ON LONGITUDINAL VENTILATION AND CONGESTED TRAFFIC

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ABSTRACT

During the past few years, emission regulations have resulted in a shift of the emphasis of ventilation design. While the main goal of the ventilation system was to provide fresh air for the dilution of pollutants, it is now smoke control during a tunnel fire. However, the reduction of vehicle emissions has also led to new and more stringent air-quality limits, e.g. the 50 ppm 30 min exposure limit for carbon monoxide CO, which is applied in new Australian tunnel projects. The exposure of drivers on their way through the tunnel has to be assessed in ventilation design and during operation. This is being done by examining the pollution concentration over the length of the tunnel.

Ventilation design is usually based on hourly average traffic and average emissions. For a longitudinal ventilation system, this gives a linear concentration profile along the tunnel section. The introduction of emission regulations for new vehicles has lead to very different emissions of individual vehicles. This paper deals with the variation of emission coefficients and the influence on the pollution profile along the tunnel. The pollution profile is being calculated using the simulation software RoadTun that allows the definition of individual vehicles with different emissions and travel speeds. While the influence is small during fluid traffic, it becomes more pronounced during congested traffic. Concentration peaks may lead to an increased exposure of individual drivers, although the peaks may remain undetected by the ventilation control system.

Key words: tunnel, ventilation, numerical simulation, individual vehicles, exposure

1. BACKGROUND

The CO exposure limit is a constraint for the new Australian road-tunnel projects. However, for this study, the tunnel geometry as well as traffic mix and emission data are not directly extracted from those projects.

Traditionally, the required fresh air for a given traffic scenario in the tunnel depends on the number of cars in the tunnel, the average emission per car in this traffic and the admissible peak concentration for this particular emission. The calculation methodology is described e.g. in PIARC (1995).

1.1. CO Exposure Limit

The ventilation design methodology as described in the PIARC reports is given for peak levels of carbon monoxide CO and turbidity. Carbon monoxide is taken as the leading gas for assessing the toxicity of the exhaust gases.

A new regulation has been applied to tunnel-ventilation design and operation in Australian tunnel projects. It defines a 50 ppm CO exposure limit for any 30 min period. The air-quality limit has been adopted from WHO goals for working environment. It is assumed that the CO level inside the vehicle is the same as in the tunnel air.

If the exposure limit was adopted only for the average tunnel user, allowing a design based on average vehicles and hourly average traffic, it would not determine the ventilation design. The typical time spend in a road tunnel is in the range of a few minutes. Therefore, the exposure limit would not be critical to the average tunnel user. However, as the exposure limit is made applicable to any individual in the tunnel, the behaviour of tunnel users has to be taken into account. The exposure of people involved in a traffic incident, such as a broken-down vehicle, or in an accident has to be examined. And – applying the exposure limit to any traffic situation and any tunnel user – the time and local variation of CO levels in the tunnel has to be examined as well.

In order to measure the exposure of individuals in a road tunnel, every tunnel user would have to be equipped with a CO meter before entering the tunnel. A close approximation could be made by examining CO meters and traffic loops that are installed at very short intervals in the tunnel. Both methods do not appear practicable. Because of the measurement technique involving a running average of the signal, it appears feasible only to assess an approximate, time average CO profile from a few CO meters in the tunnel.

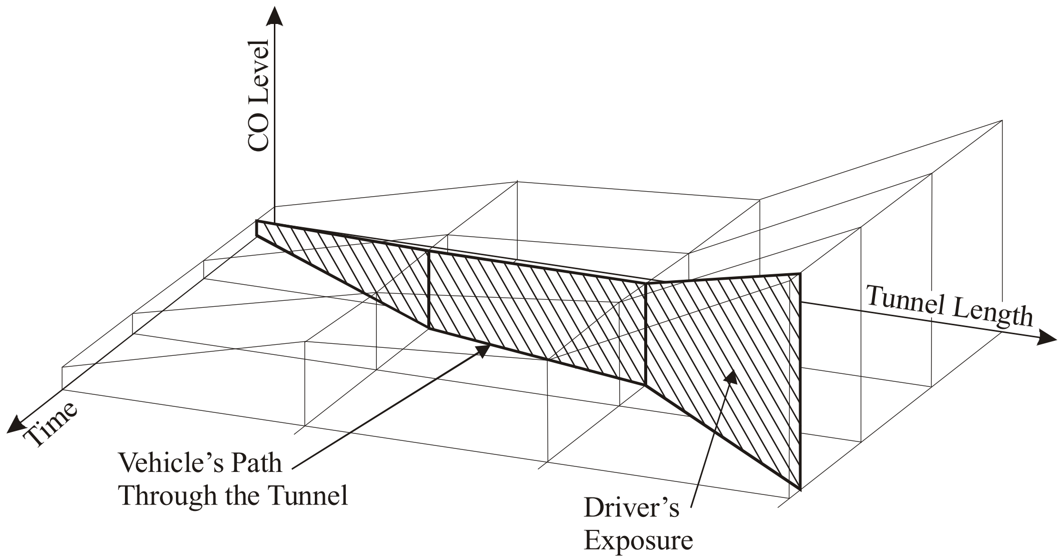

Figure 1: Assessment of a Driver's CO Exposure from Recorded Data of CO Profile and Travel Speed

Figure 1 indicates how the exposure of a driver can be assessed from recorded data of vehicle speed and CO concentration. The methodology may be used in order to estimate the remaining time until the exposure of a driver involved in an incident may exceed 50 ppm. The remaining time is equivalent to an acceptable response time for the tunnel operator to clear the incident or at least to evacuate the driver.

Although it is not feasible to measure the exposure of individual tunnel users, the local variation of CO levels in the tunnel can be examined by a numerical simulation.

1.2. Variation of Vehicle Emissions

The ventilation-design methodology as described in the PIARC reports is based on the emission of the average car in the traffic mix expected in a particular scenario.

However, looking at the introduction of new emission regulations in various countries, the question arises if the emissions of a series of average vehicles correctly represent the emission situation in a real tunnel. Assuming the introduction of new regulations within a couple of years may lead to the situation given in Table 1.

	Emission Regulation	Partition in the Traffic Mix	Relative CO Emission 2005
Cars (Petrol)	No Regulation	1 %	**8.3** *Average
	Reg. 1: 1982	2 %	2.5 *Average
	Reg. 2: 1985	33 %	1.9 *Average
	Reg. 3: 1997	64 %	0.4 *Average
HCV (Diesel)	No Regulation	20 %	**1.9** *Average
	Reg. 1: 1991	16 %	1.2 *Average
	Reg. 2: 1994	22 %	0.8 *Average
	Reg. 3: 1998	42 %	0.6 *Average

Table 1: Vehicle Classes, Partition and Relative Emission for Cars and Heavy Commercial Vehicles

As the CO emissions of the average heavy commercial vehicle HCV are only 2.3 times the emission of the average passenger car, the vehicles with the highest CO emission are the few very old passenger cars and not the HCV. Although these vehicles represent only 1% of the traffic mix, about 30 to 60 of these cars may be expected during a typical peak hour.

Furthermore, the relative emissions given in Table 1 still represent averages for a vehicle class. The emission variation within a vehicle class would be less than the variation in the total traffic mix. But still, an individual car could have several times the average emission of its class.

This paper concentrates on the variation of CO emissions for different vehicle classes. CO has been selected because of the application of the CO exposure criterion. It has to be noted, that for other pollutants, such as particles/turbidity or NO_X, the emission variation of different vehicle classes is much more pronounced.

2. ROADTUN

RoadTun (Vardy, 1976) is a computer program for the simulation of time-varying 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 pollution concentration in an entire tunnel system. RoadTun 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.

Thermal effects, such as the chimney effect due to hot smoke from a tunnel fire, can be modelled by prescribing an external pressure difference. In order to simulate the behaviour of various ventilation-control routines, measurement points are defined. The calculated values of concentration, velocity and pressure at the control points can be used as input data for the ventilation control.

RoadTun's most important feature for the subject of this paper is the traffic model. Vehicles classes and even individual vehicles can be defined applying different emission tables.

3. SIMULATION

3.1. Tunnel Geometry and Traffic

The simulations are done for a two-lane, unidirectional road tunnel of 3000 m length on level ground. The tunnel cross section is 50 m^2 and the air-flow rate is set to 250 $m^3 s^{-1}$. This gives a constant air-flow velocity of 5 $m s^{-1}$ or 18 $km h^{-1}$ in traffic direction. Piston effect of vehicles is counterbalanced by an external pressure difference. The subject of this article is not the simulation of tunnel aerodynamics. The boundary conditions have been set in order to demonstrate the specific effect.

Nonetheless, the boundary conditions are not entirely unrealistic, as in countries such as Australia, jet fans are used in order to both accelerate and limit the longitudinal air flow. The air-flow rate in the tunnel is controlled in order to optimise the air extraction for the avoidance of portal emissions.

In these examples, the traffic consists of 2000 petrol driven passenger cars and 100 diesel driven HCV per hour. All vehicles travel at the same constant speed. Vehicles of the same vehicle class enter the tunnel at constant intervals. So there appears to be some statistic variation in the traffic flow. However, clusters of high emission vehicles, such as a series of HCV travelling in short succession, have not been included in the simulation.

3.2. Fluid Traffic at 60 km h^{-1}

Figure 2 shows the CO profile along the tunnel for a vehicle speed of 60 km h^{-1}. The air intake at the left hand portal starts with a CO level of 0, assuming no background concentration. The dashed line shows the result of the calculation following the PIARC methodology. The CO concentration increases linearly from the air intake to the exit portal (on the right).

The solid line gives a typical CO profile according to the numerical calculation. Except for small deviations e.g. at x = 600 m and 2700 m, the two graphs are in very close agreement.

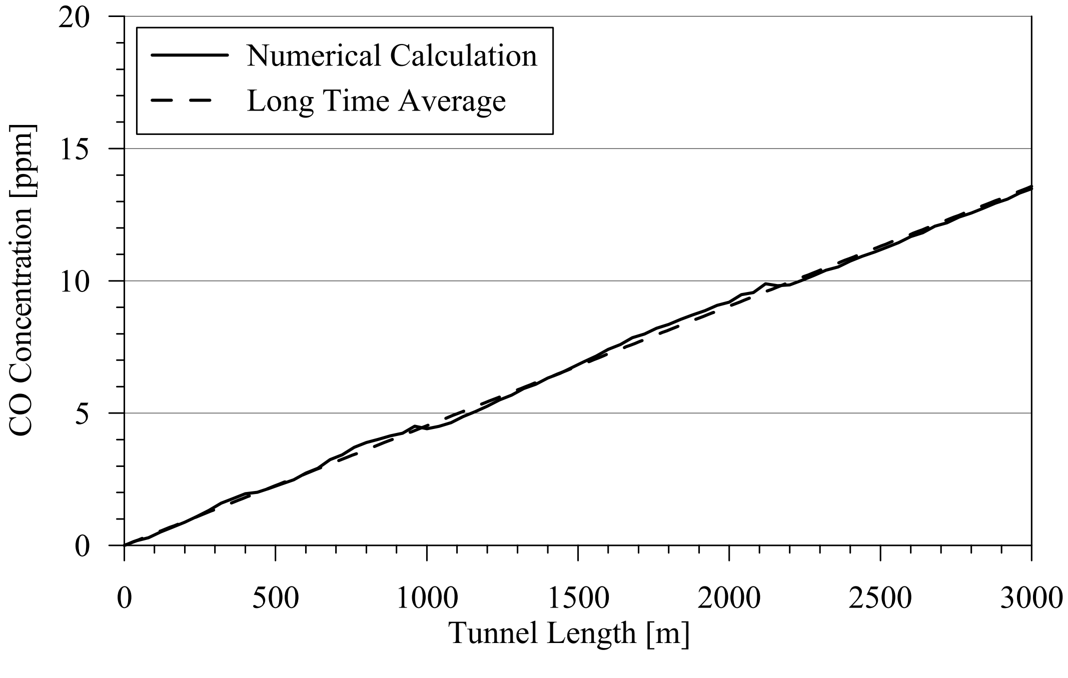

Figure 2: Calculated CO Level vs. Tunnel Length for Fluid Traffic

Of course, the peak CO level is by no means critical in terms of in-tunnel air quality limits. The CO exposure of any driver would not be critical either.

3.3. Congested Traffic at 18 km h^{-1}

Figure 3 shows the equivalent CO profile for a vehicle speed of 18 km h^{-1}, just matching the air-flow speed. As in Figure 2, the dashed line shows the result of the calculation following the PIARC methodology. The CO concentration increases linearly from the air intake (assuming no background concentration) on the left to the exit portal on the right.

The solid line gives a typical CO profile from the numerical simulation. For most part of the tunnel, the CO level is less than the linear profile. This is counterbalanced by a few distinct peaks distributed along the tunnel. Three peaks, at 700 m, 1600 m and 2500m, can be linked to passenger cars without emission regulation; the other peaks can be linked to HCVs without emission regulation.

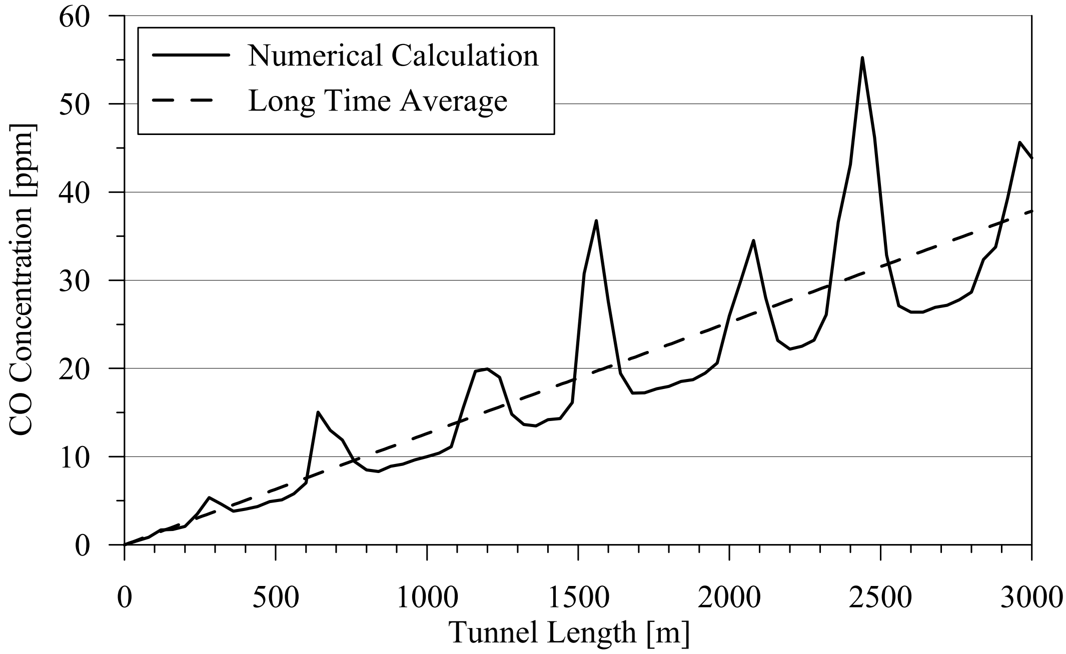

Figure 3: Calculated CO Level vs. Tunnel Length for Congested Traffic

As these peaks travel along the tunnel at the same speed as the traffic, the exposure of drivers travelling in such a peak is poorly approximated if calculated from the assumed linear CO profile.

3.4. Other Traffic Speeds

The height of the peaks can be measured by the ratio of peak concentration to average concentration. Peak heights for traffic speeds between 16 and 22 km h^{-1} are given in Figure 4. Peaks due to the variation of CO emissions of individual vehicles are only visible for a small range of traffic speeds. Once the difference of air flow and traffic speed is about 20%, the effect of individual vehicles on the pollution profile becomes negligible.

Figure 4 is not applicable as a general result. The travel-speed range and the peak height depend on a number of factors, such as emission variation and tunnel length.

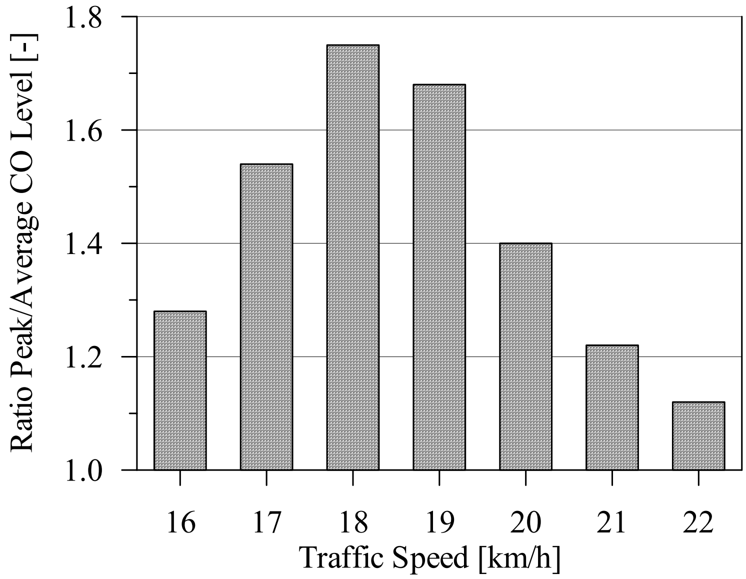

Figure 4: Relevance of Local Peak CO Levels vs. Traffic Speed (Simulation)

4. INTERPRETATION

4.1. What Happens?

Two schematic pictures demonstrate the effect of the relative speed of vehicles and tunnel air, see Figure 5.

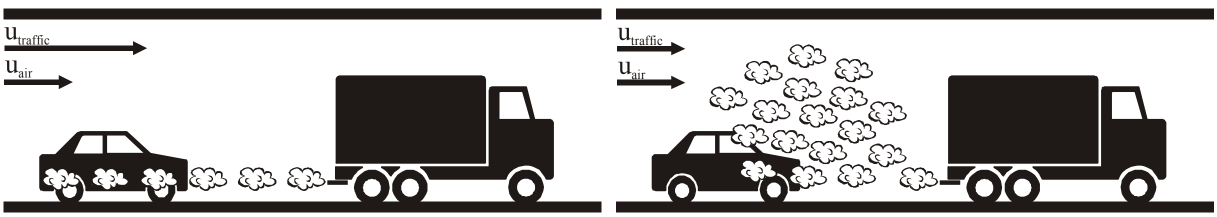

Figure 5: CO Dispersion Schematic for Fluid (Left) and Congested (Right) Traffic

During fluid traffic, the HCV's emission is trailing behind and mixing with the emission of the succeeding vehicles. This leads to a smooth CO profile along the tunnel, quite close to the CO profile that has been calculated from average emissions. The situation would be similar if the air-flow speed exceeds the vehicle speed, e.g. in standing traffic.

During congested traffic, when the air-flow speed is in the range of the vehicle speed, the HCV's emission remains close to the source, allowing the pollutant to accumulate with only minor dilution due to local turbulence or due to some relative movement between air and vehicle.

4.2. Is It a Real Phenomenon?

The peaks may be somewhat more pronounced in a numerical simulation. In real congested traffic, the vehicles do not move at exactly the same constant speed. Any variation of piston effect and ventilation adds to some relative movement between vehicles and tunnel air resulting in additional dilution. The numerical simulation, on the other hand, still applies only four emission classes for each vehicle type (cars and HCV). Real emissions of individual vehicles could be much higher than the emissions given for any vehicle class.

For this study, the variation of individual vehicle's emissions in real traffic has not been assessed. Therefore, no further quantification of the effect can be given. The CO peaks shown in Figure 3 may vary according to a series of parameters.

4.3. Are Short Term Peaks Detected by the Ventilation Control System?

As the readings of CO meters are usually processed as a running average for a time of 1 to 5 min, local peaks may not be visible during tunnel operation. Figure 6 shows a graph of the calculated CO concentration at the exit portal for the congested traffic scenario in Figure 3. Once the CO data are processed by a 1 min running average, the short term peaks are shifted and reduced. Applying a 3 min running average almost renders the variation of the CO concentration invisible.

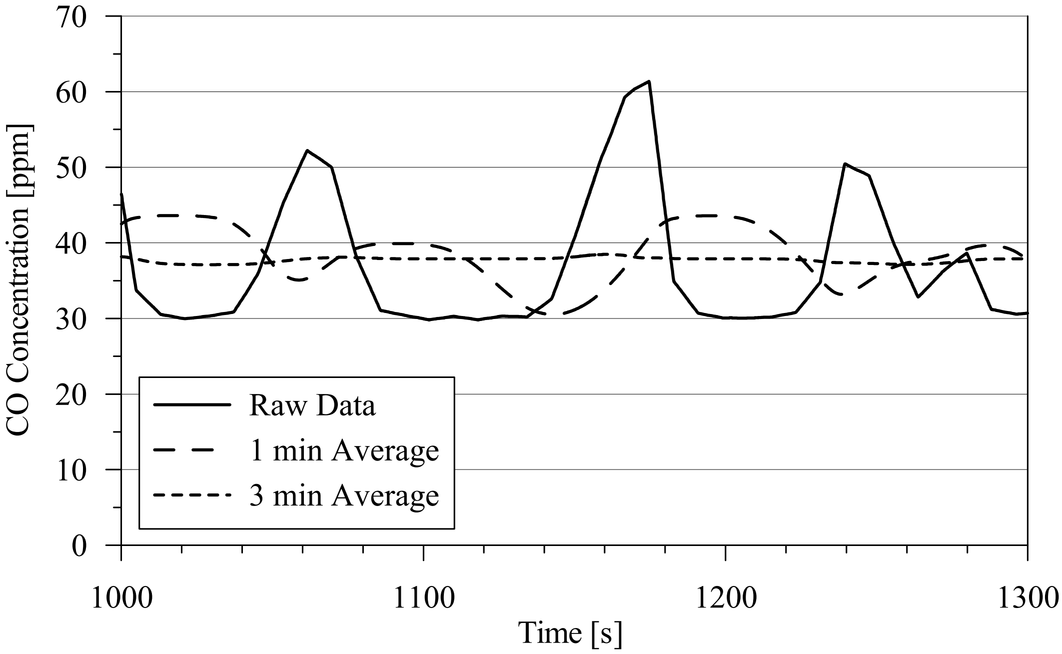

Figure 6: Calculated CO Level at the Exit Portal, Raw Data at 18 km h^{-1} and Running Average

5. CONCLUSIONS

The following conclusions can be drawn:

i. The PIARC methodology applying average vehicle emissions and assuming a linear CO profile per tunnel section appears entirely sufficient for all practical ventilation designs.

ii. For any tunnel equipped with longitudinal ventilation system, congested traffic moving at the same speed as the tunnel air should be avoided in order to avoid local peaks of pollution.

iii. As the CO exposure of individuals is impossible to examine in daily operation, it does not appear to be useful to apply such an air-quality limit to every individual. It appears beneficial for ventilation design and operation to introduce a more stringent air-quality limit that

a) is applicable to the PIARC design methodology and

b) can be tested.

This air-quality limit could be a 50 ppm local peak CO level allowing for a time average of 5 min.

6. REFERENCE

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