# 4. DESIGN AND OPERATIONAL POLLUTANT VALUES

## 4.1. INTRODUCTION

In the absence of national regulation, the admissible concentration and operation limits provided in the following sections are recommended.

Design values provide a basis for the determination of the required capacity of the tunnel ventilation system.

Operational values provide the limit levels for the different operating states, these comprise the following:

- Normal operations: where set points and threshold values defined in the design are used for the operation of the tunnel ventilation system in order to manage the pollution levels in the tunnel. These are different from design values and normally do not change with variations to traffic conditions. Set points are generally lower than the design values and are selected so that design conditions are not exceeded even considering the time-lag effects of the traffic conditions and flow inertia on the ventilation system.
- Maintenance operations: where specific limit levels are set for the protection of the health and safety of the maintenance workforce.

Closure conditions: threshold values that may not be exceeded i.e. if reached then an immediate tunnel closure is required to provide for the safety of tunnel users.

Operational values are based on measurements that are typically recorded as time averages over several minutes in order to avoid unnecessary actions as a result of short-term fluctuations. The specific action taken on reaching or approaching an operational limit is pre-determined and recorded in the operating procedures. These actions may depend on the duration as well as the magnitude of the level of pollution.

## 4.2. CARBON MONOXIDE (CO)

Table 3 gives design values for various traffic situations and the limits for tunnel operation states.

*Table 3: Design and Operation values for CO*

| Traffic situation | Design value | | Operation condition | Operation limits |
|---|---|---|---|---|
| Free flowing peak traffic 50 – 100 km/h | 70 ppm | | Normal operation* | < 100 ppm |
| Daily congested traffic, stopped on all lanes | 70 ppm | | Planned maintenance work in a tunnel under traffic** | 20 ppm |
| Exceptional congested traffic, stopped on all lanes | 90 ppm | | Threshold value for tunnel closure | 200 ppm |

* Intermediate set points and thresholds may be set at levels below the design values

** National workplace levels to be considered

To avoid excessive fresh-air demands for rarely occurring congestion conditions, a higher CO-concentration can be allowed. The 90 ppm value corresponds to the World Health Organisation (WHO) recommendation for short term-exposure (15 minutes) [4].

## 4.3. NITROGEN DIOXIDE ($NO_2$)

Nitrogen oxide (NO) and nitrogen dioxide ($NO_2$) are pollutants resulting from the combustion process. Most of the emitted nitrogen oxides ($NO_x$) consist of NO, which is oxidised into $NO_2$ in the presence of oxygen.

While in previous years $NO_x$ from combustion processes contained mostly NO (90 to 95% of the $NO_X$), the implementation of diesel vehicle exhaust gas after-treatment systems (oxygenation catalyst, DPF, SCR systems) tend to significantly increase the primary emitted $NO_2$ percentages [12]. In many European road tunnels, $NO_2$ can be up to 20 to 30% of $NO_x$ concentrations, which strongly depends on the share of diesel vehicles with exhaust gas after-treatment systems in the vehicle fleet and on the residence time of the $NO_x$ in the tunnel air. Only in tunnels with few passenger cars using diesel engines will the $NO_2$ contribution remain below 10%. Figure 1 shows, as an example, the $NO_2/NO_X$ relation as a function of total $NO_x$ concentrations for tunnels with a different share of diesel PC/LCV (red line 11%, green line 32% and blue line 57%). Note that the lines given in Figure 1 represent the best fit from data sets with significant scatter.

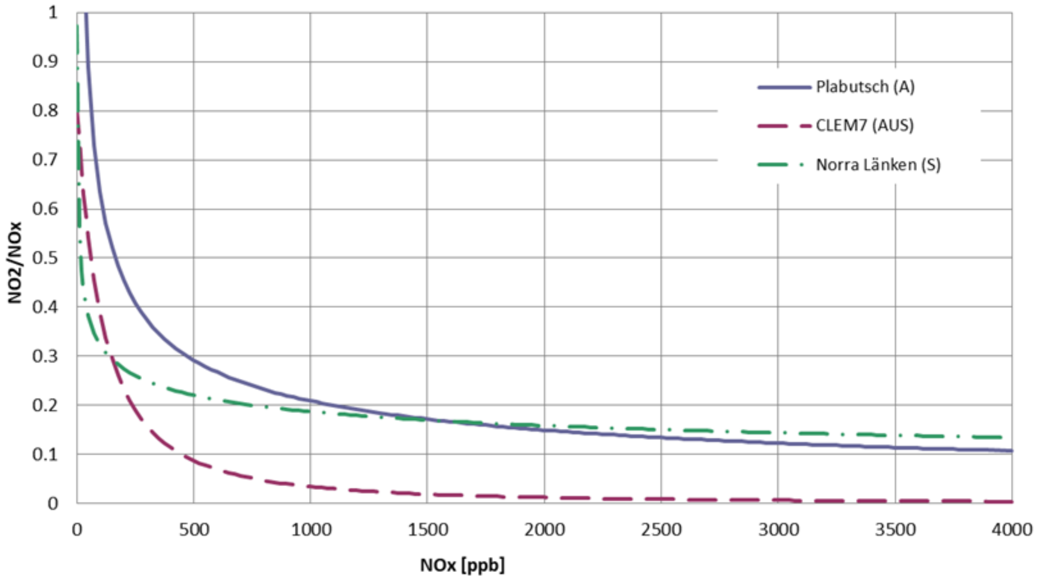


*Figure 1: $NO_2/NO_x$ ratio as a function of the $NO_x$ concentration for various tunnels [11]*

When calculating the $NO_2$ share it is recommended to apply individual values for the different vehicle types (PC gasoline, PC diesel, etc.). Values for base year 2018 emission standard A are given as an example in Table 4.

*Table 4 $NO_2/NOx$ ratio for vehicle types*

| $NO_2/NO_X$ ratio | PC gasoline | PC diesel | LCV gasoline | LCV diesel | HGV |
|---|---|---|---|---|---|
| 2018 (base year) | 0.05 | 0.33 | 0.05 | 0.32 | 0.11 |
| 2030 | 0.05 | 0.31 | 0.05 | 0.31 | 0.21 |

NO by itself is not considered a harmful pollutant at commonly encountered levels. On the other hand, $NO_2$ is noxious and can irritate the lungs and lower the resistance to respiratory infections such as influenza. For short term exposure, the 2015 WHO Expert Consultation [6] reported evidence of a causal relationship between short term $NO_2$ exposure and respiratory health impact. The US National Institute for Occupational Safety and Health (NIOSH) proposes a value of 1 ppm as a 15-minute short-term limit [14]. Whilst it is acknowledged internationally that there are potential health effects from exposure to $NO_2$, there is no clear consensus on the extent of these health effects for the general population, and no definitive guidance on generally applicable exposure limit levels. As a consequence, many countries have not set a $NO_2$ standard in road tunnels.

Where the tunnel ventilation system is also dimensioned for $NO_2$, PIARC proposed in 2000 [7] to permit an average in-tunnel concentration of 1.0 ppm $NO_2$ along the length of the tunnel at any one time as the design value.

Some countries have adopted values for different time frames. For many projects in North America the NIOSH and PIARC value of 1.0 ppm is used. France introduced a value of 0.4 ppm as an average over the tunnel length [15]. NSW (AUS) proposed a value of 0.5 ppm as a tunnel route average [13].

When defining a design value for $NO_2$, the following issues should be considered:

- there are limited options for reliable sensors to measure $NO_2$ levels in road tunnels in the lower ppm ranges (<0.5 ppm);
- there may be significant difficulties in complying with standards if design values are too demanding, with consequences for design costs and subsequent energy consumption;
- the choice of a design value in tunnels has to be made with consideration of the actual ambient pollutant levels outside the tunnels and the characteristics of the vehicle fleet (engine emission treatment technologies).

The control of the environment in tunnels regarding the levels of $NO_2$ is a challenge due to measurement accuracy (see section 11.4).

The $NO_2$ levels in urban areas vary according to the season, temperature and time of day. In areas with heavy traffic, one-hour peak levels can exceed short-term air-quality standards. Background levels of $NO_X$ have to be determined carefully if this pollutant is considered in the ventilation design.

## 4.4. Particulate Matter (PM) Emissions and Visibility

The presence of particulates leads to reduced visibility inside the tunnel. Therefore, visibility criteria are intended to support the ability of a driver to stop safely. The tunnel ventilation system must provide visibility levels that exceed the minimum vehicle stopping distance at the design speed.

There are two primary sources of PM in a tunnel, exhaust emissions and non-exhaust emissions. Exhaust emissions consist of PM emanating from the tailpipe as a result of fuel combustion. Non-exhaust PM consists of tyre and brake wear, road surface abrasion and re-suspended dust.

Visibility is reduced by the scattering and absorption of light by PM suspended in the air. The reason for reduced visibility is the occurrence of light extinction by the scattering and absorption of radiation in the visible wave-length range. The amount of light scattering and/or absorption is highly dependent upon the material, diameter and the density of the particles. In general, sulphates, nitrates, organic compounds, soot and soil are the major components that scatter and absorb light in the atmosphere. Except for mineral based re-suspended and abrasion particles, most of these components are abundant in the size range up to 0.7 µm. This is approximately the wavelength of visible light. Due to the similarity between wave length and particle diameter, there is a significant effect on visibility impairment [5].

The principle for measuring visibility in a tunnel is based on the fact that a light beam decays in intensity as it passes through air. The level of decay can be used to determine the opacity of air and is expressed as an extinction coefficient K in $m^{-1}$. Opacity meters for tunnels typically use these effects to measure visibility within the tunnel.

The extinction coefficient is expressed as:

*Equation 4*

$$K = -\frac{1}{L}.\ln\left(\frac{I}{I_0}\right)$$

Where:

$I_0$ Intensity of the light source

$I$ Intensity of the light at the receiver

$L$ Beam length between source and receiver [m]

Table 5 gives a correlation between visibility conditions, extinction coefficient and light beam length for an acceptable light level of 20% of the light source intensity.

*Table 5: Visibility condition and extinction coefficient*

| Visibility condition | Extinction coefficient K | Length of light beam L with I/Io=exp(-K L) =20% |
|---|---|---|
| Slightly hazy | 0.003 $m^{-1}$ | 536 m |
| Hazy | 0.007 $m^{-1}$ | 230 m |
| Foggy | 0.009 $m^{-1}$ | 179 m |
| Uncomfortable | 0.012 $m^{-1}$ | 134 m |

At a driving speed of 80 km/h the stopping distance with normal braking is about 85 m. Hence, even a visibility of a K-value for tunnel closing (Table 6) is sufficient to stop safely at an obstacle.

Strong fluctuations in visibility can occur. For example, visibility can be degraded as diesel-trucks move as a group, high emitting (smoky) vehicles are in the tunnel, or when the ventilation control reacts too slowly to emission peaks.

The consideration of extinction levels for ambient air (background pollution) is in most cases not needed, as even peak concentration levels in ambient air normally have no impact on short range visibility which is relevant for in-tunnel conditions. Only rare events with high PM levels in the air (e.g. bush fires, sand storms, high pollution episodes) might have an impact on short range visibility.

Vehicle exhaust consists of very small particles mainly in the range of 0.01 to 0.20 µm ([3]). Particles in this range are very effective in light extinction. Diesel combustion is the main source of combustion-related particle emissions [3]. Therefore, HGV, LCV and PC with diesel engines are the primary contributors to PM in exhaust emissions. Diesel particle filters (DPF) significantly reduce these emissions in terms of mass as well as the number of particles. Recent studies indicate that gasoline-powered vehicles with direct fuel injection also contribute to particulate-matter (PM) emissions. In addition to tailpipe emissions, vehicles also emit particulate matter due to abrasion processes (road, tires, brake wear, etc.) and re-suspension of road dust. These types of emissions occur for all vehicles and are not restricted to the use of internal combustion engines as the propulsion system. Non-exhaust particulate emissions are mainly in the size from 1 µm and upwards. Hence, they contribute strongly to $PM_{2.5}$ and even more to $PM_{10}$ concentrations, but less to light extinction [3]. While the abrasion processes correlate with driving behaviour and vehicle speed, the quantity of suspended particles is also strongly related to the cleanliness of the tunnel and the traffic mode (uni- or bi-directional traffic).

In road tunnels, the two source types of emission, ‘exhaust’ and ‘non-exhaust’, are relevant. Although both fractions have different light extinction behaviour and therefore should be treated differently, the following correlation between $PM_{2.5}$ mass concentration ($\mu$ in mg/m³) and light extinction coefficient ($K$ in $m^{-1}$) can be applied for diluted exhaust gases [2]:

Diluted exhaust gas (tunnel):

*Equation 5*

$$K = f_{vis}\,\mu$$

where the conversion factor $f_{\mathrm{vis}}$ has units $m^2$/mg.

A value of 0.0047 m²/mg is proposed for $f_{\mathrm{vis}}$ [1]. Recent measurements performed in the Landy tunnel (France) as well as in the Mt. Blanc tunnel (France/Italy) showed a correlation between opacity and mass ($PM_{10}$) in the range between 0.0033 m²/mg and 0.0067 m²/mg and confirm the range of mass and extinction correlations found in the various tunnel measurements reported in [3].

Table 6 gives design values for various traffic situations and the limits for tunnel operation states.

*Table 6: Design and Operation values for Visibility*

| Traffic situation | Design value | | Operation condition | Operation limits |
|---|---|---|---|---|
| Free flowing peak traffic 50 – 100 km/h | 0.005 $m^{-1}$ | | Normal operation* | 0.003 – 0.007 $m^{-1}$ |
| Daily congested traffic, stopped on all lanes | 0.007 $m^{-1}$ | | Planned maintenance work in a tunnel under traffic** | 0.003 $m^{-1}$ |
| Exceptional congested traffic, stopped on all lanes | 0.009 $m^{-1}$ | | Threshold value for tunnel closure | 0.012 $m^{-1}$ |

* Intermediate set points and thresholds may be set at levels below the design values

** National workplace levels to be considered