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Simulation and Measurement of Road Tunnel Ventilation

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Abstract—*A computer program for PC has been prepared to simplify studies of air flows in road tunnels and the related problem of pollution concentration due to emission from vehicles. Results from simulations include air pressures, flow rates, and pollution concentrations along the tunnel. Input data are tunnel geometry, including flow friction factors and loss coefficients, plus traffic and emission data and air pressures at boundaries. The program has been prepared in the IDA environment for modular simulation. All mathematical models have been formulated in the Neutral Model Format (NMF) [Sahlin 1994]. The program has been validated by comparisons with older programs (Malmström 1980). Advantages of the new program, as compared to traditional programs, are its great flexibility, ease of maintenance, and extendibility, as well as the very moderate implementation time. It has proved to be a useful tool for studying alternative ventilation concepts for road tunnels. Air flow rates have been measured in part of the "Söderledstunneln," a much-used road tunnel in central Stockholm. The measurements were made with tracer gas technique, which made it possible to measure without disturbing the traffic flow through the tunnel. The measurements have been compared to simulations of the air flow.*

1. Introduction

The exhaust gases from cars and lorries make ventilation necessary for road tunnels. Many different systems have been used, ranging from full transverse ventilation, i.e., where ventilation air is supplied and exhausted via terminal devices distributed along the tunnel, to longitudinal ventilation, which in one-way tunnels takes full advantage of the air flow induced by the traffic. The flow situation can be complicated; an example is two adjacent interconnected, longitudinally ventilated one-way traffic tunnels. The complexity of such schemes makes obvious the need for computer modeling.

There are many design issues, the first of which is the choice among the basic ventilation layouts. Standard variables include geographical/geological features, amount and type of traffic, fire safety, reliability, maintenance, and economical aspects. Special attention is often paid to environmental considerations such as air quality near tunnel openings, possibly resulting in demand of stack exhausts.

There is still some lack of detailed knowledge about the air flow physics in road tunnels. Compared to normal duct or pipe flow, the flow in a tunnel is influenced by the moving traffic, changing the air velocity profiles. In spite of this, normal pipe/duct procedures are used to calculate air flows in tunnels. The models used in this program are also to some extent based on duct flow models (Pursall and West 1976 and 1979; PIARC 1991).

Other examples of areas with limited knowledge are the efficiency of different locations of momentum jet fans (the distance between them, location relative to ceiling and walls) and the pressure regain when part of the tunnel air is exhausted (Kawamura et al. 1973).

The described situation emphasizes the need for full-scale tests. However, it is difficult to measure the air flow rate in tunnels, because of the large dimensions and flow rates, as well as traffic. Tracer gas measurement is a possibility, and such tests have been performed in a 1-km-long tunnel section with longitudinal ventilation.

2. The Simulation Program

2.1 Modular Simulation

During the last decade, modular (sometimes called object-oriented) simulation environments have started to emerge. The primary aims of this development are to avoid the rigidity of many earlier monolithic programs and to facilitate exchange and reuse of component models; the models are regarded as data in the new tools.

One such environment is IDA (Sahlin and Bring 1991), developed as a joint effort by the Division of Building Engineering Services at KTH (Royal Institute of Technology), Stockholm, and the Swedish Institute of Applied Mathematics.

At the heart of IDA lies a general solver for modular, differential-algebraic systems of equations. Key features of IDA are the following:

- Modeling (in NMF) is input/output free, i.e. variables have no irrevocable roles as given or calculated. Input/output free modeling naturally leads to models described by equations rather than the traditional calculation procedures, thus getting closer to the physical relationships known to the modeller.
- The system can handle algebraic as well as differential equations, including algebraic loops.
- The integration of dynamical systems uses variable timestep and order, for efficiency and for consistent, easy to use, accuracy control.

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- Sparseness in the system of equations is utilized effectively, using a variety of algorithms.
- Models can be precompiled and distributed as ready building blocks.
- Discontinuities in driving functions and in model equations are handled properly.
- Extensions to the basic equation modeling allow handling of discrete system states, as required by e.g. hysteresis.

2.2 Calculation of Air Flow

The program uses lumped parameter models, i.e., in each tunnel section only the average air speed is modelled. The present version is limited to steady state solutions, disregarding dynamics of pollution concentrations.

The air flow in any section of the tunnel system is derived from balances of air mass flow and total pressure for the whole tunnel. The steady flow energy equation is the basis for the calculations and the energy losses (or gains) are modelled similarly to normal pipe flow calculations.

The loss coefficients are in some cases calculated by the program, but they can also be given by the program user. The current lack of detailed knowledge for some of the air flow configurations precludes a completely automatic calculation of loss coefficients.

2.2.1 Undivided sections

In an undivided tunnel section, the total pressure change can be calculated by adding contributions from friction and area changes in the tunnel, vehicle piston effect, jet fans, and stack effect:

$$\Delta P_{tot} = \Delta P_{frict} - \Delta P_{area} + \Delta P_{veh} + \Delta P_{fan} - \Delta P_{stack}$$

The different contributions are

$$\Delta P_{frict} = \frac{\rho}{2} \sum_i \lambda \frac{l_i}{d_i} * Vair_i * |Vair_i|$$

where

ρ = density of air (kg/m^3)
λ = friction factor
l_i = length of tunnel segment i
d_i = hydraulic diameter of tunnel segment i
$Vair_i$ = mean air velocity in segment i (m/s)

$$\Delta P_{area} = \frac{\rho}{2} \sum_j \zeta_j * Vair_j * |Vair_j|$$

ζ_j = resistance factors for area changes, depending on areas, shape of transition, and direction of flow

$$\Delta P_{veh} = \frac{\rho}{2} \sum_k c_d * \frac{A_d}{A_{tun}} * f_d * (V\,veh_k - Vair_k) * |V\,veh_k - Vair_k|$$

c_d = drag coefficient, depending on vehicle type
A_d = vehicle cross section area (m^2)
A_{tun} = tunnel area (m^2)
f_d = factor >1 correcting the drag coefficient for the tunnel effects
$Vveh_k$ = vehicle velocity (m/s) for vehicle k

$$\Delta P_{fan} = \rho \sum_m k_{fan} * (Vfan_m - Vair_m) * |Vfan_m|$$

k_{fan} = efficiency factor for the fan
$Vfan_m$ = fan outlet velocity (m/s) for fan m

$$\Delta P_{stack} = \rho * \Delta z * g$$

Δz = change of altitude in segment (m)
g = acceleration of gravity (m/s^2).

2.2.2 Ventilation shafts

In transverse and semi-transverse systems, air is often supplied into the tunnel without any velocity in the flow direction in order to produce good mixing. Consequently, the air has to be accelerated and causes a pressure drop in the flow direction. On the other hand, when air is exhausted, it will cause a pressure gain, especially if the exhausted part of the tunnel air initially has low momentum in the longitudinal direction.

The extra pressure loss (or gain) is modelled by

$$\Delta P_{shaft} = \frac{\rho}{2} k_{shaft} * Vair_{max}^2$$

where

k_{shaft} =loss coefficient
$Vair_{max}$ =highest air velocity, before or after shaft (m/s)

A frequent approximation is that the exhausted air has mean velocity in the flow direction. The pressure gain can then be calculated from the assumption of constant total pressure. This is obviously a simplification in most cases, since, for instance, the air close to the ceiling moves slower than mean velocity when traffic is moving freely.

2.2.3 Tunnel junctions

For normal duct flow, loss coefficients in branching components can be calculated by formulae taken from HVAC handbooks (Miller 1978). The coefficients depend on flow velocities and on duct geometry, especially angles between branches. In road tunnel junctions, angles between branches tend to be more acute than in ventilation ductwork, which makes the application of duct formulae extra uncertain.

In the computer program, duct formulae are used for converging junctions, and losses are related to the air speed in the common branch. For diverging junctions, explicit loss coefficients have to be supplied by the user, and losses are related to the highest air speed in any of the three branches. In both cases, resulting air flows should be checked carefully to ensure that calculated losses are reasonable.

Table 1. NMF models in Tunnel Ventilation Library.

Model name	Function	Parameters
XtEntry	Entry portal	Tunnel area, loss coefficient
XtExit	Exit portal	Ditto
XtBrchOf	Exit junction	Tunnel areas in three branches; two loss coefficients
XtBrchOn	Entry junction	Tunnel areas in three branches; radius of point between joining branches; two parameters to calculate loss coefficients
XtAirExh	Air exhaust	Tunnel area, loss coefficient
XtAirSup	Air supply	Ditto
XtTunnel	Undivided tunnel	Friction factor; Tunnel area, hydraulic diameter plus loss coefficients at area changes; jet fan area, momentum and efficiency; vehicle speed zones

2.2.4 Tunnel portals

Wind pressure is a factor of importance, especially for longitudinally ventilated tunnels, but also for all systems for which the goal is no emission through the portals. The resulting force depends on the difference between the atmospheric overpressure at the windward side and the underpressure at the other side (this difference must be given to the computer program). Because of the distance between the two portals, there is usually a considerable damping of the influence of gusts of wind.

Naturally, the surroundings of the portals have a dominating influence, and to evaluate this factor, scale model wind tunnel tests (also simulating the ground boundary layer) are most valuable. In each specific case, the size of wind force that should be used in the design of the ventilation is, to a large extent, dependent on the acceptable risk of having to close the tunnel.

2.3 Pollution Concentrations

The pollution concentrations in a tunnel depend on air flow in the tunnel, supply and exhaust of ventilation air and emission rate along the tunnel. The emission rate depends on the stock of vehicles, the slope of the tunnel, and weather conditions. The pollutants most discussed are CO, NOx, and smoke, and it may be noted that their emissions have different characteristics relative to for instance vehicle speed.

The differential equations describing the concentrations can be integrated by the program with time varying boundary conditions. The results will describe the concentrations along the tunnel as depending on initial pollution concentration and on varying tunnel air flow, fresh air supply, exhaust rate of vitiated air, and, of course, emission rate. However, since the time variations of driving functions are relatively slow, dynamic studies are mostly not required, and the program has so far been used to calculate steady state conditions at selected points in time.

2.4 Inventory of Models

Table 1 shows the central models that have been developed for the program and their respective parameters.

Vehicle flows and speeds, ventilation air flows, fan speeds, and emission rates are given as time-varying boundary data.

To give a flavour of the NMF, the model XtEntry is shown in Figure 1 (see following page).

2.5 An Example

The layout of a fairly complicated tunnel system, simulated by the program, is shown in Figures 2 and 3. The example is fetched from the design of a planned ring road system, encircling central Stockholm.

Some key data for the simulated system are given in Table 2.

3. Measurements in the "Söderledstunneln"

3.1 The Tunnel

Söderledstunneln is a tunnel in central Stockholm, 1500 m long. It is running in north-south direction and consists of two separated tubes, one for north-going traffic and one for south-going, each with two lanes. The layout of the tunnel is schematically shown in Figure 4. Each tube is longitudinally ventilated with momentum fans to assist when the traffic is slow moving or in case of fire. The tunnel is equipped with three ventilation shafts for exhausting polluted air through chimneys, two located 500 m into the tunnel from the north end (one in the north going and one in the south-going tube), and one in the southern end of the south-going tunnel. No ventilation chimney was accepted at the northern end of the tunnel. Instead, the wall between the two tunnel tubes has openings close to the northern end to allow air from the north-going tube to be entrained into the south-going tube, with the help of momentum fans.

Because of its downtown location, the tunnel is much used. Figure 5 shows normal traffic flow rates and Figure 6 mean velocities for the traffic in the southern part of the north-going tunnel tube (Johansson 1996). The north-going traffic typically consists of 96% cars and vans, 3% lorries and 1% buses.

Normally, there is no need to use the momentum fans, but the air flow is driven by the piston force of the traffic. The

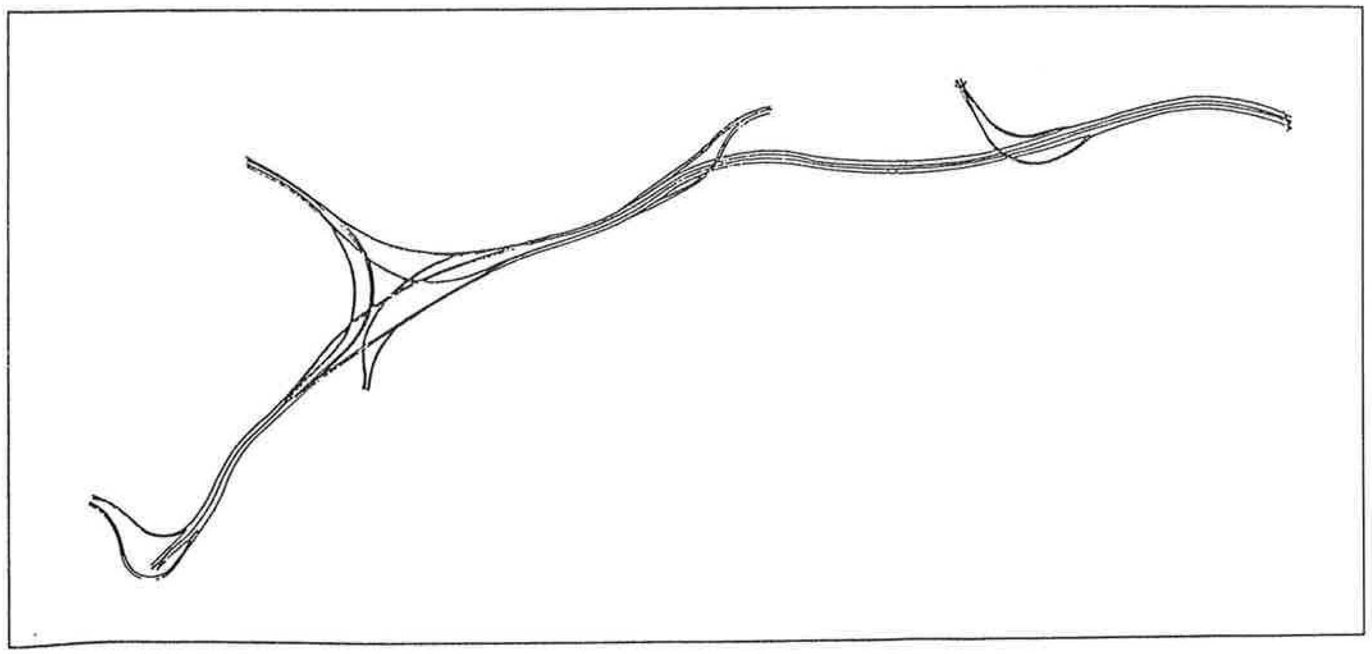

Figure 2. Map of sample tunnel system.

momentum fans are started when the concentration of pollutants in the tunnel air is high. The exhaust fans are also controlled by the degree of pollution in the tunnel air, and are started when it is necessary to protect the environment of the tunnel portals.

The southern part of the north-going tunnel tube is 1000 m long with no dividings. This part was selected for the tracer gas measurements.

```
CONTINUOUS_MODEL XtEntry

:IBSTRACT "Tunnel entry ;
    one-dir 2-part traffic, bi-dir air w TWO fractions"

/*
    |
    |________________
    1   ——>   2
     ________________
    |
    |
*/

EQUATIONS

/* ambient conditions */
    P1 = PAmb + PWind ;

/* effective density */
    IF VFAir1 > 0 THEN
        Rho := 1 / GASCON * (101325 + P1) / (T1 - ABS_ZERO) ;
        M := VFAir1 * Rho ;
    ELSE
        Rho := 1 / GASCON * (101325 + P2) / (T2 - ABS_ZERO) ;
        M := VFAir2 * Rho ;
    END_IF ;

/* conserve mass flow */
    VFAir1 * (101325 + P1) = VFAir2 * (101325 + P2) ;

/* air velocity */
    VAir = (VFAIr1 + VFAir2) / 2 / aTun ;

/* energy equation */
    P1 = P2 +
        IF M > 0 THEN Rho / 2 * (1 + Ki) * Vair**2
        ELSE 0
        END_IF ;

/* convected heat through tunnel */
    Q = IF M > 0 THEN CP_AIR_M * T1 * M
        ELSE CP_AIR_M * T2 * M
        END_IF ;

/* fraction transported through tunnel */
    XCOf =  IF M > 0 THEN VFAir1 * XCO1
            ELSE VFAir2 * XCO2
            END_IF ;
    XNO2f = IF M > 0 THEN VFAir1 * XNO21
            ELSE VFAir2 * XNO22
            END_IF ;
```

```
LINKS

/* type         name        variables... */
CarTunAmb2      Portal      POS_IN VehFa, POS_IN VehFB,
                            PAmb, PWind, POS_IN  VFAir1, T1,
                            XCO1, XNO21 ;

CarTunnel2      CarOut      POS_OUT VehFa, POS_OUT
VehFB,

                            P2, POS_OUT VFAir2, T2, POS_OUT Q,
                            XCO2, POS_OUT XCOf, XNO22,
POS_OUT XNO2f  ;

VARIABLES

/* type         name        role    description */
MassFlow        M           LOC     "mass flow [kg/s]"
Pressure        P1          OUT     "tunnel entry pressure"
Pressure        P2          OUT     "terminal 2 pressure"
Pressure        Pamb        IN      "ambient static pressure"
Pressure        Pwind       IN      "wind pressure"
HeatFlux_M      Q           OUT     "heat moved by massflow"
Density         Rho         LOC     "density of tunnel air"
Temp            T1          IN      "Temperature of neighbor 1"
Temp            T2          IN      "Temperature of neighbor 2"
Velocity        Vair        OUT     "air speed [m/s]"
NumFlow_h       VehFA       IN      "vehicle flow small [1/h]"
NumFlow_h       VehFB       IN      "vehicle flow big [1/h]"
VolFlow         VFAir1      IN      "air volume flow 1 [m3/s]"
VolFlow         VFAir2      OUT     "air volume flow 2 [m3/s]"
VolFract_y      XCO1        IN      "fraction CO of neighbor 1"
VolFract_y      XCO2        IN      "fraction CO of neighbor 2"
FractFlow_y     XCOf        OUT     "fract CO moved by flow"
VolFract_n      XNO21       IN      "fraction NO2 of neighbor 1"
VolFract_n      XNO22       IN      "fraction of neighbor 2"
FractFlow_n     XNO2f       OUT     "fract NO2 moved by flow"
PARAMETERS

/* type       name    role   def min max   description */

/* easy access parameters */
area          aTun    S_P    50 SMALL BIG  "cross section area [m2]"
factor        ki      S_P     1 SMALL BIG  "Loss coeff for inlet"

END_MODEL
```

Figure 1. Sample NMF code.

3.2 Test Methodology

The tracer gas (SF$_6$) was injected into the tunnel air close to the opening and a distance of 940 m could be allowed for mixing of the gas and the air (see Fig. 7). All tests were made with traffic in the tunnel, which of course enhanced the mixing. When the momentum fans were running, they increased the mixing further. It is interesting to note, that, in spite of these mixing enhancing factors and a mixing length of about 100 tunnel tube diameters, the gas concentration in the plane of measurement was not completely homogeneous. This was shown by comparisons between measured values, taken in four different positions (see Fig. 8).

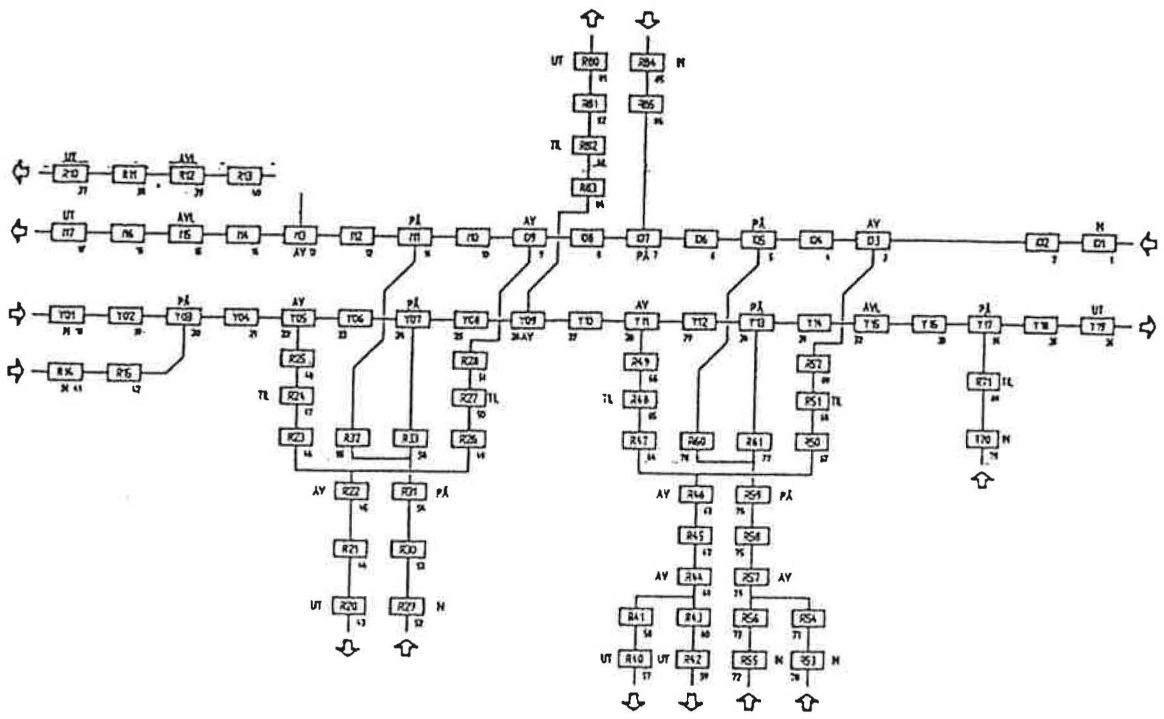

Figure 3. System schema showing module decomposition.

The tracer gas was supplied from a pressurized container by means of a valve and a flow measuring device, which latter mainly was used for keeping the supply rate constant. The supplied amount and rate was measured by weighing the container and measuring the corresponding time with a stop watch. The injection point was located at a side wall, a little more than 1 m above the tunnel floor.

In the plane of measurement air was taken out to the analyzing equipment, which was located in a room beside the tunnel, through soft plastic tubes. From the start of tracer gas supply, there was first a time delay of several minutes before the tunnel air with tracer gas reached the test section, then a delay due to transport through the plastic tubes, and finally, a delay due to the time constant of the analyzing equipment. "Steady state" conditions, with a constant tracer gas concentration, was never reached. The recorded signal always fluctuated, and the concentration on which evaluation of air flow rate was based had to be estimated as a mean, when a "quasi-steady" state had been established.

Tests were also made with fans running. There were then some unexpected problems. The first test day the exhaust fans didn't work. All fans were normally controlled from an office several kilometers from the tunnel and communication with the operator was via telephone. This caused some misunderstandings and delays. Uncertainty regarding which fans that actually were running meant that some tests could not be used.

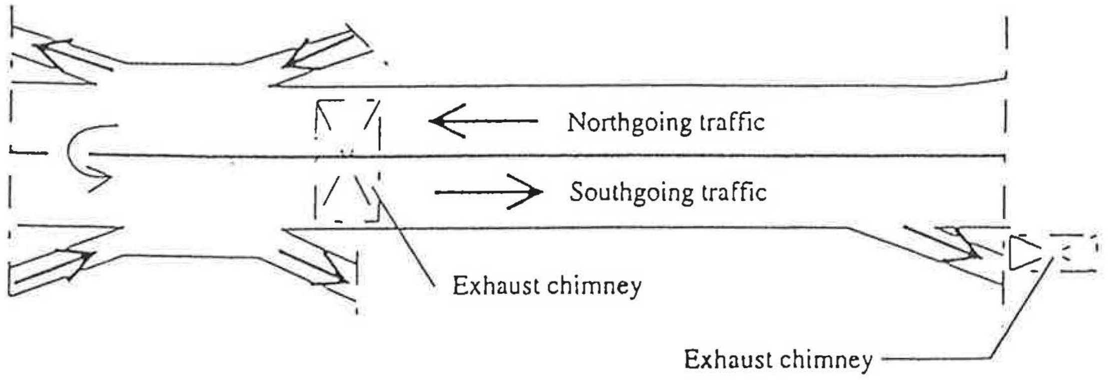

Figure 4. Layout of studied section of "Söderledstunneln."

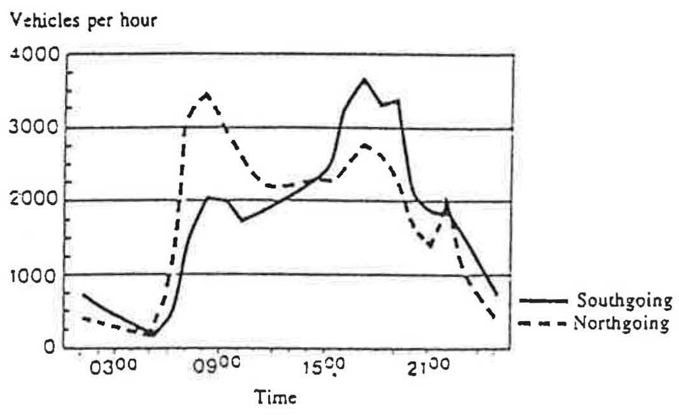

Figure 5. Normal traffic flow rates.

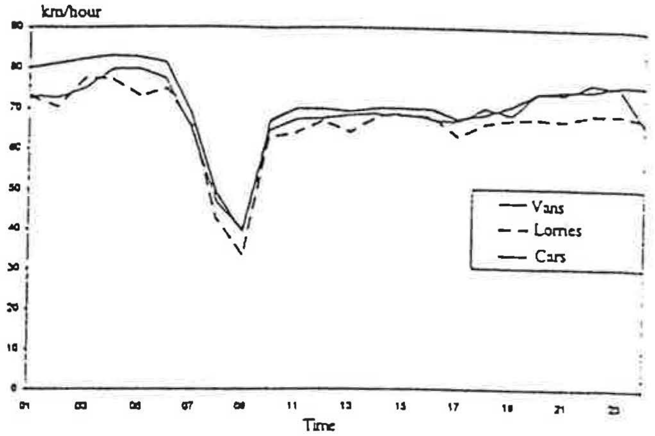

Figure 6. Mean velocities.

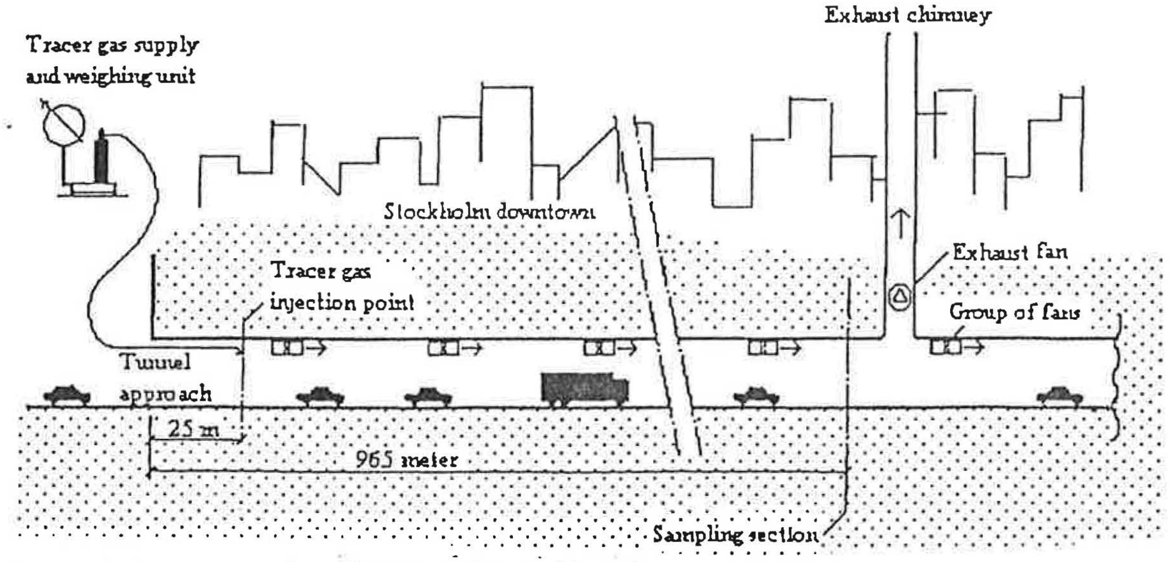

Figure 7. Longitudinal section through measured part of tunnel.

3.3. Test Results and Comparisons with Simulations

Test were made at three occasions: December 1993, September 1994, and October 1994.

Measured air flow rates were, with no momentum fans running, in the range 270–330 m³/s (depending mainly on traffic conditions); with every second row of momentum fans running, 390–430 m³/s; and with all momentum fans running, in the range 430–480 m³/s. The measurements made in the afternoon of December 20, 1993, have been chosen for the comparisons with simulations. The reasons for this choice are: the measurements were made during a time of day when traffic flow rate and speed are rather constant (compare Figures 5 and 6, and Table 4); the traffic was counted during this period. (Traffic counting was not available at the other occasions). The documentation of which fans that were running was also reliable for this period.

The results are shown in Table 4 together with results of simulations. Input values (normal) for some central parameters to the simulations are given in Table 3. These values have been selected, based on previous experiences, and have not been fitted to the measured values.

Table 4 gives simulation results calculated with normal parameter values; some results, where parameters have been varied to illustrate sensitivity to parameter choices, are shown in Table 5.

As can be seen from Table 4, the differences between measured and calculated values are acceptable.

In this tunnel, the momentum fans are located in compact rows, of six fans each, in the tunnel ceiling. The distance between rows is rather short. These factors are the cause for the low efficiency assumed for the momentum fans, and also the cause for the higher value assumed, when only every second row is running.

3.4 Simulation of the Total Tunnel Air Flow

The first case in Table 4 (no fans) is the normal case. Results of the simulation for this case are given in Figure 9. The simulations have been made assuming the same traffic flow rate in the southgoing tunnel as in the north-going.

4. Discussion

New simulation environments allow rapid generation of efficient application tools. The modular structure of these environments facilitates fast development and maintenance of programs based on equation based models. Component models formulated in the Neutral Model Format make the

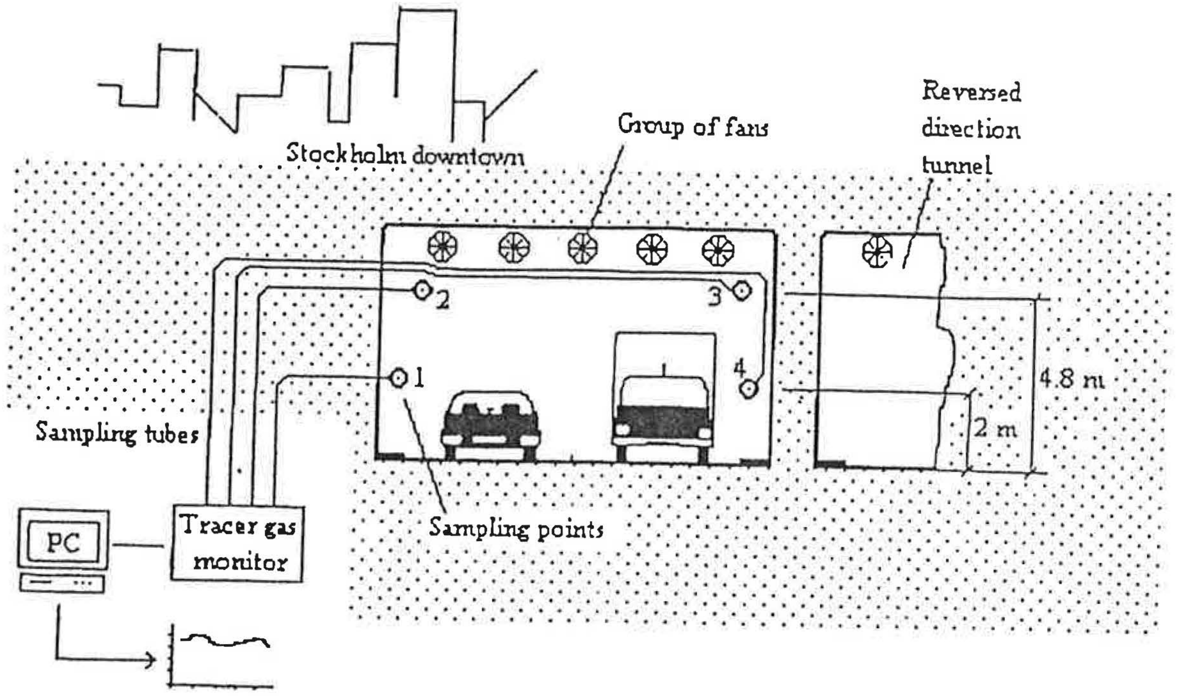

Figure 8. Location of measuring points in cross-section.

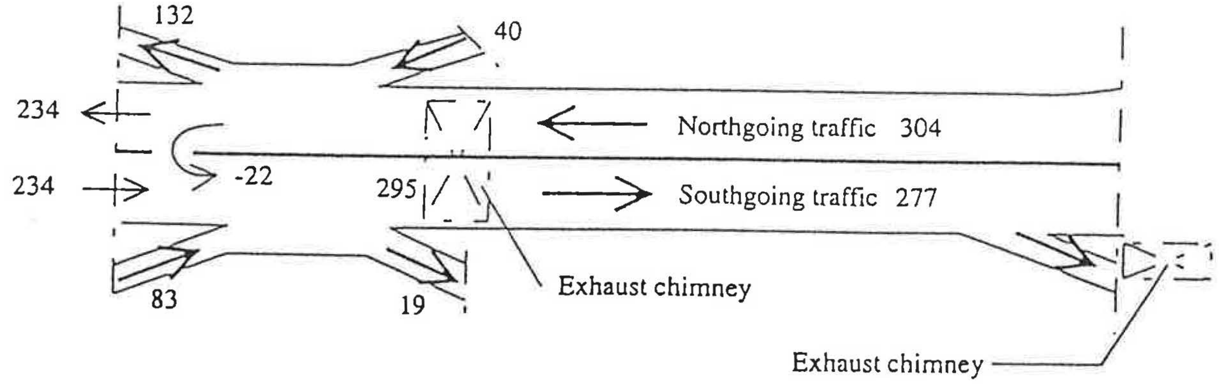

Figure 9. Calculated air flows [m³/s] for normal case (no fans running).

Table 2. Key data for sample system.

Number of components:	71
Number of equations in system matrix:	631
Total number of variables in components:	2705
Calculation time on a 90 Mhz Pentium:	66 s

Table 3. Normal parameter values for air flow simulations.

Parameter description	Normal value
Wall friction coefficient	0.020
Cross section area [m²], cars	2.0
Ditto, lorries and buses	7.0
Vehicle drag coefficient, cars	0.30
Ditto, lorries and buses	0.60
Fan efficiency [%], all fans running	50
Ditto, every second row running	60

Table 4: Comparison between measured and calculated air flows.

Measurement No.	Time of Measurement [veh/h]	Total traffic flow [m³/s]	Exhaust air flow [m³/s]	Momentum fans running	Calculated air flow [m³/s]	Measured air flow [m³/s]
2	13:15-13:30	2516	0	none	304	324
6	15:05-15:25	2576	0	every 2ⁿᵈ row	424	426
14	15:35-15:55	2572	0	every row	469	473

Table 5. Influence of parameter changes on calculated air flows.

Measurement number	2			6		14	
Time of measurement	13:15–13:30			15:05–15:25		15:35–15:55	
Total traffic flow [veh/h]	2516			2576		2572	
Exhaust air flow [m /s]	0			0		0	
Momentum fans running	none			every 2nd row		every row	
Parameter changes	normal	changed	changed	normal	changed	normal	changed
Fan efficiency				60	80	50	60
Wall friction	0.020	0.025					
Vehicle draf coeff.							
- cars	0.30		0.40				
- large vehicles	0.60		0.75				
Calculated air flow [m /s]	304	283	333	424	451	469	494
Measured air flow [m /s]	324			426		473	

assumptions behind an application program easily accessible and understandable for the intended user group of consultant engineers. A general solver for differential-algebraic systems with algebraic loops allows handling of arbitrary tunnel networks. A program based on these principles has been developed. Additionally , a version to handle fires in road tunnels has been prepared. Work on a graphical user interface is underway, also based on the general purpose IDA environment.

Measurement of air flow rates have been made in a tunnel in central Stockholm. Measured and simulated values show good agreement.

Acknowledgment

The program has been prepared for the company: VBB Theorells AB, Box 1261, 171 24 Solna, Sweden. They have contributed to the specification and testing of the program.

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Modelling Progressive Hardening of Shotcrete in Convergence-Confinement Approach to Tunnel Design

P. P. Oreste and D. Peila

Abstract—*The progressive hardening of shotcrete used for tunnel supports is of great importance because it influences the support response to ground movements and therefore the stresses induced in the shotcrete lining. This paper presents a new model, which can take into consideration the hardening of concrete and provides the convergence-confinement curve of the supported tunnel. The model is used to back-analyse the measurements taken in the Kielder Experimental tunnel and presented in technical literature. An axisymmetrial numerical model (FLAC code) has been also set up for comparison with the proposed model results. Both the in-situ measurements and the numerical results using FLAC are in good agreement with those computed using the proposed convergence-confinement method.*

1. Introduction

The mechanical behaviour of a shotcrete layer, which is often used as a first support in tunnelling, varies over time as a result of concrete hardening. This phenomenon should be taken into account in tunnelling design because the stress release around the tunnel depends on the distance from tunnel face (Panet and Guenot 1982) and, thus, on excavation rate or time. For this reason, the global behaviour of a supported tunnel is influenced by both the increase in stresses related to the tunnel advancement and the increase in mechanical properties of the shotcrete as it hardens. Therefore, the most critical conditions may occur before the full strength of the shotcrete is reached.

This effect can be studied by using complex three-dimensional numerical analyses that are able to model the tunnel excavation advance and the progressive hardening of the concrete (Gartung et al. 1979; Gioda and Ghaboussi 1977), or by using two-dimensional numerical models that can evaluate the stress release caused by the distance between the tunnel face and the studied section, and consider the corresponding shotcrete properties by referring to its life time (Lembo Fazio and Ribacchi 1994).

Fujimori et al. (1985), Fujino and Suzuki (1988), and Pöttler (1990) have studied the hardening behaviour of shotcrete by assigning different hypothetical values of elasticity modulus (varying from 2000 MPa to 7000 MPa) in their analyses.

The convergence-confinement method, on the other hand, does not usually take the shotcrete-hardening phenomenon into account. Moreover, if the ground convergence-confinement has been calculated—for example, by taking into account complex mechanical behaviour (i.e., elasto-plastic with a peak and residual behaviour, with strain softening, etc.)— the support lining is often modelled as a strict lining defined by a single parameter, i.e., by a lining equivalent stiffness.

This paper describes a new approach for the convergence-confinement method—one that considers the progressive hardening of shotcrete, evaluates the stresses inside the shotcrete lining, and models the effect of a further support element such as steel arches, without making a composite material of different equivalent stiffness values. This approach is presented and discussed on the basis of some examples and a comparison of the results of a finite difference numerical model.

The model is based on the concept that the internal tunnel radial pressure, at each point of the convergence-confinement curve, is directly linked to the distance between the tunnel face and the studied section. Therefore by defining the excavation and support sequence adopted in the tunnel, it is possible to define the time from the concrete installation and its consequent mechanical properties. The computation of the convergence-confinement curve is carried out using a finite difference approach, and at each computational step the corresponding concrete mechanical properties are updated.

2. Proposed Model

The new proposed convergence-confinement method computes stresses and displacements in a tunnel concrete lining by taking the progressive hardening of concrete into account. The rock mass mechanical behaviour is assumed to be elasto-plastic with strain softening Hoek and Brown yield (peak and residual) criteria (Hoek and Brown 1980; Brown et al. 1993).

The main steps of the proposed method are:

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