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AIR POLLUTION SHORT CIRCUIT EFFECTS OF ROAD TRAFFIC TUNNEL PORTALS

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ABSTRACT

In the design of road traffic tunnels, the air quality inside of traffic tunnels is an important factor, especially for long road traffic tunnels. The air quality inside the traffic tunnels usually depends on the emission of the cars passing through the traffic tunnel and the rate of tunnel ventilation. In specific situations the concentration of air pollution in traffic tunnels depends also strongly on aerodynamic short circuit (unwanted recirculation) effects that occur around the tunnel portals. At certain meteorological conditions (wind speeds and wind directions), due to the influence of wind vortexes, induced by the tunnel portal geometry, a significant part of the exhaust gasses, blown out of the tunnel portal of the outgoing traffic, is transported to the tunnel portal used by ingoing traffic. Even upstream effects, i.c. air pollution effects upwind, can be seen. Without measures the concentrations of air pollution in the traffic tunnel can reach very high levels.

In this study these effects are investigated for a new to be built road traffic tunnel. This tunnel with a total length of approximately 800 m, consists of 2 major tunnel ducts, a four-lane duct and a two-lane duct, separated from each other by a closed wall. The four-lane duct is for one-way traffic in northern direction. The two-lane duct will be used during the morning rush hour for traffic in southern direction and in the evening rush for traffic in northern direction. Therefore, during the morning rush there will be traffic in opposite directions in the two ducts of the new tunnel. In these situations short circuit effects of air pollution coming from one tunnel duct to the other are known to take place, depending on the meteorological conditions and the design of the tunnel portal. The amount of short cut defines the amount of ventilation needed to control air quality inside the tunnel and should therefore be reduced as far as possible.

In order to determine the amount of air pollution short circuit, a scale-model (1:150) of the tunnel was built. The short circuit effects near the tunnel portals were thoroughly researched, using tracer gas measurements executed in the Peutz atmospheric boundary layer windtunnel in Mook in the Netherlands. For different meteorological conditions, the influence of different tunnel portal designs on the rate of short circuit was determined. Investigated were the influences of tunnel portal canopy, smoke fences and extended (individual) tunnel portals. In worst case situations the rate of air pollution short circuit can be over 50%, which means that the concentration of the air pollution transported to the ingoing tunnel portal, can be higher than 50% of the concentrations of the emitted air pollution of the outgoing tunnel portal. Based on the windtunnelstudy, a specific tunnel design can be made in

order to minimise the short circuit effects. With a good tunnel portal design the rate of air pollution short circuit effects can be limited to 10%. The results of the concentration measurements performed in the windtunnel were illustrated using smoke dispersion tests in the windtunnel, which helps to understand the measured phenomena.

Key Words: Air Pollution, Road Traffic Tunnel

1. INTRODUCTION

Peutz bv performed wind tunnel research into the air pollution (aerodynamic) short circuit occurring at the tunnel portals of a planned road traffic tunnel under a sea canal. The existing road traffic tunnel is the tunnel through which the motorway passes under the sea canal. The existing 2 x 2-lane tunnel is being stretched to the limit by the volume of traffic during the (morning and evening) rush hours. Therefore a new road traffic tunnel is planned to the east of the present road traffic tunnel.

The planned road traffic tunnel has a total length of approximately 800 m and will consist of a tunnel with a total of 6 traffic lanes, i.e. a western tube with 2 lanes and an eastern tube with 4 lanes. The new 2-lane road traffic tunnel will be used during the morning rush hour for traffic travelling south. In this situation it is possible, owing to traffic moving in opposite directions in tubes located alongside one another, that aerodynamic short circuit may occur. Figure 1 (mouth of the tunnel south) and figure 2 (mouth of the tunnel north) show the situation of both tunnel portals of the new road traffic tunnel.

This research concentrates on the air pollution short circuit occurring with the new road traffic tunnel. The research provides insight into the effects of a range of structural variants for the tunnel portals on the air pollution short circuit at the tunnel portals. As an indicator for the aerodynamic short circuit occurring, use was made of the short circuit percentages determined by means of wind-tunnel research.

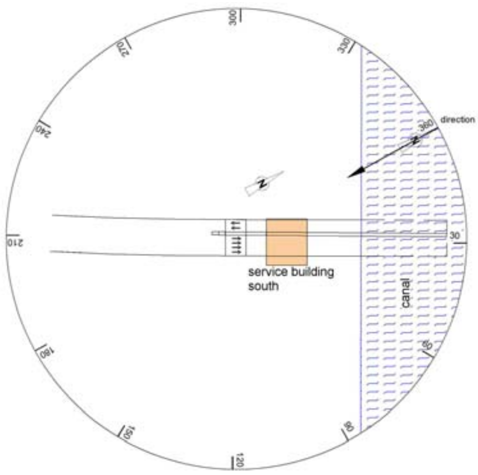


Figure 1: Road Traffic Tunnel.
Situation South, 2 lanes out, 4 lanes in.

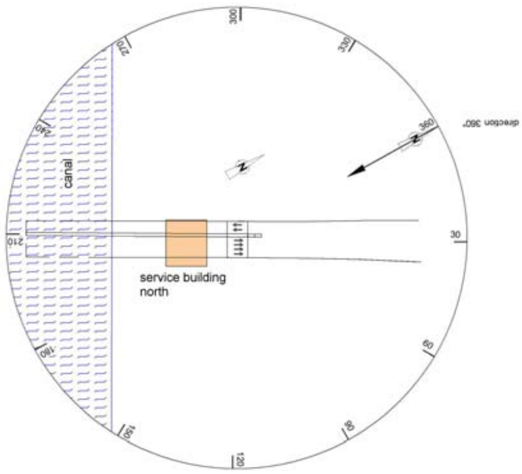


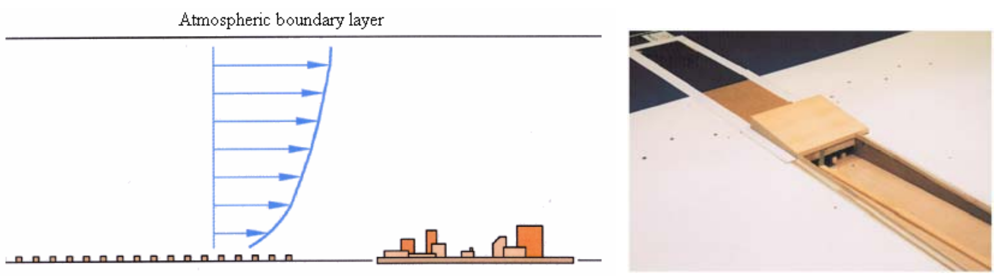
Figure 2: Road Traffic Tunnel.
Situation North, 2 lanes in, 4 lanes out.

2. STARTING POINTS

The planned road traffic tunnel will consist of a tunnel with a total of 6 traffic lanes, i.e. a western tube with 2 lanes and an eastern tube with 4 lanes, see figure 1 and 2. Following realisation of the road traffic tunnel, the traffic travelling south will pass through the present road traffic tunnel (2 x 2-lane) and traffic travelling north through the 4-lane tube of the new road traffic tunnel. The 2-lane tube of the new road traffic tunnel will be used during the morning rush hour for traffic travelling south and during the evening rush hour for traffic travelling north. This "variable direction of travel" means that a total of (existing tunnel and the additional new road traffic tunnel) a minimum 4 and a maximum of 6 traffic lanes will be available, both in the southerly and northerly direction, allowing traffic flow to be improved.

If the 2-lane tube of the new road traffic tunnel is used for traffic travelling south (morning rush hour), it is possible that traffic moving in opposite directions in adjacent tubes could lead to aerodynamic short circuit occurring. This means that some of the traffic emissions to the air, caused by the traffic emerging from the tunnel, can be directly taken into the other tube by the traffic driving into that tunnel (due to both the wind and ventilation and the movement of the traffic). These effects depend on the meteorological conditions (wind speed and wind direction) and the tunnel portal geometry. In order to determine the effect of air pollution short circuit a scale model (1:150) of the road traffic tunnel was built to test in the atmospheric windtunnel. Figure 3 shows the atmospheric boundary layer and a model of the tunnel portal. The average (constant) air velocity in the tube of the new road traffic tunnel should be 5 m/s (ventilation design criteria). The aerodynamic effect nearby the tunnel portal depends strongly on the relation between the air velocity in the road traffic tunnel and the (free field) wind speed at 10 metres high, so the research is made for different speed ratios.

Figure 3: Atmospheric boundary layer and scale model of the tunnel portal.



3. WINDTUNNEL STUDY

Figure 4 shows the atmospheric boundary layer windtunnel, the model and surrounding equipment.

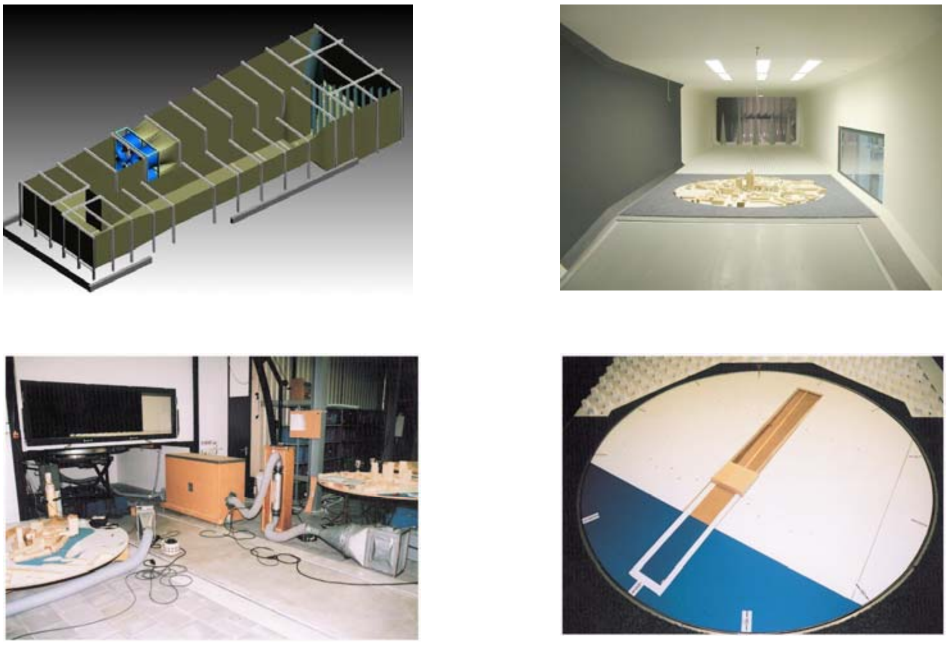


Figure 4: Peutz atmospheric boundary layer windtunnel, model and surrounding equipment.

For the purposes of this research into the road traffic tunnel, the situation with 4-lane traffic in a northerly direction and 2-lane traffic in a southerly direction is relevant (morning rush hour). For the northern tunnel portal, the 4-lane exiting and 2-lane entering situation was therefore taken. For the southern tunnel portal, the situation considered was with 2 lanes of exiting traffic and 4 lanes of traffic entering the tunnel.

In the possible situation with 6 lanes of traffic travelling in a northerly direction (evening rush hour), there would be no traffic travelling in the opposite direction and therefore no aerodynamic short circuit occurring.

The concentration measurements for the flow research were carried out using tracer gas (isobutylene) in combination with PID monitors. The measured concentrations were being corrected for background concentrations.

Variant research

The following structural variants were considered in this research (for the north portal of each variant, a photo of the modified scale model is included, see Figures 5 through 10):

- *Variant A: Present design (Figure 5)*
  Smoke barrier with canopy (canopy 50% open).

Length smoke barrier approx. 20 metres;
- *Variant B: Present design without canopy (Figure 6)*
  Without smoke barrier and canopy, central reservation with wall approx. 1 metre high;
- *Variant Cl: Present design with raised smoke barrier (Figure 7)*
  As A, in addition smoke barrier raised to ground level;
- *Variant C2: Present design with lengthened and raised smoke barrier (Figure 8)*
  As Cl, raised smoke barrier with approx. 20 metres of extra length (total approx. 40 metres);
- *Variant Dl: Present design with extended exit (Figure 9)*
  As A, in addition tube exit extended by approx. 20 metres;
- *Variant D2: Present design with extended exit extension (Figure 10)*
  As Dl, tube exit extended by a further approx. 20 metres (total approx. 40 metres);

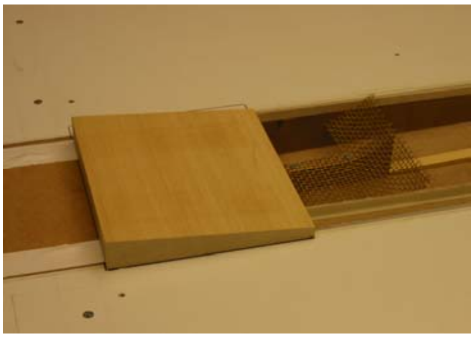


Figure 5 (variant A)

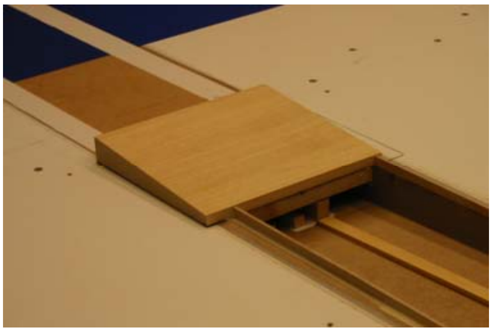


Figure 6 (variant B)

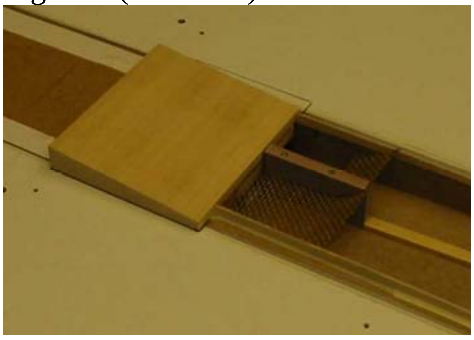


Figure 7 (variant C1)

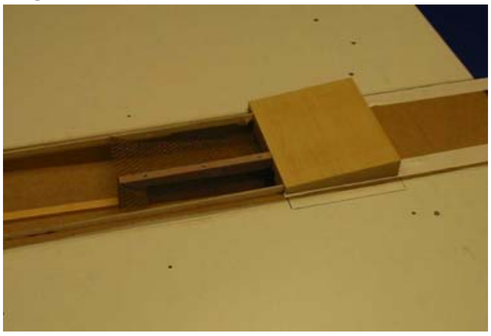


Figure 8 (variant C2)

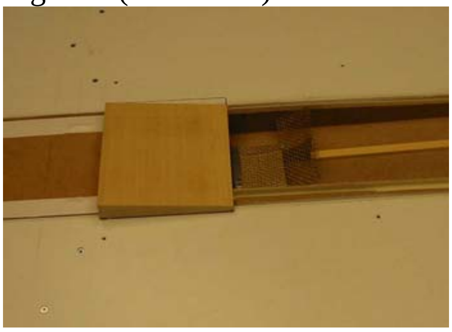


Figure 9 (variant D1)

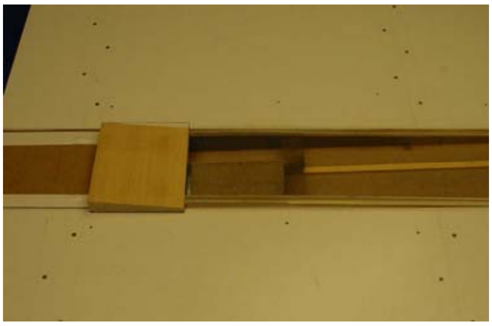


Figure 10 (variant D2)

The extent of air pollution short circuit is determined in part by the relationship between the ventilation speed in the tube (V_t, constant 5 m/s) and the wind speed in the environment at 10 metres high (V_w, variable). For the purposes of this research, the following 3 speed ratios were applied:

$V_w / V_t = 2$ wind speed 10 m/s, ventilation speed 5 m/s
$V_w / V_t = 1$ wind speed 5 m/s, ventilation speed 5 m/s
$V_w / V_t \sim 0$ wind speed ~ 0 m/s, ventilation speed 5 m/s

It should be however noted that, owing to measuring circumstances, the lowest speed ratio was approximated by applying V_w= 0.6 m/s at a V_t of 5 m/s (in fact V_w/V_t = 0.12).

This wind-tunnel research therefore involved 36 variants, i.e. 6 structural variants for 3 different speed ratios for both tunnel portals. To verify the measurements, a set of control measurements were performed (reproducibility).

Measurement results air pollution short circuit

The concentration measurements in the wind-tunnel resulted for each structural variant, each speed ratio (V_w/V_t) and each wind direction in an emission concentration at the exit (representing concentration of exhaust gasses resulting from the traffic exiting the tunnel tube) and an immission concentration at the entrance of the other tube. The immission concentrations were determined downstream in the tube. In figure 11 an example of a measured situation is given. The measurements revealed that the aerodynamic short circuit occurring at the speed ratio $V_w / V_t \sim 0$ is virtually unaffected by the wind direction, owing to the relatively low wind speed.

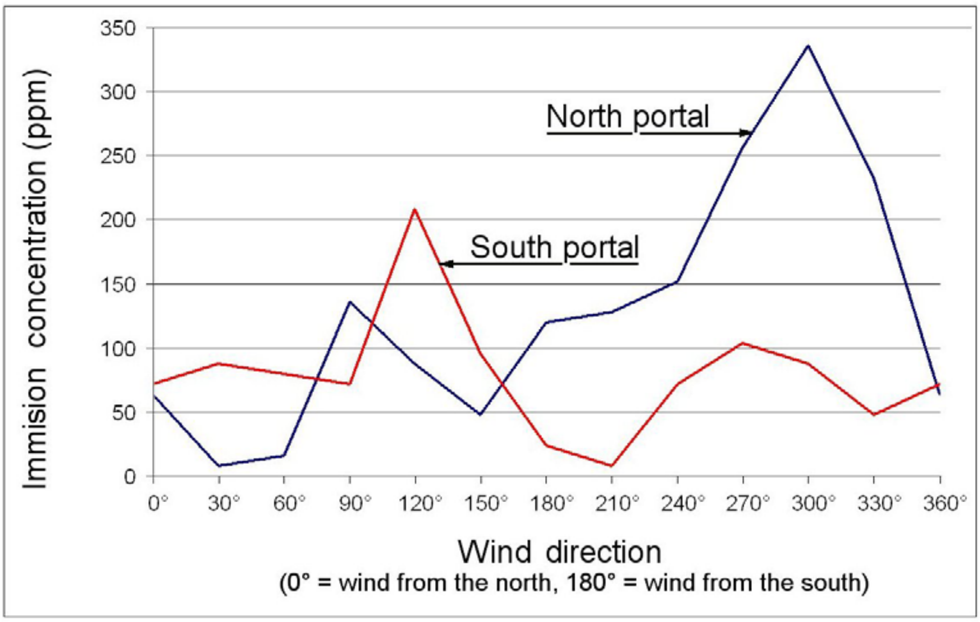


Figure 11: Example of measured immission concentration (ppm) downstream in road traffic tunnel tube as a function of wind direction (°): $V_w / V_t = 2$, variant A, emission concentration from emitting tube approximately 800 ppm.

4. CALCULATIONS

4.1. Calculation of air pollution short circuit

For a given wind speed and wind direction, the emission concentration at the exit and the immission concentration downstream from the entrance can be used to calculate the short circuit percentage. The formula below is used for this:

$$R = \frac{C_{immission}}{C_{emission}} \bullet 100\% \qquad [1]$$

Whereby:

- -R = short circuit percentage [%]
- -$C_{emission}$ = emission concentration exit [ppm];
- -$C_{immission}$ = immission concentration entrance (downstream, corrected for background concentration) [ppm].

4.2. Results of the calculations for short circuit

The short circuit percentage is determined on the basis of the emission and immission concentrations found for each measurement, using formula [1]. The minimum and maximum air pollution short circuit percentages occurring are given in table 1.

Table 1: minimum and maximum air pollution short circuit percentages for several design variants; tunnel portal north and south.

Tunnel portal north						
	V_w = 10 m/s, V_t = 5 m/s		V_w = 5 m/s, V_t = 5 m/s		V_w = 0,6 m/s, V_t = 5 m/s	
variant*	minimum	maximum	minimum	maximum	minimum	maximum
A	ca. 1%	ca. 42%	ca. 5%	ca. 17%	ca. 1%	ca. 6%
B	ca. 8%	ca. 53%	ca. 8%	ca. 35%	ca. 10%	ca 12%
C1	ca. 1%	ca. 34%	ca. 2%	ca. 19%	ca. 1%	ca. 2%
C2	ca. 0%	ca. 20%	ca. 1%	ca. 17%	ca. 1%	ca. 2%
D1	ca. 1%	ca. 32%	ca. 1%	ca. 20%	ca. 0%	ca. 1%
D2	ca. 0%	ca. 18%	ca. 1%	ca. 13%	ca. 1%	ca. 1%

Tunnel portal south						
	V_w = 10 m/s, V_t = 5 m/s		V_w = 5 m/s, V_t = 5 m/s		V_w = 0,6 m/s, V_t = 5 m/s	
variant*	minimum	maximum	minimum	maximum	minimum	maximum
A	ca. 1%	ca. 26%	ca. 4%	ca. 15%	ca. 2%	ca. 3%
B	ca. 6%	ca. 39%	ca. 7%	ca. 27%	ca. 8%	ca 10%
C1	ca. 2%	ca. 21%	ca. 2%	ca. 15%	ca. 1%	ca. 2%
C2	ca. 1%	ca. 14%	ca. 2%	ca. 15%	ca. 1%	ca. 4%
D1	ca. 2%	ca. 22%	ca. 2%	ca. 14%	ca. 1%	ca. 2%
D2	ca. 2%	ca. 12%	ca. 1%	ca. 10%	ca. 1%	ca. 1%

4.3. Reproducibility

The accuracy of the concentration measurements is approx. 5 ppm, which leads to a level of inaccuracy in the short circuit percentages of 1 to 2%.
A comparison of the short circuit percentages from control measurements with the short circuit percentages from the standard measurements shows that these can be reproduced with sufficient accuracy (+/- 2%).

5. CONSIDERATIONS

From the measurements and calculations made for the planned road traffic tunnel, it appears that the maximum air pollution (aerodynamic) short circuit occurs at a speed ratio of $V_w / V_t = 2$. The short circuit occurring at the other speeds tested ($V_w / V_t = 1$ and $V_w / V_t \sim 0$) is generally (considerably) lower.

At the north portal, the maximum air pollution short circuit occurs with a north-westerly wind (300°). At the south portal, the maximum aerodynamic short circuit occurs with a south-easterly wind (120°). This corresponds to expectations in this respect; the occurrence of "slipstream effects" at the mouth of the tunnel in the tunnel trough in these situations means that a significant portion of the emissions from the 4-lane tube is sucked back into the 2-lane tube.

Table 1 shows that at the north portal, with variant A (present design), the aerodynamic short circuit would reach a maximum of approx. 42%. At the south portal, the short circuit in this variant would be a maximum of approx. 26%.
In the case of variant B (present design without canopy), the air pollution short circuit would reach a maximum of approx. 53% at the north portal and approx. 39% at the south portal.

In the case of Cl (present design with raised smoke barrier), the air pollution short circuit would reach a maximum of approx. 34% at the north portal and approx. 21% at the south portal.

In the case of C2 (present design with extended and raised smoke barrier), the air pollution short circuit would reach a maximum of approx. 20% at the north portal and approx. 14% at the south portal.

In the case of Dl (present design with extended exit), the air pollution short circuit would reach a maximum of approx. 32% at the north portal and approx. 22% at the south portal.

In the case of D2 (present design with extended exit extension), the air pollution short circuit would reach a maximum of approx. 18% at the north portal and approx. 12% at the south portal.

The above considerations per variant show that the maximum short circuit occurring at the south portal is in all cases less than that at the north portal, which is a consequence of the situations considered above. For the northern tunnel portal, the 4-

lane exit and 2-lane entrance situation was considered, while for the southern tunnel portal the 2-lane exit and 4-lane entrance situation was considered. The determining slipstream in the former situation is present over a larger polluted area of emission than in the latter, whereby in the former situation a larger portion of the emissions will be sucked into the other tube by means of (aerodynamic) short circuit.
This research has revealed that the most air pollution short circuit occurs in variant B (present design without canopy).

Virtually the same amount of short circuit is also present in variants Cl (present design with raised smoke barrier) and variant Dl (present design with extended exit), but less than with variant A (present design). Raising the smoke barrier to ground level would reduce the maximum air pollution short circuit occurring in relation to variant A (present design) by approx. 5 - 8%; extending the exit by approx. 20 metres reduces the maximum air pollution short circuit occurring in relation to variant A (present design) by approx. 4 - 10%, all depending on the tunnel portal under consideration (north or south).

In the case of variant C2 (present design with extended and raised smoke barrier) and variant D2 (present design with extended exit extension), the amount of short circuit is virtually the same, but less than in the case of variants Cl and Dl. By extending the raised smoke barrier by approx. 20 metres, the maximum aerodynamic short circuit occurring in relation to variant Cl is reduced by a further approx. 7 - 14%. In relation to variant A (present design), the maximum short circuit occurring is reduced by approx. 12 - 22%. By lengthening the exit by another approx. 20 metres (total approx. 40 metres), the maximum aerodynamic short circuit occurring in relation to variant Dl is reduced by a further approx. 10 - 14%. In relation to variant A (present design), the maximum short circuit occurring is reduced by approx. 14 - 24%.).

6. CONCLUSIONS

On the basis of the starting points, the wind-tunnel research and the calculations concerning the aerodynamic short circuit occurring at the tunnel portals of the planned road traffic tunnel, it can be said that:

- the maximum air pollution short circuit occurring for the present design would be approx. 42%;
- if the present design were to be implemented without canopy and smoke barrier, the maximum air pollution short circuit would increase to significant more than 50%;
- raising the smoke barrier (to ground level) would reduce the aerodynamic short circuit in relation to the present design by approx. 5 - 8%, depending on the tunnel portal in question (north or south);
- extending the exit (by approx. 20 metres) would reduce the aerodynamic short circuit in relation to the present design by approx. 4 - 10%%, depending on the tunnel portal in question (north or south);
- extending the raised smoke barrier to approx. 40 metres would reduce the aerodynamic short circuit in relation to the present design by approx. 12 - 22%%, depending on the tunnel portal in question (north or south);

- extending the exit to approx. 40 metres would reduce the aerodynamic short circuit in relation to the present design by approx. 14 - 24%%, depending on the tunnel portal in question (north or south).

On the basis of the research carried out, insight has been obtained into the various flow effects, such as slipstream effect and thinning so that, taking undesired short circuit effects into account, a well-considered choice of structural variant can be made.

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