The ventilation is switched OFF when the extinction coefficient drops below 0.002 /m.

With the advanced control routine, the state of the ventilation is changed if low flow velocities are present concurrent with poor visibility (high extinction). Consequently, it is ensured not to ventilate against excessive natural forces. Using this method, the natural ventilation is implicitly used when applicable.

Synthetic traffic conditions are not suitable for testing ventilation-control routines. They correspond to a natural traffic flow for only very short periods of time. Therefore, real traffic data were used. The data came from the Reutherberg tunnel in Germany. The data were collected over a period longer than four hours as the number of cars and trucks every 5 min. Traffic volume and proportion of trucks were fitted to the traffic volume for the Aecherli tunnel. The statistical variation in traffic flow remained unchanged.

Figure 2 displays an example of calculations applying both control scenarios. At the measurement points, the extinction coefficient is below the legal limit (table 1) in both control routines (upper diagrams in figure 2). The simulations result in a very different behaviour of the ventilation. The ‘simple’ routine runs the ventilation for longer time, than the ‘advanced’ routine, which includes the flow velocity. The time-dependent distribution of the extinction coefficients in the two cases are similar. The highest values are reached using the ‘simple’ routine. When possible, the ‘advanced’ control routine benefits from the natural ventilation by reducing instead of increasing ventilation power. However, the parameters for the control routine must be chosen carefully. If the limit for the minimum flow velocity is increased to 1.0 m/s, the difference between the ‘advanced’ and ‘simple’ control routine vanishes.

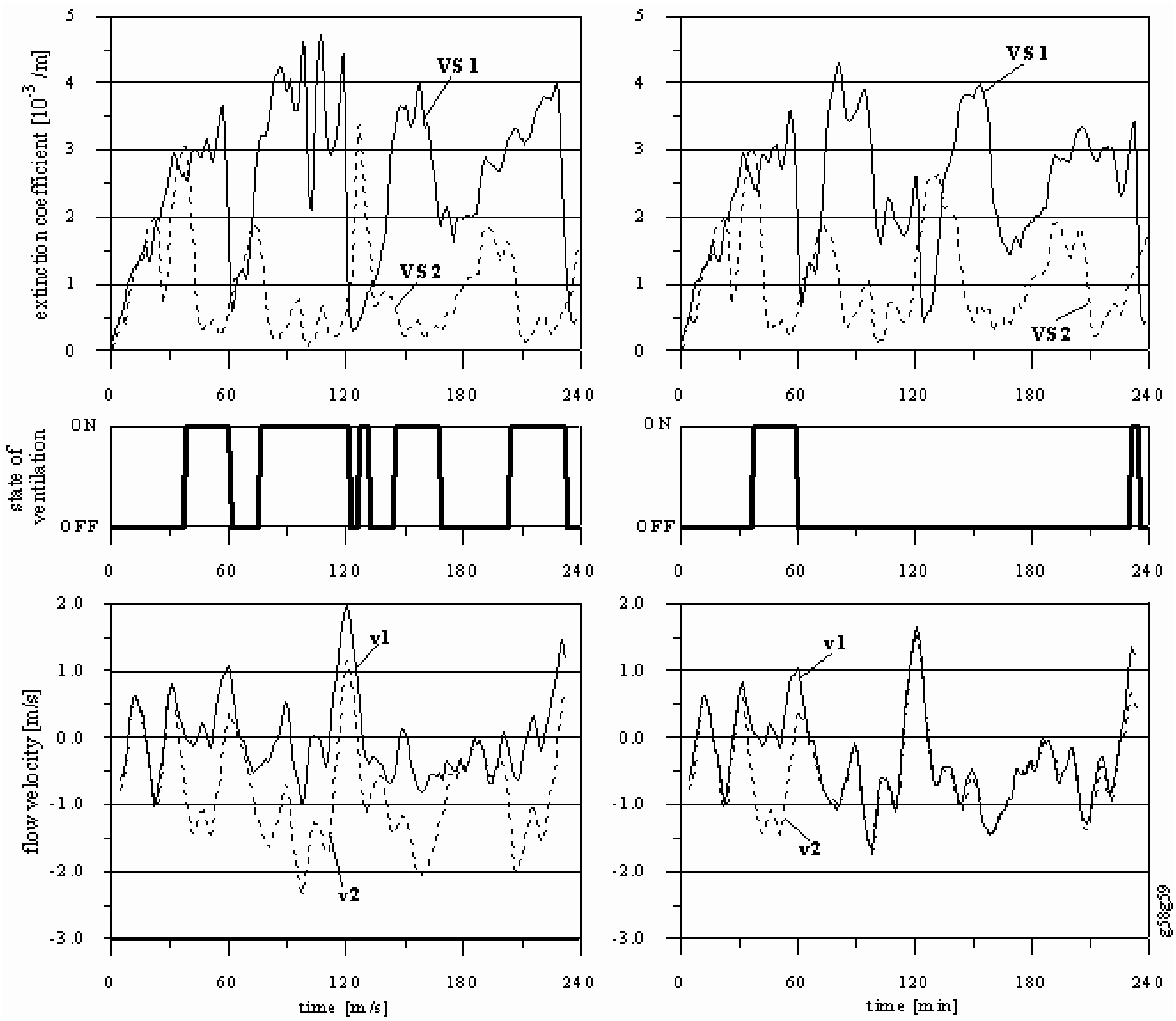

Figure 2: Time-dependent extinction coefficient, state of ventilation and time-averaged flow velocity

for the ‘simple’ (left) and ‘advanced’ (right) control routine

The simulation of the unsteady behaviour of the flow in the Aecherli tunnel demonstrates that a flow rate of 60 m^3/s is adequate, when

- the required time for the concentration of the exhaust fume to reach the maximum permissible value is long
- the fresh-air supply due to natural ventilation is adequate in most traffic conditions
- the tunnel air may exit the portals without restrictions due to environmental considerations

The calculation of the fresh air demand and simulation of the unsteady behaviour of the ventilation showed that the ventilation in the Aecherli tunnel will rarely run. Situations with need of ventilation are distinguished by low flow velocities over a longer period of time. Whether this is due to balanced traffic or to a meteorological pressure is of minor importance.

A higher ventilation flow rate aids the control of the ventilation. For the Aecherli tunnel, we finally recommended a ventilation design with a flow rate of 80 m^3/s.

5. TIME SCALES

From the simulation of the dynamic processes related to the tunnel ventilation, the question arose whether or not the results of our study might be applicable to other tunnels and ventilation systems. We came to the conclusion that these processes are related to time scales that are characteristic for the tunnel, the traffic volume and the ventilation system. The time scales have been determined for the Aecherli tunnel using simulations of the unsteady flow applying theoretical traffic conditions rather than the real ones used in the previous sections. The goal was to distinguish few parameters that adequately describe the behaviour of the system that consists of tunnel geometry, traffic and ventilation.

Traffic scale

The first time scale is related to the traffic. It is derived from the vehicle velocity and the tunnel length and gives the time a vehicle needs to pass through the tunnel.

t_T = (tunnel length) / (traffic velocity) (1)

This time scale describes how the pollution emerges within the tunnel. If there is a single vehicle with high emission rates, the value of t_T describes the duration of this singular event. In the Aecherli tunnel, the authorised speed is 80 km/h. This gives $t_T \approx 1.5$ min.

Aerodynamic scale

The aerodynamic time scale is the most difficult one to estimate. It describes the time the tunnel flow needs in order to reach a steady-state condition after a change in traffic volume, ventilation or external pressures has taken place. It is a function of traffic volume, traffic velocity, ventilation system and tunnel geometry. It is related to the inertia of the tunnel air.

t_A = f (traffic volume, traffic velocity, tunnel geometry...) (2)

For the Aecherli tunnel this time scale is in the order of 5 to 8 min (there is about 110'000 kg air in the tunnel). The aerodynamic scale is more important for smoke control than for regular tunnel ventilation.

Ventilation scale

The ventilation time-scale describes the time it takes for the concentration distribution to adjust succeeding a significant change in traffic volume or a single emission event (e.g. a vehicle with exceptional high emission rates). It depends on the average flow velocity in the tunnel and the length of a tunnel section. The flow velocity can be due to natural ventilation

t_{VN} = (tunnel cross-section * tunnel length) / (natural ventilation flow rate) (3)

or induced by the ventilation system

t_{VS} = (tunnel cross-section * tunnel length) / (ventilation flow rate) (4)

In the Aecherli tunnel, the value of t_{VN} is in the range between 15 and 22 min depending on the traffic condition. The meaning of the time scale t_{VS} varies somewhat depending on the ventilation system of the tunnel. For a longitudinal ventilation, it requires a period of t_{VS} to exchange the tunnel air completely. In a semi-transverse or transverse ventilation, the maximum concentration is reduced to about 40%. In the Aecherli tunnel t_{VS} is about 20 min for a flow rate of 80 m^3/s and 27 min for a flow rate of 60 m^3/s.

Concentration scale

The time scale of concentration describes the time it takes for the concentration of the exhaust fume to reach the admissible value under balanced traffic conditions.

t_C = (tunnel cross-section * length) / (typical fresh-air requirement) (5)

In the Aecherli tunnel, the concentration time-scale is about 120 min for free flowing bi-directional traffic.

Interpretation of time scales

The ratio of t_{VN}/t_T describes the stability of the natural ventilation. When few vehicles with high emission rates go through a tunnel, the pollution concentration might rise above the threshold value within few seconds. If t_{VN}/t_T is sufficiently low (e.g. lower than 5), there is no need to start the ventilation immediately. The control routine could delay the action, because natural ventilation will remove the pollution within a few minutes. In the Aecherli tunnel, the ratio t_{VN}/t_T is in the order of 10 to 14 depending on traffic conditions. Only with asymmetric traffic will the natural ventilation be sufficient. Asymmetric traffic increases the natural ventilation. A low value of the ratio t_{VN}/t_T is especially found in tunnels with unidirectional traffic. The strong natural ventilation in a tunnel with free flowing uni-directional traffic will keep the value of t_{VN}/t_T in the order of 3 to 4.

The ratio t_{VS}/t_T gives the ability of the ventilation system to react after a single emission event when natural ventilation cannot remove the pollution. The traffic time scale t_T will always be much smaller than the ventilation time scale t_{VS}. Therefore, the ventilation of a road tunnel is a very inert system. Changes take time. The time scale t_{VS} should be considered when a ventilation is designed for a tunnel with a low fresh-air demand due to a low traffic volume. It should be sufficiently low in order to enable adequate fast response from the ventilation system. The value of the ratio t_{VS}/t_T is 13 for the Aecherli tunnel assuming a ventilation flow rate of 80 m^3/s.

If the value of the ratio t_C/t_{VN} clearly exceeds unity, mechanical ventilation will rarely be used. Natural ventilation will be sufficient under most traffic conditions. On the other hand if the ratio is less than unity, the ventilation system will run practically the entire day. For the Aecherli tunnel, the value of t_C/t_{VN} is in the order of 6 to 8. Mechanical ventilation will rarely be used.

At values of t_C/t_{VS} clearly exceeding unity, the control of the ventilation is better to handle than at lower values. In the Aecherli tunnel, the value of t_C/t_{VS} is about 6 assuming a volume flow rate of 80 m^3/s. For the smaller flow rate of 60 m^3/s, the ratio is reduced to 4.5. It is obvious that for a ratio t_C/t_{VS} less than unity, the ventilation system will not work properly, as the fresh-air demand is not met by the flow rate supplied by the ventilation system.

Ventilation design using time scales

Traditionally, ventilation design is based on the computation of the fresh-air demand calculated using averaged vehicle-emission factors. When the ventilation flow rate meets the fresh-air demand, it is assumed that the ventilation system will work properly. Some claim that the decreasing vehicle emissions invariably abolish the need of ventilation systems in a few years time. However, drivers have become more critical to the air quality they meet in road tunnels. In Swiss and German road tunnels there have been complaints about bad visibility in road tunnels even though the maximum extinction coefficient as recommended by PIARC 7 [3] was met.

When the calculation of the fresh-air demand and the value of the ratio t_C/t_{VN} shows that a tunnel ventilation will run regularly, it is not necessary to take other time scales into account.

On the other hand, when the ventilation will rarely be used, it should be designed sufficiently powerful to react to a single emission event within a reasonable time. An example: The calculated fresh-air demand for a tunnel is, say, 55 m^3/s due to a low traffic volume. The tunnel is 4 km long and has a tunnel cross-section area of 50 m^2. In this case, the ventilation system needs more than one hour to clean the tunnel air after a few high-emission vehicles have passed through the tunnel. This is not acceptable even if the calculated fresh-air demand is met. One viable approach is to design the ventilation system using the time scales mentioned above under consideration of all relevant boundary conditions.

6. CONCLUSIONS

1. If asymmetric traffic conditions are taken into account, the design of a longitudinal ventilation with one central exhaust port leads to a flow rate exceeding the predicted fresh-air demand. The piston effect of the traffic supports the ventilation in one part of the tunnel and inhibits it in the other part.
2. If in such a tunnel
   - the time scale for the concentration of the exhaust fumes to reach the threshold value is long,
   - the fresh-air supply due to natural ventilation is sufficient in most traffic conditions and
   - the tunnel air may exit the portals unhindered,

   the design parameter is neither the flow rate calculated for asymmetric traffic conditions nor the fresh-air demand from steady-state computation based on vehicle emissions under constant traffic. The ventilation flow rate is calculated from relations between the characteristic time scales of concentration, emission and traffic. Using this approach, the re-design of the ventilation system for the Aecherli tunnel amounted to an immense cost reduction.
3. The decreasing vehicle emissions lead to a reduced fresh-air demand calculated from averaged vehicle-emission factors. But when it is expected

that the ventilation will rarely be used, it should be sufficiently powerful to react to a singular emission event within a reasonable time.

4. The unsteady behaviour of tunnel ventilation, either longitudinal or transversal, can be estimated from time scales of concentration, emission and traffic.

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